Authors response to Professor Don Forbes review – Reviewer 1

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.

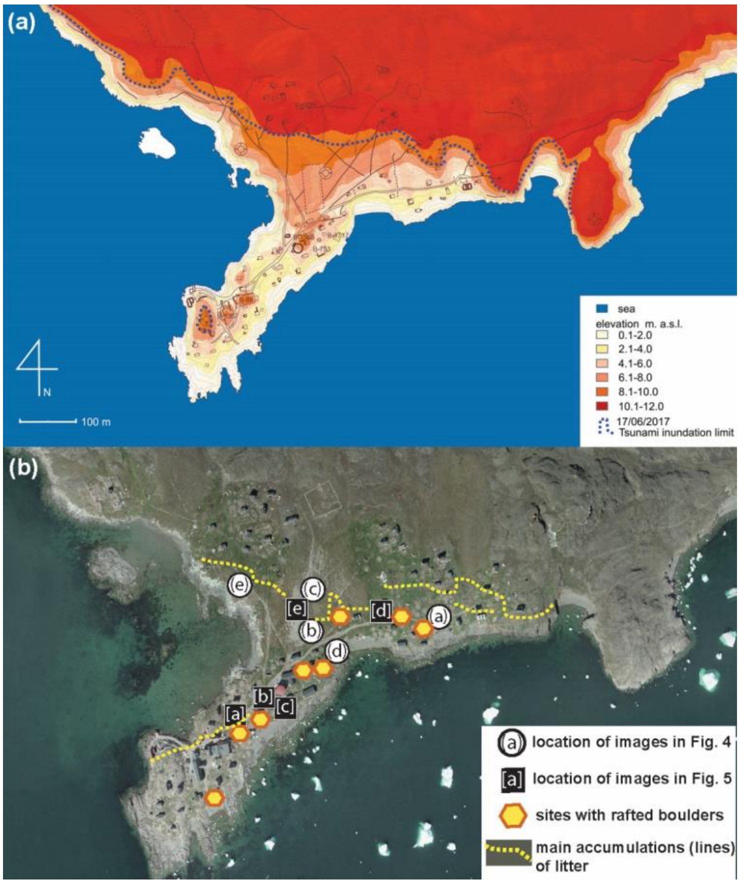

Figure 3. (a) Digital elevation model (2-m DEM, https://www.pgc.umn.edu/data/arcticdem/) of Nuugaatsiaq with marked tsunami inundation limit (wave flooded the terrain up to 8 m a.s.l). (b) Overview map of the settlement with marked location of images from Fig. 4 and 5. Lines of litter visible in the 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.

Author's response to Dr Dan Shugar Review: Reviewer 2

The paper by Strzelcki and Kaskolski provides a useful contribution to efforts to understand large tsunamis triggered by landslides in high latitudes. These megatsunamis can be extremely destructive, but are rare enough that opportunities to study them are rare. The data and insights described in the paper stem from a field reconnaissance exercise two years after the event, and so it is likely that much of the more delicate evidence was eroded away prior to the authors' arrival on site. In general, the paper is well-written. My main issue is that I was underwhelmed by the level of detail presented and as a result, I can't recommend publication in its current state.

Both authors (Strzelecki and Jaskólski) thank you for your general comments and suggestions. We agree with you that Karrat Fjord tsunami provided very rare opportunity to study not only the geomorphological effect, but also observe how destructive was the wave for coastal infrastructure. Most of your general suggestions were already raised by the Reviewer 1 and we explained the corrections in response to his review, so in this response we only focus on specific comments.

GENERAL COMMENTS

The title should be changed. Warming is not actually addressed in the paper, and it is not clear whether warming would have had an effect. The landslide was triggered by an earthquake, and while permafrost thaw may have hastened collapse, these details are not known (at least not from this manuscript). I was surprised by the lack of quantitative observations in the paper. For example, could the observed coastal erosion be quantified from field measurements, or satellite/DEM analyses?

As I said earlier, the paper is generally well-written but there are some grammatical issues and odd turns of phrase. I have elected not to mention them here, as I feel those are secondary issues and can be fixed later. More importantly, the issue of insufficient detail in the results needs to be addressed.

Author's Response: We have modified the title and add new paragraphs on study site characteristics, history of the settlement and more data on coastal relief changes, vegetation and infrastructure damages. Please keep in mind that we had a chance to spend only 2.5 days in this abandoned site which is under threat of another tsunami, so considering time spend in the field and health and safety matters it would be difficult to extract more for collected data.

SPECIFIC COMMENTS

L23 – The language about "shocking" the public is rather sensationalistic and I'm not sure is actually fair. Also, the use of the term "Arctic" is not really appropriate. While the 2017 landslide was north of the Arctic circle, many of the other events described in the text are subarctic.

Author's Response: Thanks for the comment. We modified our sentence and wrote about tsunamis in cold regions (i.e. Arctic and subarctic).

L31 – For the Tyndall/Taan landslide, there are a few other papers that the authors may wish to familiarize themselves with:

1. Bloom and others wrote about the landscape modifications

https://www.sciencedirect.com/science/article/abs/pii/S0169555X19305215 2. George

and friends did some modelling https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2017GL074341

3. Haeussler and colleagues published a paper based on field data (mostly in submarine realm): https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2018JF004608

Author's Response: Thank you very much for suggestions. We have added Bloom et al. 2020 and Haeussler et al. 2020 to our reference list. We have noticed that you are the co-author of those interesting paper (Congratulations on those important contributions to cold region tsunami research. We are particularly impressed with the potential of fan deltas to preserve information of the tsunami impact).

L69 - I find this "50% larger" an odd statement (and I realize it's more or less exactly

what Gauthier said). The volume of Lituya 1958 was ~30x10ˆ6 m3, and the reported

volume of the Karrat 2017 landslide was 35-58 x 10ˆ6, so a range of 17-93% larger.

Author's Response: Thank you for suggestion. We have added the volume estimations to the text.

L73 – No need to describe who led the expedition or where they are from.

Author's Response: Thank you for suggestion. However, we would like to keep the name of the team and group leader in the text to acknowledge their tremendous research effort. This is a common practise in Arctic research community.

L90 – Here (and elsewhere), I found the descriptions of the deposits lacking in detail to

the point where they are not particularly useful for other studies.

Author's Response: Thank you for your comment, whenever we could we have added information about tsunami deposits thickness and dominant grain size.

L102 – As above, the description of "modified the relief of cliffs" is far too ambiguous.

Modified how? Can you explain the changes via some maps perhaps?

Author's Response: Thank you for your comment. We have explained the cliff relief modifications in the next sentence informing that the edges of the sedimentary cliffs were gullied, and the steep cliff slopes were spread with eroded blocks of tundra and litter (Fig. 2e).

Regarding your question the we have made an attempt to apply remote sensing analyses to calculate erosion. The ArcGIS DSAS tool have shown a smaller change in the boundary line than the probable measurement error interval. As the coast around the settlement is predominantly rocky, the wave did not trigger significant erosion. The major erosional effects was limited to erosion and redeposition of tundra bluffs (1-2 m width). We treated this as a coastal landscape remodelling and showed in the pictures in Figure 2 & 5

L111 – I don't understand what "modified by snow-melt flow tsunami deposits accumulations" means.

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).

L120 – The idea that the finer deposits were trapped by vegetation and so didn't travel as far as the coarser material is very interesting. Do you have any way to quantify (or even qualify) the vegetation prior to the tsunami? My understanding of your results are that they are limited to the post-tsunami landscape for the most part.

Author's Response: Thank you for your comment. The vegetation trapping the finer deposits was a working hypothesis we formulated in the field. Now, with time, and watching couple of short movies taken by local inhabitants during the event, we know that the vegetation was not so dense as present. We discussed our findings of relatively thin and scares preservation of tsunami deposits with leading experts in the field, which led us to the conclusiton that because of small amount of marine deposits sored tiny, pocket beach along predominantly rocky coast the tsunami did not transfer significant amounts of fine (sand, gravel) deposits on land. Therefore, we have decided to delete this fragment.

L130 – What are "point foundations"? Do you mean the building is set on top of (aboveground) boulders or concrete piers at the corners?

Author's Response: Thank you for your question, indeed we meant that the building is set on top of (aboveground) pier foundations. We have changed point foundation to pier foundation.

L144 – The section on waste is interesting but especially vague.

Author's Response: Thank you for your comment. We are aware that our paper lack the detailed analysis of the scale of the threat, but it seems to us that the presence and exposure of waste to harsh weather conditions is undoubtedly a threat itself. With this paragraph we would like to draw the attention of the local authorities that the mere presence of these materials in the Arctic environment poses a potential threat to the environment, and natural disasters associated with e.g. landslides, tsunamis or thawing permafrost can cause an ecological disaster.

L159 – I am really surprised to see no mention of the Vaijont disaster here. Yes, this was in a reservoir and not the ocean but the mechanisms are very similar.

Author's Response: Thank you for your suggestion, you are right the mechanisms of the catastrophe were similar, but in our research we focus on the coastal environment in polar region.

L180 – This paragraph would benefit from some numbers describing the areas being described. So for example, you state that Benjamin mapped 20 rock avalanches along a "short section" of coast. What is short? 100m? 100km?

Author's Response: Thank you for your comment. We have added the missing information – the coast studied by Benjamin et al. 2018 was ca. 25 km long.

L185 – Why is this described as a "pilot study"?

Author's Response: Thank you for your comment. We treated our work as a pilot study meaning that we were the first research team to map the geo-ecological and infrastructural effects of the wave. We have deleted this unnecessary term.

L189 – If you are going to state that the "scientific community did not really believe. . ." you definitely need a citation or two to back up that claim.

Author's Response: Thank you for your comment. We have modified the sentence to get rid of the journalese.

L195 – The conclusions raise several points that were not actually discussed specifically in the text. Similarly, Table 1 contains information that was not described in-text.

Author's Response: Thank you for your comment. We have developed our discussion using the data presented in Table 1. We also have added new paragraph in section 3 Research area - 3.2 Settlement history and economy where we present the key facts on Nuugaatsiaq settlement. Where we have mentioned about community abandonment too.

Fig 4 – I found that it was not easy to compare panels (a) and (b) since they are from slightly different vantages. Panel (c) is also confusing. The red buildings are damaged or destroyed? And the yellow buildings were moved from where?

Author's Response: Thank you for your comment. We have prepared a new Figure 4 (now Figure 6) , hope now it is much clearer to notice the infrastructure damages and changes.

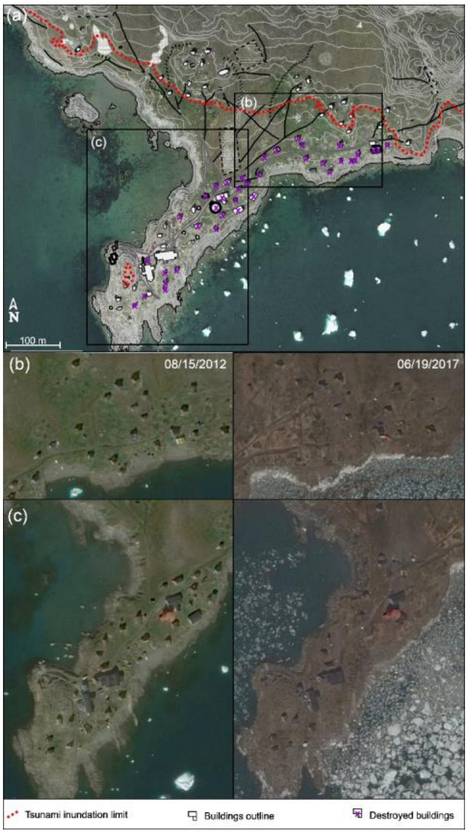

Figure 6. Scale of destruction in settlement infrastructure. (a) General overview of area inundated by tsunami with location of damaged buildings. The inventory of tsunami-induced changes of settlement infrastructure are based on interception of aerial images, local spatial plans and field surveying. Background ortophoto & technicalmap: nunagis.gl.; (b) Satellite image of settlement before the tsunami impact (15th August 2012) and; (c) Satellite image of settlement after the tsunami impact illustrate the scale of destruction and dislocation of buildings (19th June 2017) Background Google Earth Image © 2020 Maxar Technologies.

REVISED MANUSCRIPT WITH ALL CHANGES MARKED:

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

~~Tsunamis unleashed by rapidly warming Arctic degrade coastal landscapes and communities – case study of Nuugaatsiaq, western Greenland~~

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Abstract

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.

Commented [A1]: REVIEWER: 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.

On the 17th of June 2017, a massive landslide which mobilized ca. 35–58 million m^3 of material entered the Karrat Fjord 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. Here we report the results of the field survey of the surroundings of the settlement focused on the perseverance of infrastructure and landscape damages caused by the tsunami, carried out 25 months after the event.

1 Introduction

Although known to the research community for at least 60 years, the occurrence, scale and impacts of tsunamis in cold regions (Arctic and subarctic) still shock the wider public. 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.

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Although known to the research community for at least 60 years, the occurrence, scale and impacts of Arctic tsunamis still shock the wider public. Even as Arctic tsunamis are often presented in media coverage as a part of polar myths, 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.

The unstable nature of Arctic landscapes in terms of permafrost-thawing or glacier retreat-or earthquake- induced landslides provide potential tsunami sources. The effects of waves are particularly destructive in fjords and narrow straits, where a constraining topography can amplify the wave heights. For instance, the landslide which entered Lituya Bay in Alaska in 1958 triggered the giant tsunami wave with runup height of over 500 m (Miller, 1960). Another wave (runup over 190 m) recorded in coastal Alaska (Taan Fjord, 2015) was caused by the landslide from local slopes destabilized by the retreat of Tyndall Glacier (Dufresne et al., 2018; Higman et al., 2018). In the last hundred years tsunamis were recorded also in Norwegian fjords e.g. the Tafjord 1934 event (e.g. Harbitz et al., 2014).

In Greenland, due to the recent climate change (i.e. shrinking of glaciers and permafrost thawing) many mountain slopes were destabilized and released numerous tsunamigenic landslides. For example, in November 2000 a landslide from Paatuut mountain triggered a tsunami (runup ca. 50 m) which destroyed Qullissat town (Disko Island, western Greenland) and destabilized shores along Vaigat Strait even up to 150 km from the landslide site (Dahl-Jensen et al., 2004; Buchwał et al., 2015). The same region was also hit by a tsunami after the Niiortuut landslide in 1952, as mentioned in the recent inventory of Greenland landslides carried out by Svennevig (2019).

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). Our study provides insights into the geo-ecological and socio-economic impacts of an Arctic tsunami hazard and focuses on an inventory of lasting extreme wave effects in a coastal settlement landscape and the affected community two years after the event.

2 Materials and Methods

This study is based on field observations carried out in July 2019. We followed the post-tsunami traces mapping described in the seminal paper of Szczuciński (2012) on post-depositional changes of onshore tsunami deposits. It is important to note that the visit occurred 25 months after the event, which means that at least two spring melt-out seasons happened between the event and the mapping. It is likely that some of the tsunami traces (particularly fine deposits, tsunami salt covers and iceberg erosional and depositional marks) were partly erased from the landscape. The largest boulders and litter lines were marked with a handheld GPS. We took a careful survey of the vegetation cover change, as suggested by Buchwał et al. (2015) in their study of 2000 Paatuut tsunami impact on an Arctic shrub ecosystem. We photographed each settlement building or facility (e.g. cemetery, playground, harbour, heliport) and noted any visible infrastructure and landscape degradation. We observed some signs of human action on the site, focused on removing most of the toxic substances left in the settlement, that is petrol. In order to properly understand the scale of post-tsunami changes we compared a series of aerial images (available at NunaGIS portal: www.nunagis.gl), field photos, online movies taken in the settlement before and after the wave, and settlement spatial planning maps and risk assessment documents published by the local government. Apart from land-based photos, we collected a number of aerial images using a DJI Mavic Pro drone. As our UAV was not allowed to enter the no-fly zone above the settlement centre, we took oblique images from the recommended distance. Information about landslide genesis and some of the tsunami wave characteristics were extracted from remote-sensing analyses produced by USGS (Bessette-Kirton et al., 2017) and the collection of geophysical reports published soon after the event (Clinton et al., 2017; Chao et al., 2018~~7~~; Gauthier et al., 2018; Butler, 2019; Poli, 2017; Paris et al., 2019).

3 Research area

3.1 Geographical setting

The surrounding landscape is mountainous (mountain ranges with numerous summits and plateaus reaching 2000 m a.s.l) and is characterized by one of the highest relief in western Greenland (Roberts et al. 2013). The major role in shaping the present-day geomorphology was played by retreating Uummannaq ice stream system (UISS) which left the diverse set of glacial landsystems in fjords, mountains and valleys of the region. The landscape was dissected by selective linear glacial erosion with lowlands dominated by glacial scour and mountain ranges occupied by cirque, plateaus, and valley-type glaciers (Lane et al. 2016). Lane et al (2016) classified banks of Karrat fjord and southern coasts of Qeqertarsuaq island, where studied settlement is located, to areal scour terrestrial landsystem exposed after the retreat of two northern branches of UISS (Umiamako Isbrae and Rink Isbrae). Ice streams significantly modelled the topography of local fjords. Dowdeswell et al. (2016) described submarine landscape (Rink Fjord and Karrat Isfjord) a system with relatively smooth seafloor, broken by bedrock ridges and pinnacles that divide the fjord into several deep basins. Bathymetry maps derived from multibeam echo soundings data acquired in 2007-2014 and compiled by Rignot et al. (2016) revealed that the entrance to Karrat Isfjord is 600 m deep, 5 km wide, with a sill at 400 m depth about 160 km from Rink Isbrae The deepest basin of the fjord (1100 m) is located ca. 25 km to the east of Nuugaatsiaq. Fjord near the settlement is shallow with seafloor depths 0-240 m.

Nuugaatsiaq coastal landscape is predominantly rocky with an undulating and ragged coastline dissected by narrow coves and headlands (Fig.2a). Rocky coves along southern coast of Nuugaatsiaq are filled with narrow beaches underlaid by rocky bedrock (Fig. 2a). Beach deposits are thin (< 1m) and composed of mixed coarse sand and gravel deposits as well as boulders deposited by icebergs or left along the shores by retreating ice streams. The largest cape in the area, located to the SW of the settlement centre is characterized by bare rocky surface with well-preserved signs of glacial scour e.g. striations and polished bedrock (Fig.2b). Close to the shoreline most of smooth rocky hollows were filled with accumulations of boulders (ca. 0.2-0.5 m in diameter). The Nuugaatsiaq harbour (site 7 in Fig. 1c) is backed by the cliffed coast (between 2-4 m high) formed in bedrock (ca. 0-2 m .a.s.l.) and overlaid by 1.5 – 3 m layer of soils/glacial deposits and covered with dense tundra (Fig. 2c). At the base of the cliff narrow (1-3 m wide) mixed sand-gravelly beaches are present.

3.1.2 Geology

The dominant rocks in the region are Archean gneisses mixed with supracrustal rocks of the Palaeoproterozoic Karrat Group (Sørensen and Guarnieri, 2018). The slopes of Ummiammakku mountain where the tsunamigenic landslide occurred are composed of gneisses (Archean) overlain by quartzites (Palaeoproterozoic) and schist of the so-called Karrat Group (Mott et al., 2013).

3.1.3 Permafrost

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 km^2 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.

3.1.4 Vegetation

This area is a part of the mid-arctic oceanic vegetation zone (Bay 1997). The vegetation comprises a shrub-grassland system, with commonly found circumpolar species including *Carex ursina*, *Cassiope* heath, *Salix glauca*, *Festuca groenlandica*, *Puccinellia groenlandica*. Coastal grasslands are dominated by dense Honckenyo-Elymetum mollis associations (Lepping & Daniëls 2007). Inspection of satellite images and photographs taken in Nuugaatsiaq before the event suggest that grassy-tundra covers dominated the top of coastal bluffs and stripe of coastal lowlands between the predominantly rocky shore and main coastal road passing the settlement from west to east. During our fieldwork we noticed very dense and relatively high (0.4 – 0.6 m) grassy meadows covering coastal lowlands, and recolonizing abandoned playgrounds, roads, backyards. The observed post-event vegetation cover in study area was significantly denser and higher than in other settlements visited in the region in the same season.

3.2 Settlement history & economy

Nuugaatsiaq is a settlement in the district of Uummannaq in the Avannaata Kommunia. Nuugaatsiaq is located in the south of the Qeqertarsuaq Island (Fig.1), dominated by Snehætten (Nuugaatsiap Qaqqaa) mountain range The island is separated from Karrat Island located between Karrat Fjord and Karrat Isfjord by the Torsuuk strait. The closest settlement is Illorsuit and lies about 35 km south-west.

Nuugaatsiaq was probably settled shortly after 1918. In 1923 it was proposed in Grønlands Landsråd to divide the municipality of Illorsuit. For this purpose, a new Udsted had to be built. Udsted (roughly translatable as outlying settlement): Udsteder were smaller trading settlements, which were administered by an Udsteds administrator. Most of the Udsteders later became villages. In 1925 Nuugaatsiaq was granted Udsteds status and in the same year a dwelling was built for the Udsteds administrator. In 1926 the village received a school chapel. In 1930 Nuugaatsiaq already had 119 inhabitants. In the same year a shop with a warehouse was built and in 1936 a packing house (Madsen 2009). In 1960 the population reached its maximum with 159 people. In 2017 the settlement had 102 inhabitants (bank.stat.gl).

Nuugaatsiaq has been living mainly from halibut fishing, while some time ago there was still seal hunting and catfish fishing. A small trading branch of Royal Greenland with a maximum of ten employees stored the fish. Other jobs were in administration, at Pilersuisoq, in tourism and at Atuarfik Saamu School, which taught twelve students in grades one to nine and also offered a library and youth leisure activities. There was also a day care centre, the post office, an infirmary, and a village hall. Majority of buildings were located on undulating coastal lowland between 1 to 4 m a.s.l. (Fig.3a)

There is a small quay on the headland that gives the village its name. Most of the boats were usually launched directly at the water's edge in small harbour. In the north is the heliport Nuugaatsiaq. In winter, the traffic was by snowmobile and dog-sledge.

Nukissiorfiit (state utility company) supplied the village with electricity via the power station in the east and with fresh water via a tank. Garbage was burned or dumped into the sea. TELE Greenland provided the telecommunications.

The events of June 17th 2017 resulted in the evacuation of settlement and abandonment of community which last till present. Currently former inhabitants of Nuugaatsiag were relocated to Uummannaq and Qaarsut settlement placed over 100 km south of Nuugaatsiaq (Fig.1).

~~3~~4 Results and discussion

~~3.1~~4.1 Landslide and tsunami characteristics

According to the analysis of seismic precursors of the Event carried out by Butler (2019), the tsunami was a direct result of the landslide triggered by the following sequence of processes. An earthquake ruptured the fault surface and released the hanging wall ca. 1000 m above the sea, and a head scarp was created and transformed into a rock avalanche which entered the fjord, causing the wave. Gauthier et al. (2018) calculations suggest that the Karrat fjord landslide was much larger (~35-58 x10ˆ6 m^3) than the famous tsunamigenic rockslide into Lituya Bay, Alaska in 1958 (~30x10ˆ6 m^3). Interestingly, on the map of the Nuussuaq Basin showing landslide prone areas published by Pedersen et al. (2002), the Karrat Fjord region is not marked as a potential risk area. ~~Gauthier et al. (2018) suggested that the Karrat fjord landslide was approx. 50% larger than the famous tsunamigenic rockslide into Lituya Bay, Alaska in 1958. Interestingly, on the map of the Nuussuaq Basin showing landslide prone areas published by Pedersen et al. (2002), the Karrat Fjord region is not marked as a potential risk area.~~

A field survey carried out by a group of researchers led by Professor Fritz from the Georgia Institute of Technology (Schiermeier, 2017; https://ce.gatech.edu/news/after-recon-trip-researchers-say-greenland-tsunami-june-reached-300-feet-high) found evidence that the wave runup height was ca. 90 m at the landslide site, and up to 50 m on the opposite side of the Karrat Fjord. Numerical modelling of the landslide and wave performed by Paris et al. (2019) indicates that the Nuugaatsiaq located ca. 32 km from the landslide was hit by three 1 – 1.5 m high waves, inundating the settlement over a period of ca. 3 minutes.

~~3.2~~4.2 Landscape degradation

~~4~~3.2.1 Soil and tundra cover

The striking feature of the Nuugaatsiaq post-tsunami landscape is a dense and high (0.4-0.6 m) grass that covers a significant part of the settlement (Fig. 2a). Two years after the event most of the blocks of eroded soil, rafts of tundra, boulders, or litter that were found were almost entirely hidden in a high grass cover (Fig. 4a). The wave has torn blocks of tundra (shrubs, mosses, grass) off the coastal slope and deposited them on land (Fig. 4 b, c). We have noticed that a significant removal of tundra cover, soil erosion, and associated formation of rills or small gullies (0.2-0.6 m deep) concentrated on surfaces exposed after the washing away of buildings. Tundra and soil were also eroded along the cliffed coast of the harbour (Fig. 4 d, e). At a few places along the main road and in the surroundings of the playground the vegetation cover (grasses) was covered by a thin layer of tsunami deposits (3 – 7 cm) composed mainly of marine gravels mixed with coarser sands. Salty patches with dead-vegetation were observed mainly across the saddle between southern coast and local harour (site 6 in Fig. 1c). After analyzing the video coverage of the event and post-event images (please check list of online resources in references), we assume 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.

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Commented [A3]: 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?

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Commented [A5]: Line 90: Salt patches "covering the exposed or inundated grounds" – I'm unsure what this means – occurs on noninundated surfaces as well?

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Such spots were surrounded by lush grassy tundra. Tundra was compressed also by tsunami-derived boulders both eroded from beaches and melted out of icebergs (Fig. 3b).

~~The striking feature of the Nuugaatsiaq post-tsunami landscape is a dense and high (0.4-0.6 m) grass that covers a significant part of the settlement. Two years after the event most of the blocks of eroded soil, rafts of tundra, boulders, or litter that were found were almost entirely hidden in a high grass cover (Fig. 2a). The wave has torn blocks of tundra (shrubs, mosses, grass) off the coastal slope and deposited them on land (Fig. 2 b, c). We have noticed that a significant removal of tundra cover, soil erosion, and associated formation of rills or small gullies (0.2-0.6 m deep) concentrated on surfaces exposed after the washing away of buildings. Tundra and soil were also eroded along the cliffed coast of the harbour (Fig. 2 d, e). At a few places along the main road and in the surroundings of the playground the vegetation cover (grasses) was covered by a relatively thin layer of tsunami deposits. In the same area and along the coast salty patches were observed covering the exposed or inundated grounds. After analyzing the video coverage of the event and post-event images (please check list of online resources in references), we assume that some parts of the grass cover were squashed by the fragments of icebergs washed on shore by the wave.~~

~~3.2.2~~ 4.2.2Coastal erosion

We recognized two main effects on coastal geomorphology induced by tsunami impact. The tsunami erosion was concentrated on the low bluffs of tundra along the coast between narrow beaches (section of the coast between sites 1-4-5 in Fig. 1c, Fig 2a). Eroded blocks of tundra cover were deposited on land (Fig. 4b). The returning wave caused additional erosion of bluffs edges and dissected them by a series of rills/gullies (Fig. 4d). The direction of the wave flow recorded in the orientation of deposited litter, buildings, marine deposits, boulders, and tundra blocks suggest that the wave overwashed the section of settlement through a saddle (site 6 in Fig. 1c) between the middle beach (site 4 in Fig. 1c) and local harbour (site 7 in Fig. 1c), and modified the relief of cliffs in the harbour. The edges of the sedimentary cliffs were gullied, and the steep cliff slopes were spread with eroded blocks of tundra and litter (Fig. 4e). Two years after the event, normal coastal processes (wave and tidal action) did not manage to remove or redistribute the eroded blocks of tundra and litter from the slopes and bases of the cliffs (Fig.2c).

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~~3.2.3~~3.2.2 Tsunami deposits and boulders

During the field survey the tsunami deposits were found in two areas located in the direct proximity to small beaches in the central part of settlement (between sites 4 and 5 in Fig. 1c). Gravel eroded from narrow beaches

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Formatted: Indent: Left: 0.71 cm, No bullets or numbering was deposited along the main road (ca. 30 - 50 m from the shore), where the thickness of deposits exceeds 8-10 cm Fig. 5 a,b). Thin layer of tsunami deposits (3 – 5 cm), most probably reworked by snow-melt flow (Fig. 5 e, f) were found in the saddle (playground area) between site 4 and 7 (see Fig. 1c). The general scarcity of tsunami deposits can be explained by the geomorphology of the local coastal zone, dominated by sediment-free rocky capes and coves with narrow (7-20 m wide), gravel-dominated beaches (Fig 2a). Apart from gravel deposits washed from local beaches waves transported boulders which were found in the inundated terrain in 2 main types: groups of smaller boulders (a-axis ca. 0.2-0.4 m) deposited on marine gravels along the local road, and separated larger boulders (a-axis over 1.0 m), washed up to 100 - 120 m inland between beach and local harbour (Fig. 5 b,f). In a few places we found pats of marine gravels and boulders deposited up to 100 m from the shore and surrounded by dense grass cover (Fig. 5 c,d). Based on the inspection of videos taken during the event we correlated their location with the deposition of icebergs. In comparison with other Greenlandic coastal zone transformed by a tsunami i.e. Paatuut 2000 tsunami (Buchwał et al., 2015) the thickness, extent, and diversity of tsunami deposits found in Nuugaatsiaq was much smaller, what we associated with sediment-poor beach source and predominantly rocky coastal relief with sediment-free and glacially scoured surfaces. We detected the recognizable difference in tsunami landscape modification between the areas of wave overflow covering most of the saddle in central part of settlement (site 6, Fig. 1c) and area of wave uprush and drainage covering eastern part of the settlement (terrain between sites 1 and 2, Fig. 1c). In the first zone, tsunami eroded material (sand, gravel, boulders) from largest beach in the settlement and fragments of sedimentary and tundra bluffs covering rocky coastal slopes (site 4– Fig. 1c) and transported this mixed load of deposits through settlement to the harbour (site 7, Fig. 1c). This explains larger number of sites and zones with accumulations of tsunami deposits, signs of tsunami erosion and infrastructure destruction concentrated in this zone. In the second area, tsunami waves approached rocky coastal zone, almost sediment free, and inundated grassy lowland carrying mainly community litter and only small amount of sediments, which was difficult to trace in lushy tundra vegetation inspected 2 years after the event. (Fig. 3 a,b). Thin tsunami deposits (modified by snow-melt flow tsunami deposits accumulations) (Fig. e, f) were found in the lowland (playground area) between site 4 and 6 (see Fig. 1c). The general scarcity of tsunami deposits can be explained by the geomorphology of the local coastal zone, dominated by sediment-free rocky capes and coves with narrow (7-20 m wide), gravel-dominated beaches (Fig 2 d,e). Apart from gravel deposits washed from local beaches waves transported boulders which were found in the inundated terrain in 2 main types: groups of smaller boulders (a-axis ca. 0.2-0.4 m) deposited on marine gravels along the local road, and separated larger boulders (a-axis over 1.0 m), washed up to 100 - 120 m inland between beach and local harbour (Fig. 3 b,f). Only a few and separate gravel grains were found in the dense grass at the border, suggesting that vegetation could capture most of the finer deposits carried by waves in the first few meters of the flooded vegetation cover. In a few places we found pats of marine gravels and boulders deposited up to 100 m from the shore and surrounded by dense grass cover (Fig. 3 c,d). Based on the inspection of videos taken during the event we correlated their location with the deposition of icebergs. In comparison with other Greenlandic coastal zones transformed by a tsunami e.g. Paatuut 2000 tsunami (Buchwal et al., 2015) the thickness, extent, and diversity of tsunami deposits found in Nuugaatsiaq was much smaller.

Commented [A7]: 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.

4.2 Settlement degradation

4.3.1 Infrastructure damage

Before the tsunami event the Nuugaatsiaq community infrastructure was composed of 94 buildings (houses, services and administration buildings, dog kennels, technical facilities etc.). The wave destroyed 45 buildings (48% of the original infrastructure) within: 22 buildings were fully swept away from land, 23 buildings were partly broken and 11 of them were moved between 2 m to over 100 m from original location (Fig. 6). Most of the buildings were constructed on a wooden frame, covered with wooden boards and settled on pier foundations. Only a few of the settlement buildings were built on a metal frame coated with corrugated metal sheet settled on a concrete frame foundation. The first type of building (with pier foundations) were not strong enough to resist the wave impact and were pushed by the tsunami or in some cases washed away to the fjord (Fig. 7 a,c).

In those buildings which were not moved but still affected by the wave, we observed some damage of their wooden lining, as well as a deposition of marine sediments and litter in the ground floor area. The typical damages observed in buildings which were pushed by the tsunami but remained on land were: *broken windows and doors, devastated interior*. In contrast to buildings with pier foundations, much smaller damages were observed in buildings with concrete frame foundations. These, due to a more stable anchoring in the ground, gave a much higher resistance to the wave impact. The most common damages included broken walls, bowed and twisted metal construction frames (Fig. 7 b, d). It should be considered extremely fortunate that the fuel tanks situated at the power plant (which were one of the first parts of infrastructure hit by tsunami) were not destroyed and no leakage of petrol was reported (Fig. 7b).

4.3.2 Assessment of social, economic and environmental impacts of tsunami in Nuugaatsiaq.

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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).

3.3 Infrastructure damage

3.3.1 Building damages

We counted the damage of 26 buildings. 15 of them were fully swept away from land, 11 partly broken and moved between 2 m to over 100 m from original location (Fig.4). Most of the buildings were constructed on a wooden frame, covered with wooden boards and settled on point foundations. Only a few of the settlement buildings were built on a metal frame coated with corrugated metal sheet settled on a concrete frame foundation. The first type of building (with point foundations) were not strong enough to resist the wave impact and were pushed by the tsunami or in some cases washed away to the fjord (Fig. 5 a,c).

In those buildings which were not moved but still affected by the wave, we observed some damage of their wooden lining, as well as a deposition of marine sediments and litter in the ground floor area. The typical damages observed in buildings which were pushed by the tsunami but remained on land were: *broken windows and doors, devastated interior*. In contrast to buildings with point foundations, much smaller damages were observed in buildings with concrete frame foundations. These, due to a more stable anchoring in the ground, gave a much higher resistance to the wave impact. The most common damages included broken walls, bowed and twisted metal construction frames (Fig. 5b, d). It should be considered extremely fortunate that the fuel tanks situated at the power plant (which were one of the first parts of infrastructure hit by tsunami) were not destroyed and no leakage of petrol was reported (Fig. 5b).

3.3.2 Remaining waste & material

From the perspective of environmental protection, 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 tanks, the removal of batteries and engines from machines and vehicles, we mapped significant amounts of waste (Fig. 5).

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 the event. Knowing that plastic waste is a serious problem of Arctic coastal environments we paid particular attention to recording sites with a large accumulation of this type of material. In Nuugaatsiaq plastic litter is widespread not only along narrow beaches (already mixed with beach sediments), but also spread across the inundated zone of the settlement, and subject to further transport by strong winds (Fig. 5). 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.

3.4 Assessment of social, economic and environmental impacts of tsunami in Nuugaatsiaq.

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. The Paatuut tsunami (2000) damaged an already abandoned settlement of Qullissat. 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).

3.5 Arctic coastal communities threatened by tsunamis – rising risk and rising awareness

One of the most evident effects of Arctic climate warming is the increased operation of geohazard processes along the circumarctic coasts (e.g. Fritz et al., 2017). The majority of these processes pose a significant threat to Arctic coastal communities and man-made infrastructure (e.g. Forbes et al., 2010; Radosavljevic et al., 2016; Jaskólski et al., 2018). Most of the recent Arctic coastal change studies concentrated on accelerated coastal erosion rates in locations spread across the Arctic region and associated them with diminishing sea-ice extent, longer exposure to storm wave impacts, and thawing coastal permafrost (e.g. Farquharson et al., 2018; Irrgang et al., 2018; Gibbs et al., 2019; Isaev et al., 2019). Also, in glaciated parts of the Arctic, such as Greenland or Svalbard, coastal research focused on the response of coastal zone to increased delivery of glacial sediments (e.g. Bendixen et al., 2017; Strzelecki et al., 2018). At the same time little attention was paid to Arctic tsunami hazards whose effects are devastating to both human and natural coastal environments. The recent examples of Arctic tsunamis in Alaska (Taan 2015) and Greenland (Paatuut 2000, Karrat 2017) demonstrate how severe impacts on coastal environments and communities can be. It is important to note that with continued warming (favouring permafrost thaw, glacier retreat, or extreme meteorological phenomena), such tsunamigenic landslides are going to be far more frequent.

To put it into a Greenlandic perspective, the recent mapping of potential tsunamigenic landslides performed by Svennevig (2019) indicated 564 landslides just between Sigguup Nunaa and Qeqertarsuaq in West Greenland. Benjamin et al., (2018) mapped 20 rock avalanches just along one short section of southern coast of Nuussuaq Peninsula in a direct proximity of Vaigat Strait (similar avalanche triggered Paatuut tsunami in 2000). Svennevig et al. (2019) demonstrated that the area around the Karrat Fjord landslide has continued to be active and another tsunamigenic landslide is highly probable.

Although beyond the scope of this pilot study, here it is important to mention another type of extreme phenomena impacting Greenlandic coastal zone – waves triggered by iceberg-roll events that are powerful enough to erode local beaches and wash away coastal infrastructure (Long et al., 2018). Calving of Greenlandic glaciers also produces extreme waves that are able to erode glacial landforms and lead to substantial degradation of coastal landscape (e.g. Lüthi and Vieli, 2016). Earlier, even the scientific community did not really believe that such extreme events were possible, but with global warming and sea level rise, such landslides, glacier calvings and iceberg rolls are going to be far more common. Despite the potential significance of these changes, relatively little is known of extreme processes that control Arctic coastal environments or how they might change in the future.

4.4 Arctic coastal communities threatened by tsunamis – rising risk and rising awareness

One of the most evident effects of Arctic climate warming is the increased operation of geohazard processes along the circumarctic coasts (e.g. Fritz et al., 2017). The majority of these processes pose a significant threat to Arctic coastal communities and man-made infrastructure (e.g. Forbes et al., 2011; Radosavljevic et al., 2016; Jaskólski et al., 2018). Most of the recent Arctic coastal change studies concentrated on accelerated coastal erosion rates in locations spread across the Arctic region and associated them with diminishing sea-ice extent, longer exposure to storm wave impacts, and thawing coastal permafrost (e.g. Farquharson et al., 2018; Irrgang et al., 2018;; Isaev et al., 2019). Also, in glaciated parts of the Arctic, such as Greenland or Svalbard, coastal research focused on the response of coastal zone to increased delivery of glacial sediments (e.g. Bendixen et al., 2017; Strzelecki et al., 2018) or rocky coast interaction with coastal permafrost (e.g. Strzelecki et al. 2017; Lim et al. 2020). At the same time little attention was paid to Arctic tsunami hazards whose effects are devastating to both human and natural coastal environments. The recent examples of Arctic tsunamis in Alaska (Taan 2015) and Greenland (Paatuut 2000, Karrat 2017) demonstrate how severe impacts on coastal environments and communities can be. It is important to note that with continued warming (favouring permafrost thaw, glacier retreat, or extreme meteorological phenomena), such tsunamigenic landslides are likely to be far more frequent.

To put it into a Greenlandic perspective, the recent mapping of potential tsunamigenic landslides performed by Svennevig (2019) indicated 564 landslides just between Sigguup Nunaa and Qeqertarsuaq in West Greenland. Benjamin et al., (2018) mapped 20 rock avalanches just along one short section (ca. 25 km) of southern coast of Nuussuaq Peninsula in a direct proximity of Vaigat Strait (similar avalanche triggered Paatuut tsunami in 2000). Svennevig et al. (2019) demonstrated that the area around the Karrat Fjord landslide has continued to be active and another tsunamigenic landslide is highly probable.

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5 Conclusions

Based on the observations we have drawn the following conclusions:

- The Karrat Fjord event is the first known example of Arctic tsunami which directly impacted an Arctic inhabited settlement and forced it evacuation;
- The scale of tsunami damages, including destruction of a majority of buildings (48% of settlement community infrastructure) and a high risk of another event, prevents the community to return to the settlement;
- Apart for housing facilities, 3 waves destroyed most public service buildings e.g. school, power plant, shopping centre, administration centre, seafood processing plant;
- Among the waste accumulations left in the area are: electronic equipment, rotting food supplies, faecal matter, sledge-dog carcass, as well as ammunition and a lot of municipal waste, including a large quantity plastic. Most of the waste is completely unprotected and exposed to weather conditions and wildlife;
- The geomorphological effects of tsunami were less pronounced than in previously described examples of Arctic tsunami impacts (Lituya 1958, Paatuut 2000, Taan 2015) which can be explained by the local coastal morphology and geology (rock dominated coasts with small and sediment-poor beaches) and relatively low waves heights (1-1.5 m);
- Mapped tsunami deposits included gravel-dominated beach sediments, boulders and material which melt out from fragments of ice-bergs stranded on land;
- Two years after the event the effects of tsunami erosion was still detectable on the surface of local roads and edges of sedimentary cliffs along the local harbour;
- In the warming Arctic region, the landslide-triggered tsunamis become one of the most important geo-hazards with profound effects on the functioning of coastal communities and landscapes.

Commented [A9]: Re "mapped tsunami deposits" – These need to be shown on the map.

~~**4 Conclusions**~~

~~Based on the observations we have drawn the following conclusions:~~

- The Karrat Fjord event is the first known example of Arctic tsunami which directly impacted an Arctic community and destroyed an inhabited settlement;
- The scale of tsunami damages, including destruction of a majority of buildings and a high risk of another event, prevents the community to return to the settlement;
- Apart for housing facilities, 3 waves destroyed most public service buildings e.g. school, power plant, shopping centre, administration centre, seafood processing plant;
- Among the waste accumulations left in the area are: electronic equipment, rotting food supplies, faecal matter, sledge-dog carcass, as well as ammunition and a lot of municipal waste, including a large quantity plastic. Most of the waste is completely unprotected and exposed to weather conditions and wildlife;
- The geomorphological effects of tsunami were less pronounced than in previously described examples of Arctic tsunami impacts (Lituya 1958, Paatuut 2000, Taan 2015) which can be explained by the local coastal morphology and geology (rock dominated coasts with small beaches) and relatively low waves heights (1-1.5 m);
- Mapped tsunami deposits included gravel-dominated beach sediments, boulders and material which melt out from fragments of ice-bergs stranded on land;
- Two years after the event the effects of tsunami erosion was still detectable on the surface of local roads and edges of sedimentary cliffs;
- In the warming Arctic region, the landslide-triggered tsunamis become one of the most important coastal hazards with geo-ecological effects and are analogous to coastal erosion observed in ice-rich permafrost parts of the region (Siberia, Alaska, Yukon).

Author contributions. M.C.S and M.J.W designed the study and carried out fieldwork. M.W.J analysed the aerial imagery and settlement spatial plans data. M.C.S guided the intellectual direction of the research. Both authors wrote the manuscript.

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Data availability. Data in this paper can be made available for scientific use upon request to the authors

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Figures and Tables

Observed tsunami impacts in Nuugaatsiaq		
Environmental	**Social**	**Economic**
• Landscape degradation (tundra and soil erosion, salt residues, coastal erosion) • hazardous materials left on site and exposed to harsh climate • waste accumulations • rotting food supplies easily accessible to wildlife	• separation of the community, relocation of people to Uummannaq and Qaarsut • loss of a logistic point for expeditions (hunting, fishing) for other settlements • loss of settlement continuity • loss of sentimental value • relocated people forced to pay more expensive rent in new substitute premises • isolation and adaptation difficulties in a new place • 39 people evacuated https://knr.gl/da/nyheder/39-evakueret-fra-nuugaatsiaq • 4 fatalities, 9 injured https://knr.gl/da/nyheder/fjeldskred-i-karrat-isfjorden-skyld-i-flodb%C3%B8lge • death of sledge dogs (during the inventory found 4 carcasses)	• costs of relocation, reparations and accommodation recognized in the budget for 2018 in the municipality of Naalakkersuisut DKK 14,877,000 (Forslag til TILLÆGSBEVILLINGSLOV for 2017, from 2018/8) • the need to allocate substitute accommodation and a one-off compensation payment of DKK 50,000 • impoverishment and loss of property (new premises are not given) • at least 27 sites with destroyed community infrastructure

Future risk reduction actions in Arctic coastal communities	
Earth science and remote sensing research community: • mapping and detection of landslides and recently slopes exposed from glacier ice or with significant degradation of permafrost • mapping/re-mapping seabed topography of deglaciated fjords and embayments • monitoring of present-day slope processes (slope stability) • investigations of paleo-records of waves • design of databases with seismic, remote sensing, geophysical and sedimentological information of past and recent tsunamigenic landslides and associated waves	Local authorities: • funding tsunami alert network • preparation of evacuation plans/delimitation of safe zones • consideration of tsunami and landslide hazard in spatial plans/documents • establishment of insurance procedures and securing financial reserves to cover post-event costs of relocation and reinstalment of communities in new locations

Table 1. Summary of tsunami effects on coastal landscape and Nuugaatsiaq community and recommended hazard risk reduction actions.

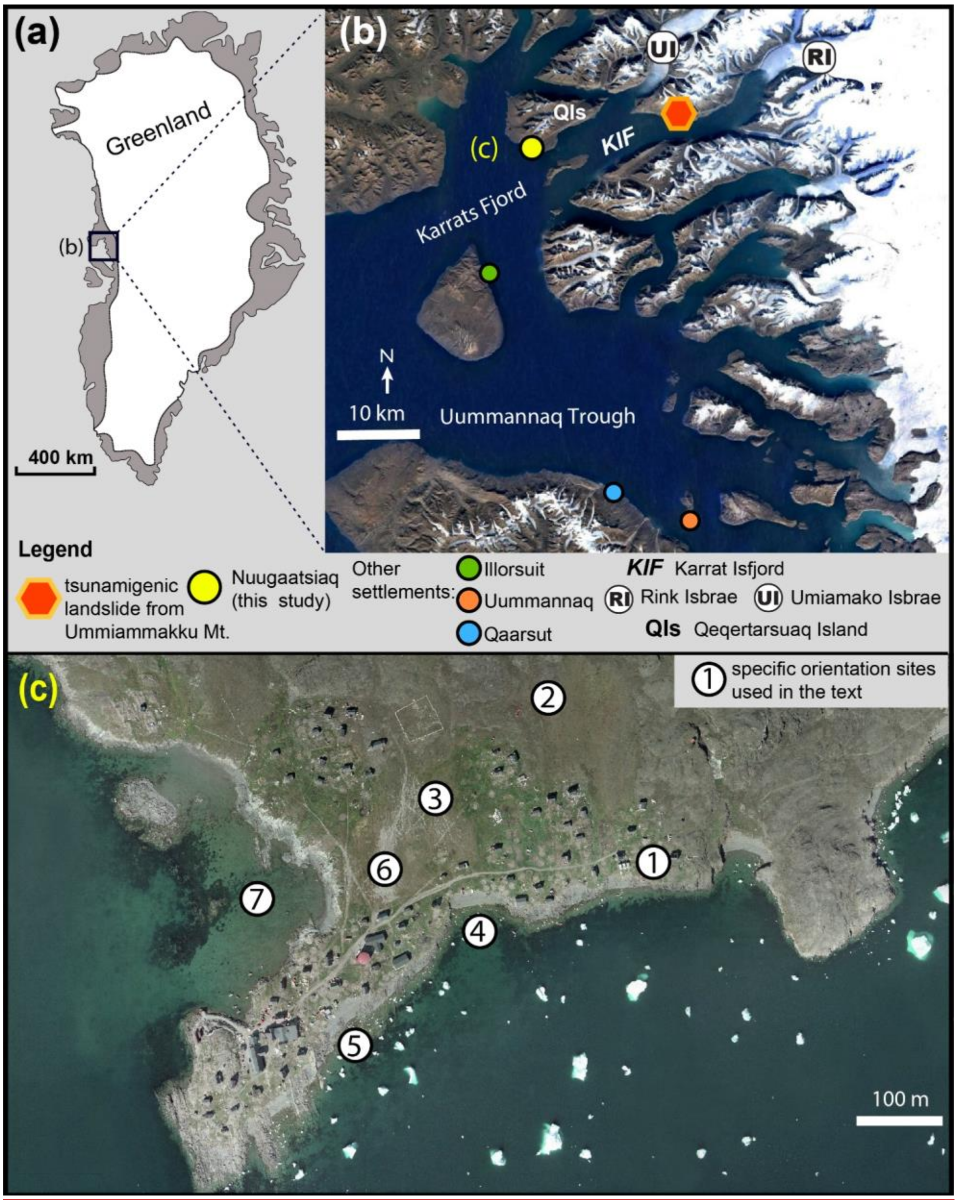


Figure 1. Location of study area. a) General position of Karrat Fjord in western Greenland (Source: Google Earth); b) Karrat Fjord area, where tsunamigenic landslide occurred on 17 June 2017 and inundated settlement of Nuugaatsiaq; c) Aerial image of Nuugaatsiaq before the event (nunuagis.gl), Number in circles mark orientation sites used in the text 1 – area with first line of buildings destructed by tsunami, 2 – heliport above the tsunami inundation limit, 3 – playground area, partly flooded by tsunami, 4 – first beach eroded by tsunami; 5 – second beach eroded by tsunami; 6 – saddle between beach(4) and harbour; 7 – local harbour.

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.

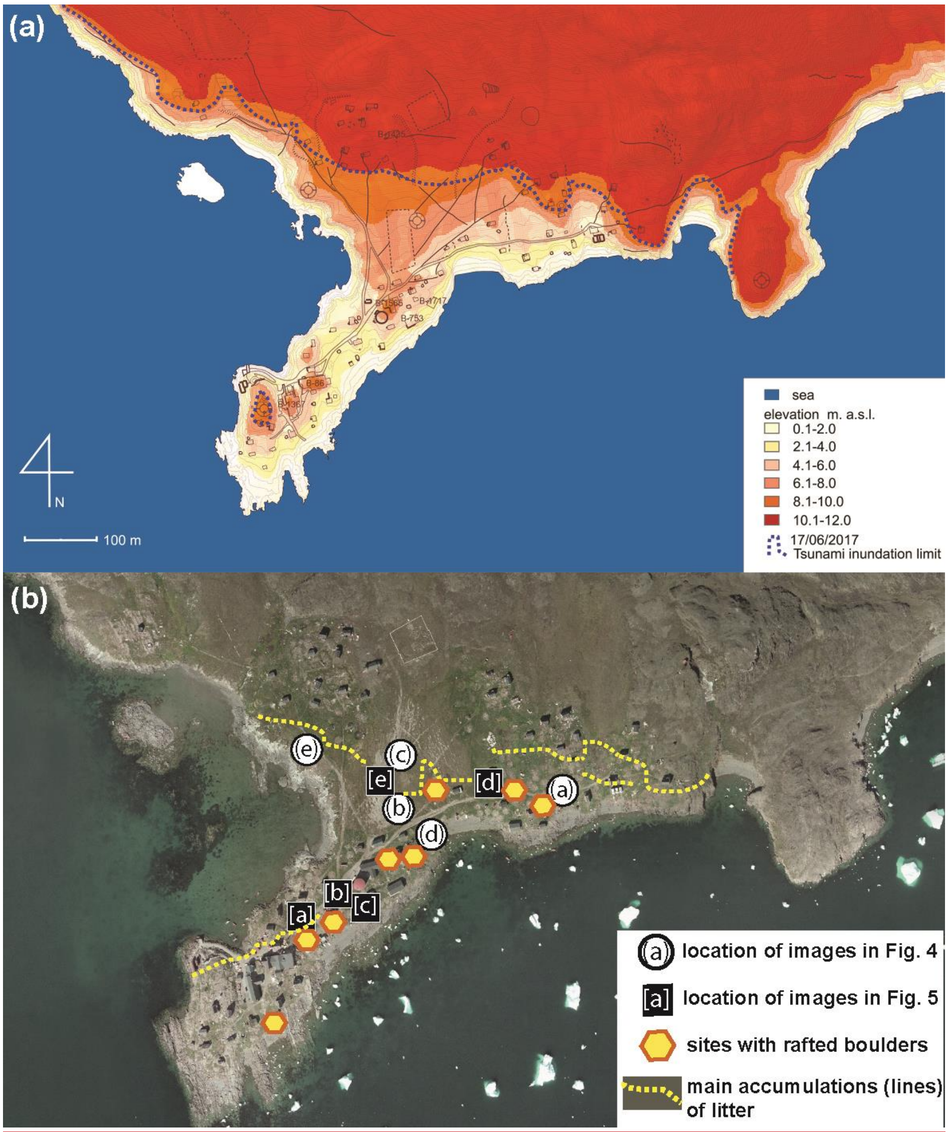
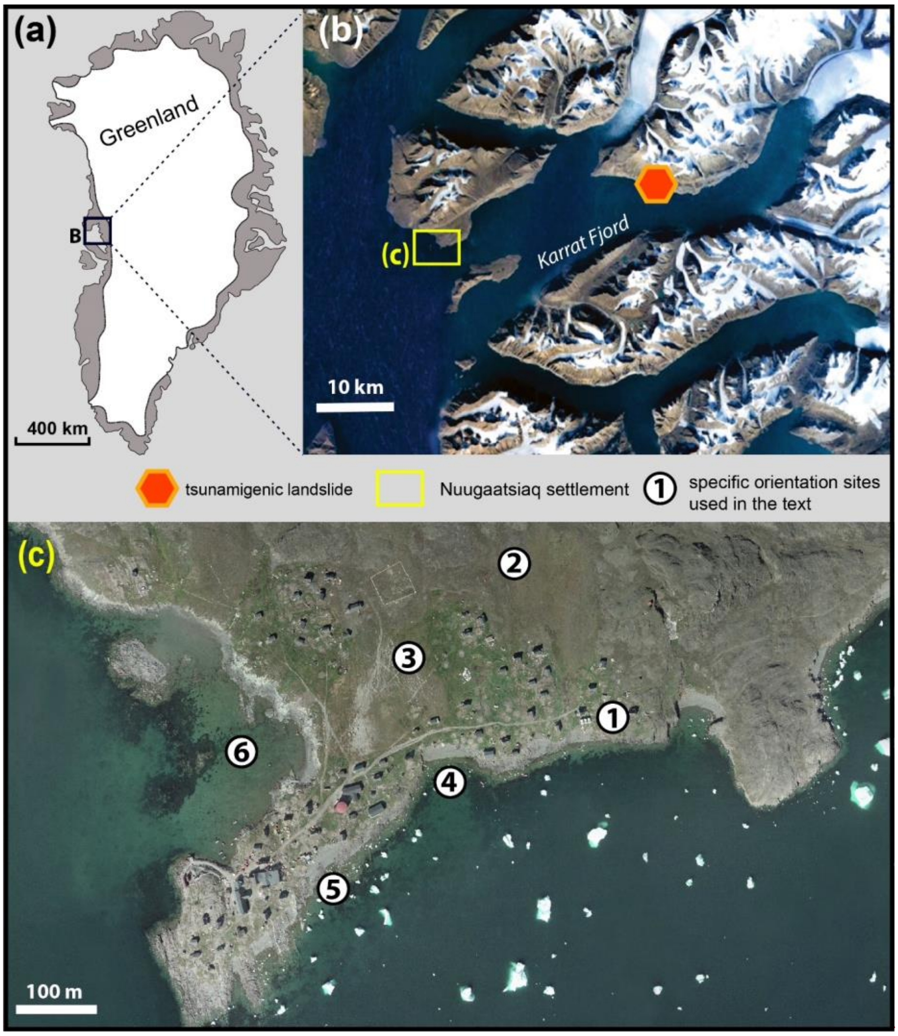


Figure 3. (a) Digital elevation model (2-m DEM, https://www.pgc.umn.edu/data/arcticdem/) of Nuugaatsiaq with marked tsunami inundation limit (wave flooded the terrain up to 8 m a.s.l). (b) Overview map of the settlement with marked location of images from Fig. 4 and 5. Lines of litter visible in the 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



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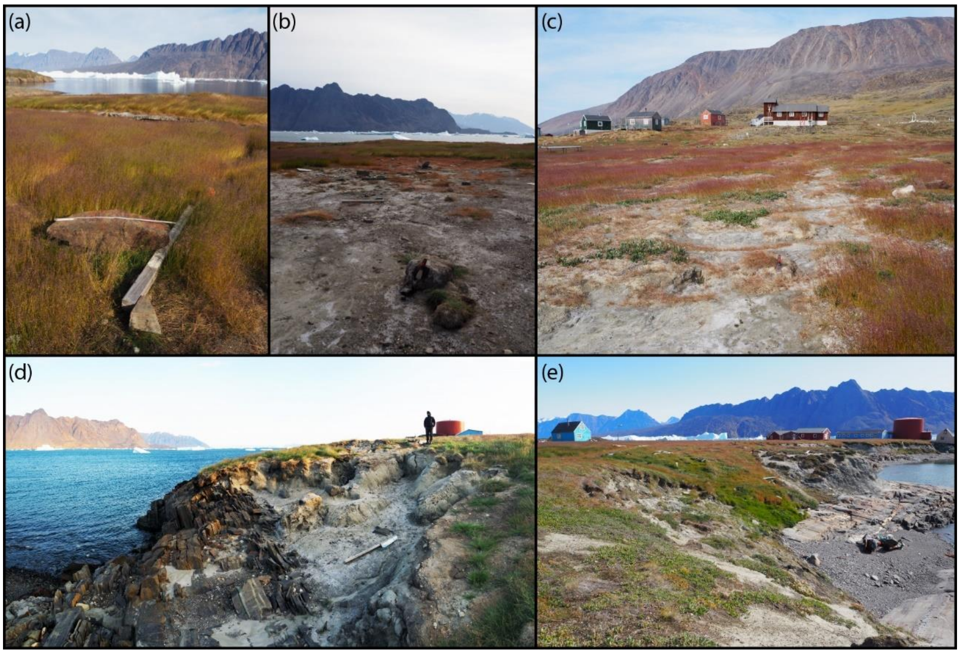

Figure 4. Examples of tsunami effects on tundra and soil covers in Nuugaatsiaq two years after the event. (a) High grass covers eroded tundra blocks, boulders and litter deposited by tsunami; (b) eroded tundra block/raft deposited on the coastal lowland inundated by tsunami with thin layer of redistributed marine sediments and salt covers; (c) deposited tundra and soil blocks and gullied ground surface by wave which backwash to the fjord; (d) eroded edges of low bluffs above the small beach (site 4 in Fig. 1c); (e) cliffed coast heavily dissected by tsunami which overwashed the saddle (site 6 in Fig. 1c) between beach (site 4 in Fig. 1c) and drained to local harbour (site 7 in Fig. 1c).**Figure 2.** Examples of tsunami effects on tundra and soil covers in Nuugaatsiaq two years after the event. (a) High grass covers eroded tundra blocks, boulders and litter deposited by tsunami; (b) eroded tundra block/raft deposited on the lowland inundated by tsunami with thin layer of redistributed marine sediments and salt covers; (c) deposited tundra and soil blocks and gullied ground surface by wave which backwash to the fjord; (d) eroded edges of low bluffs above the small beach (site 4 in Fig. 1c); (e) heavily dissected by tsunami which overwashed the lowland area between beach (site 4 in Fig. 1c) and drained to local harbour (site 6 in Fig. 1c).

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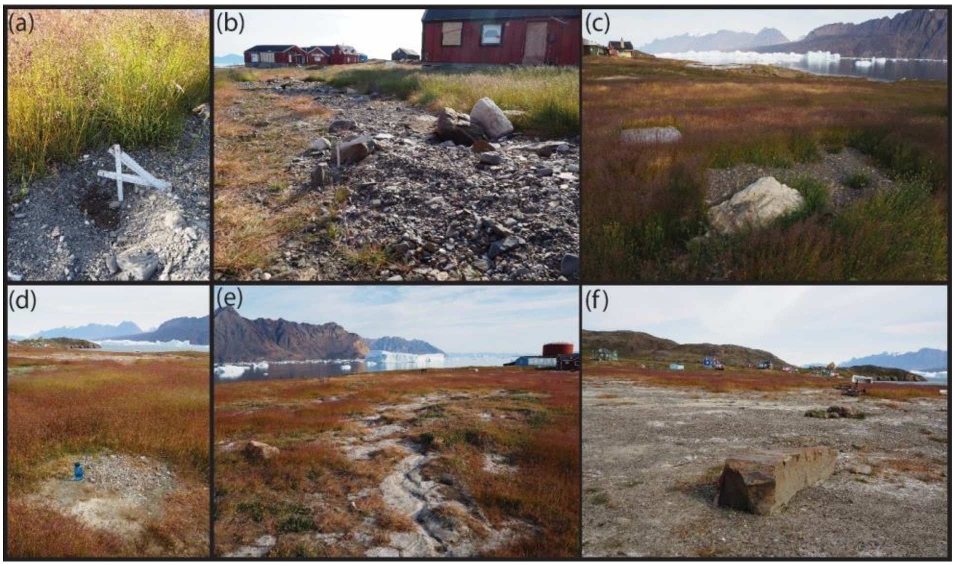

Figure 5. Examples of tsunami deposits preserved in Nuugaatsiaq two years after the event. (a) Ca. 4-6 cm thick cover of marine gravels covering grass vegetation; (b) Up to 10 cm thick layer of tsunami deposits eroded from local beach and deposited on road and grass vegetation; (c) Melt-out material from iceberg (gravels and mud) and ca. 100 cm long boulder thrown onshore by tsunami; (d) Deposits melted-out from iceberg washed on shore by waves; (e) rills eroded in soil and tsunami deposits by returning wave; (f) Over 100 cm long boulder moved by wave on the thin layer of gravels and eroded soil deposits. Note salty surfaces and eroded tundra rafts in the background.

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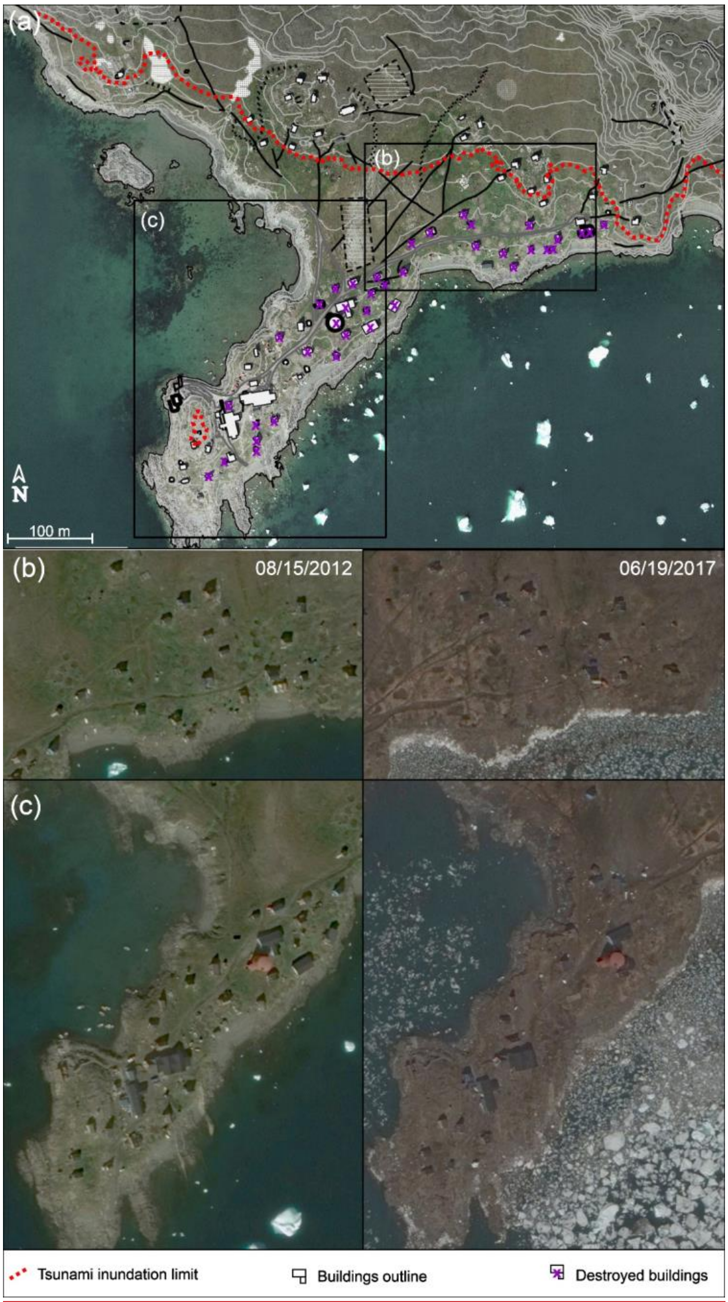

Figure 6. Scale of destruction in settlement infrastructure. (a) General overview of area inundated by tsunami with location of damaged buildings. The inventory of tsunami-induced changes of settlement infrastructure are based on interception of aerial images, local spatial plans and field surveying. Background ortophoto & technicalmap: nunagis.gl.; (b) Satellite image of settlement before the tsunami impact (15th August 2012) and;

1290 (c) Satellite image of settlement after the tsunami impact illustrate the scale of destruction and dislocation of buildings (19th June 2017) Background Google Earth Image © 2020 Maxar Technologies.

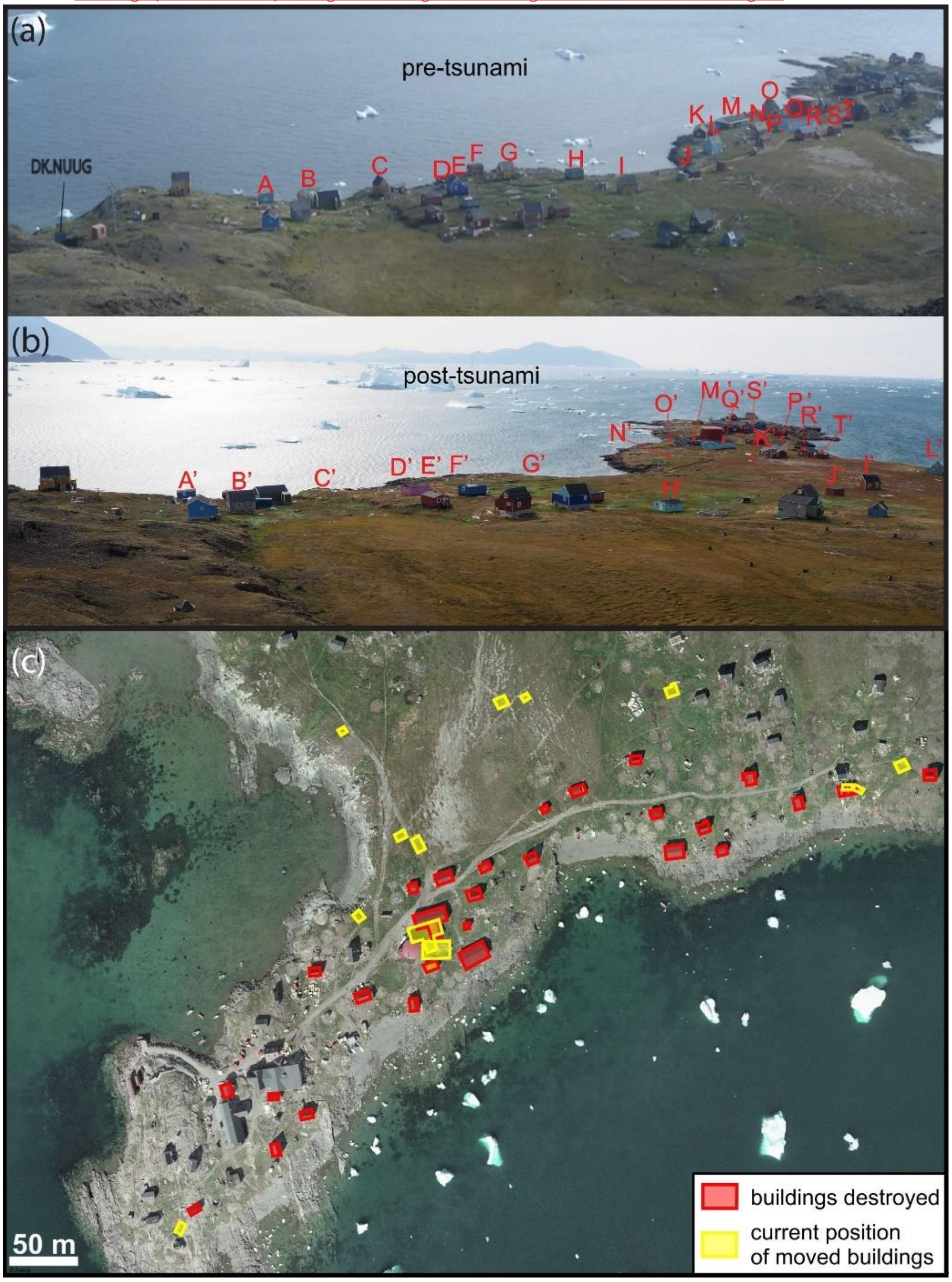

Figure 4. Scale of spatial changes in settlement infrastructure. (a) Buildings position (A, B, C … etc.) before the tsunami based on oblique image taken in 2010 (after Clinton et al., 2017); (b) Position of buildings (A', B', C'…etc.), recognized in 2010 image, after the tsunami impact. Photo taken in July 2019 (this study). (c) Inventory of tsunami-induced changes

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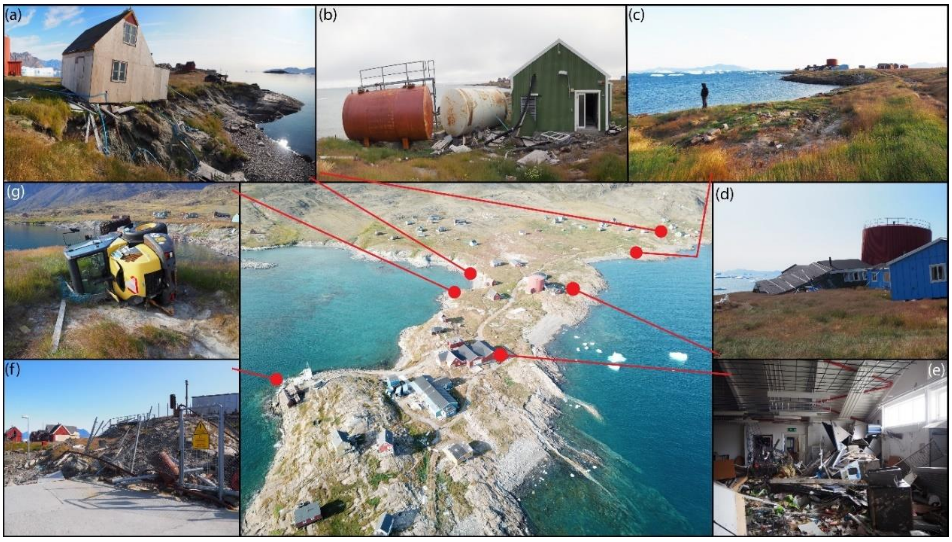

Figure 7. Examples of infrastructure damages caused by 2017 tsunami in Nuugaatsiaq. (a) Wooden house removed by wave from point foundation transported several dozen of meters; (b) Fuel tanks washed away from concrete frames and pushed towards power plant. Note large accumulation of litter and tsunami deposits around and inside the buildings; (c) site of former building position, which was destroyed and swept away by tsunami. Note broken wooden point foundations, media connections and erosional gullies; (d) Smashed and collapsed wooden school building moved towards major water tank; (e) Interior of local shopping centre passed by tsunami. Note large amounts of litter and rotting food supplies and twisted and bowed metal frame construction; (f) Partly-torn metal fence around fuel storage site which acted as a trap for litter transported by tsunami; (g) example of heavy machine knocked over by waves.

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