Tidal-dominated fjord head deltas of Svalbard insusceptible to environmental shifts - how confident we are in remotely sensed detection of their morphodynamical changes?

Jan Kavan[1,2], Zofia Owczarek[1], Martin Hanáček[2], Maria A. Jensen[3], Mateusz C. Strzelecki[1],
1 Alfred Jahn Cold Regions Research Centre, Institute of Geography and Regional Development, University of Wroclaw, Poland
2 Polar-Geo Lab, Department of Geography, Faculty of Science, Masaryk University, Czechia
3 Arctic Geology, University Centre in Svalbard, Norway

Abstract

The accelerated climate warming in the Arctic is accompanied by enhanced glacier melt and subsequent increase of sediment transport from land to sea. This is often expressed in dramatic changes of the coastal zone where deltas are dominant features on the edge between terrestrial and marine environment. Deltas are sensitive indicators of such changes. However, long-term studies of Arctic delta development are relatively scarce and lack precision. Areal extent of ten tidal dominated fjord head deltas within the Svalbard Archipelago was examined. The shallow marine environment of deltas resulted in high areal extent variability as delimited from the satellite images. The variability depends on the exact date and time of image acquisition with respect to actual tidal phase i.e. sea water level. The areal extent of most of the deltas varied within few square kilometres with the exception of Braganzavågen delta system where the changes of areal extent exceeded 100 km2 . The actual delta shoreline position can extend up to 4 km between the minimum and maximum extent of the delta. At the same time, the main morphological features of deltas – tidal islands, channels and creeks were characterized by high spatial stability. It was also demonstrated that the high variability of the fjord head delta extent delimitation may affect long-term studies where only limited historic data are available.

Keywords: fjord head delta, remote sensing, areal extent, Svalbard

Introduction

River deltas are one of the most complex coastal geoecosystems that record climatic, tectonic, and anthropogenic impacts on the coastal zones (Anthony 2015). Their development occurs when sediment deposition in river mouths is more abundant than its removal and reworking by marine processes (wave, current, or tidal action) and their geomorphology is later on controlled by this interplay of erosional and depositional processes. Evans (2012) poetically described deltas as great continental dustbins to underline their role in storage of sediment derived from terrestrial erosion. What is often overlooked, deltas are the largest coastal landforms on Earth (e.g. Ganges-Brahmaputra, Mekong, or Lena deltas) (Evans 2012).

Deltas are also substantial landforms of Arctic coastal zones delivering about 13% of the global freshwater flux (Overeem et al. 2022). Importantly, Arctic deltas differ from those developing in lower latitudes as their geomorphology is strongly affected by action of river and sea ice and the stability of their main features such as channels, islands and shores is controlled by underlying permafrost making them ice-dominated environments (e.g. Lauzon et al. 2019; Pilouras et al. 2021; Overeem et al. 2022). Recently, Chan et al. (2023) emphasized the role of bottom-fast ice in the formation of Arctic-delta-specific forms – submarine shallow ramps that surround the deltas and function as breakwaters protecting them from wave erosion. Among other ice-controlled processes Overeem et al. (2022) accentuated the importance of river-ice jams in causing large floods submerging delta plains and affecting thermokarstic lake landscapes. At this point, however, it is important to note that in the case of Arctic delta systems we are dealing with a kind of duality in terms of regional studies coverage and delta development controls similar to that known from Arctic coastal change studies.

There is a striking geomorphological difference between quickly eroding deltas impacted by intensified storms in ice-rich permafrost coasts of northern Alaska, Siberia or Yukon and often more resilient and prograding coasts of still glaciated parts of the Arctic such as Svalbard or Greenland (e.g. Overduin et al. 2014; Bendixen & Kroon 2016; Strzelecki et al. 2017; Kavan and Strzelecki 2023). Many of the big Arctic deltas such as Mackenzie or Lena are threatened by climate change related increased thermoabrasion and subsidence. On the contrary, deltas fed by glacier rivers in south-western Greenland are rapidly prograding, becoming the extraordinary advancing delta systems of the warming world (Bendixen et al. 2017). Number of those prograding systems are representing a unique cold region type of deltas - tidal-dominated fjord head deltas – developing in head of fjords in reaction to enhanced sediment delivery from rapidly melting glaciers. But despite that fjord head deltas are abundant coastal landforms in glaciated sectors of the Arctic (e.g. Canadian Arctic Archipelago, Greenland, Svalbard, Novaya Zemlya, Iceland), relatively little is known about mechanism controlling their morphological and sedimentological adaptation to shifts in climate or modes of sediment supply and redistribution. Those systems differ in terms of morphology and sedimentological structure and response to sea level fluctuations and other controlling factors from standard fan shaped deltas built by rivers and developed along open coasts and/or different section of the fjord e.g. Lønne and Nemec 2004, Mercier and Laffly 2005, Bendixen and Kroon 2016. In head of fjords the influence of tidal action has a stronger influence on landform development and exchange of waters than in fluvially=dominated counterparts.

Interestingly, although Svalbard Archipelago is often treated as a sensitive indicator of environmental changes in European Arctic, there are almost no studies on Svalbard fjord head delta systems evolution during the last decades so far. The exception are the delta systems in Dicksonfjorden and Van Mijenfjorden in central Spitsbergen. In the first system Jensen et al. (2016) suggested c. 2 km progradation between 1938 and 2011 aerial photos but were not able to confirm the tidal phase when the images were taken. Wave generated spit systems on the tidal flat provides possible measures of the high tide line, but active spit systems are not easy to distinguish from relict spit system, particularly on older aerial images of restricted quality. Kim et al. (2022) recorded important elongation and landward movement of selected observed spit systems. Kvam (2018) in her detailed study on depositional processes active in Dicksonfjorden documented aggradation of the tidal flat since the 1950´s and confirmed the stability of major tidal channels and linked it to the cohesive properties of the muddy tidal flat deposits. In Braganzavågen a detailed study of channel positions since the 1970´s was conducted by Faucherre (2011), suggesting that especially the feeder channels had stable positions. Studies by Eriksen (2013) and

Jensen et al (2019) have shown a more dynamic pattern closer to active fan systems on the side of the tidal flat.

As can be seen in Figure 1 – there is a noticeable concentration of developing fjord head deltas in the central part of Spitsbergen– representing inner fjord environments, sheltered from the impact of waves and protected by sea-ice for longer periods than along western coast of the island. In Petuniabukta, northernmost branch of Billefjorden also located in the heart of the island, with well-developed tidal flat system (Borówka 1989), Strzelecki et al. (2015) tried to assess the role of delta system in capturing sediment transported by local rivers from rapidly deglaciating valleys. Their pilot study detected the high efficiency of the system in capturing sediments transported from local outwash plains and glacial valleys. More recently, Gilbert et al. (2018) provided the first palaeogeographical reconstruction of the infilling history of Adventdalen fjord-valley system and determined onset of fjord head delta formation ca. 9 ka BP.

To date however, little is known about the progradation rates of modern Svalbard tidal dominated fjord head deltas and determination of the accurate position of delta front. This is an important deficiency that prevents coastal change researchers from accurately quantifying the rate of progradation of deltas on the island. Noteworthy, the relationship between fjord head deltas areal extent and local tides is missing in the literature. The exact date and time of image acquisition (thus consequently also the tidal phase) might be a crucial factor for further identification of progradation/erosion trend in these systems. This study therefore quantifies the uncertainty of tidal-dominated fjord head deltas delimitation and its dependency on the actual sea water level (i.e. tidal phase) for major systems in Svalbard (Fig. 1). In that way it aims to bridge this methodological gap and demonstrate the significance of input data quality check to draw a robust conclusion on the decadal scale development of the coastal areas. Secondly, this study sought to verify the stability of tidal channels and islands observed previously in Dicksonfjorden, Braganzavågen deltas. To do so remote sensing analyses of tidal channels, creeks and islands were carried out in a fjord head delta developing in Mudderbukta. Moreover, it tries to use these outcomes for interpretation of the fjord head delta system morphology and overall hydrologic and sediment budget dynamics.

Study site

Svalbard has experienced a glacier readvance during the Little Ice Age with the glacier maximum extent around 1900 (Martín-Moreno et al. 2017). The 20th century is then marked with relatively rapid deglaciation and consequent landscape processes. The average annual mass balance of Svalbard glaciers since late 1930s was highly dependent on climate warming. Svalbard experiences rather cold climate with the mean annual air temperature almost constantly rising from about -8°C to present -3°C since the beginning of the 20th century in the central part of the archipelago (Christiansen et al. 2012, Nordli et al. 2014, 2020). Geyman et al. (2022) reported the mean mass balance change for every 1°C of summer temperature increase to be -0.28m/year. Similarly Schuler et al. (2020) summarized the field observations of mass balance on Svalbard glaciers emphasizing the increasing speed of mass loss in the last decades. The central part of Svalbard where most of the study sites are located is experiencing probably the most dramatic changes due to its continental climate with low precipitation and high summer temperatures (Przybylak et al. 2014). Massive retreat since the Little Ice Age is reported for small valley type glaciers (e.g. Rachlewicz et al. 2007, Kavan 2020a) and unlike other parts of Svalbard the ablation zones extended to the upper zones of local glaciers (Malecki, 2016; Kavan and Haagmans 2021).

The ten delta systems are spread within the Spitsbergen Island, the largest island of the Svalbard Archipelago (Figure 1). Svalbard is positioned on the edge of the long-term winter sea ice extent. The northern and eastern part of Svalbard experiences prolonged sea ice cover duration in comparison to southern and western Svalbard influenced by warmer Atlantic waters. The inner fjords protected from direct influence of warm ocean currents from west and limited wave actions together with minimal mixing of water column are however favourable for prolonged sea ice cover duration. The tidal amplitude recorded in Longyearbyen is around 1.5 m but in the extreme cases (storm surges) it can rise up to 2.5 m. Such amplitude is similar in both two largest inner fjord systems - Isfjorden and Van Mijenfjorden (Kowalik et al. 2015).

The delta systems chosen for this study were not studied in detail except for the Dicksonfjorden delta which was described in theses of Holthuis (2018) and Kvam (2018) or by Jensen et al. (2016) and the Braganzavågen system studied by Faucherre (2011), Eriksen (2013) and Jensen et al (2019). The grain size analysis of samples from the tidal flat of Dicksonfjorden delta was examined recently in Golikova et al. (2022). The Holocene evolution of the two deltas (Dicksonfjorden and Nathorstelva) are described in Joo et al. (2019). The history of the Adventelva delta might be derived from the formation of three pingos on its surface. Yoshikawa and Nakamura (1996) reported ages of the pingos from 7000 BP for the farthest from the sea, 2800 BP for the middle one up to 160 BP for the one close to actual shoreline. They concluded that the growth of pingos was related to the development of permafrost and transgression leading to progradation of the delta system. Gilbert et al. 2018 captured a phase of rapid growth of Adventdalen fjord head delta in a response to peak of paraglacial sedimentation in early to mid-Holocene period. The massive delta system in Van Mijenfjorden – Braganzavågen – was affected by massive surge of neighbouring Paulabreen around 600 BP which has dammed the whole Kjellstromdalen valley and formed probably the largest Svalbard lake during the whole Holocene (Lyså et al. 2018). The lower part of the former lake is now the largest delta system presented in the study.

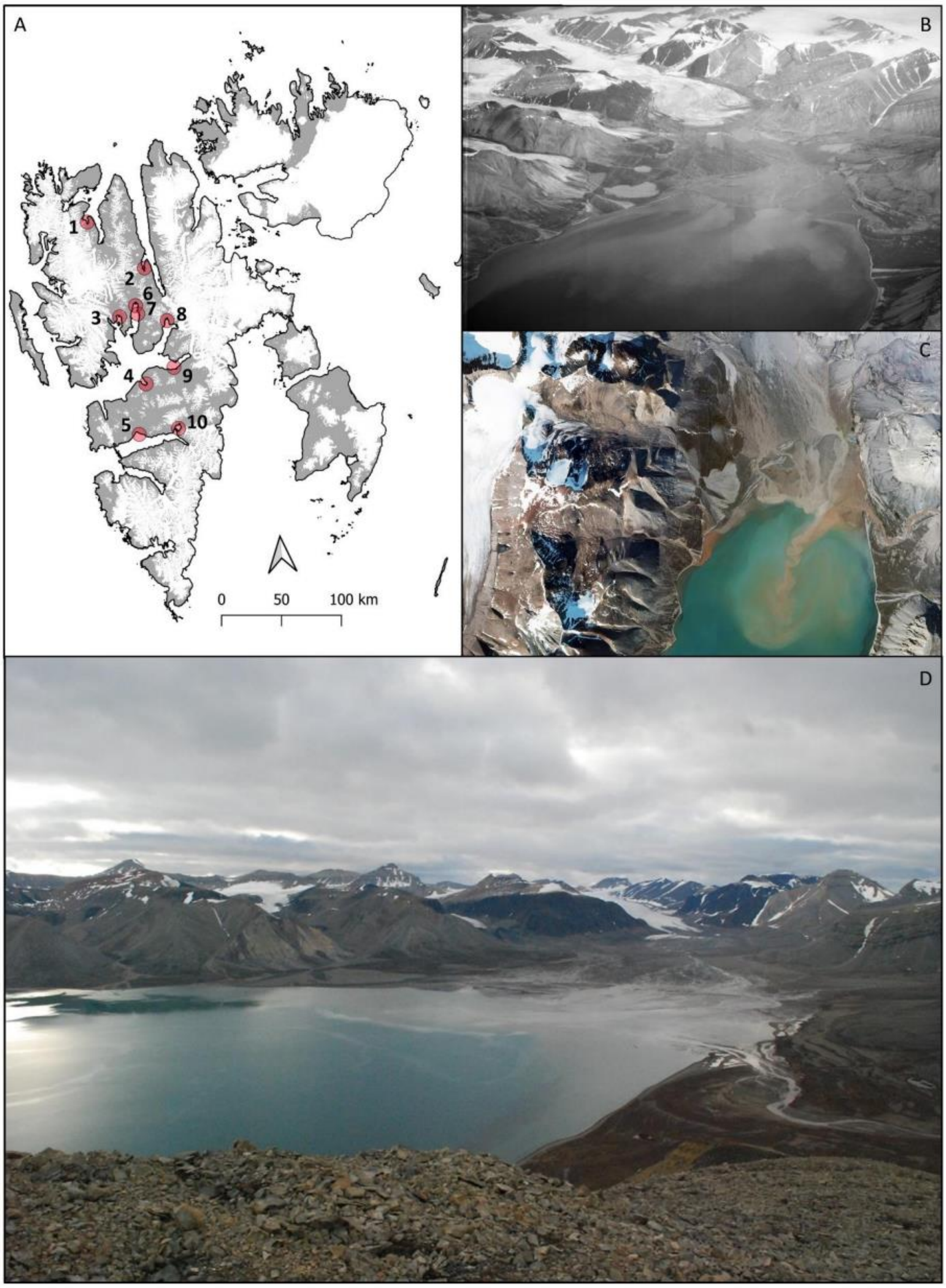

Figure 1 – Svalbard archipelago and location of the deltas studied; indication of the deltas corresponds to the indication used in Figure 2 (A); Petuniabukta delta system (marked as 8 on the map in panel A) in 1936 (B) and 2011 (C) (photos acquired from the Norwegian Polar Institute) with a land-based view on the delta system (D)

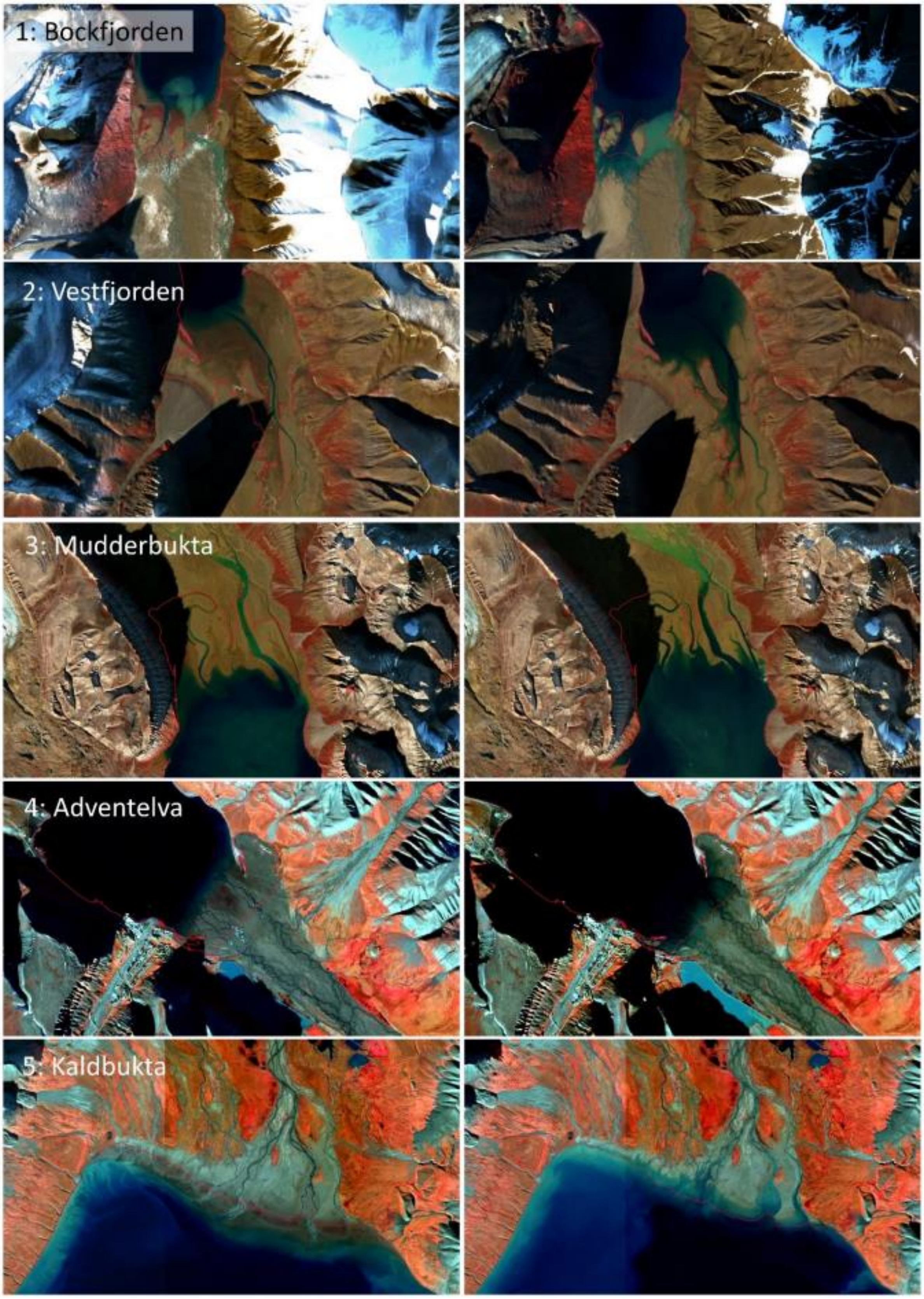

Figure 2 – comparison of the minimum and maximum areal extent of the deltas studied as acquired from the Sentinel-2 images during the summer 2021; the red line indicates the coastline as mapped by Norwegian Polar Institute; for location of the deltas refer to Figure 1

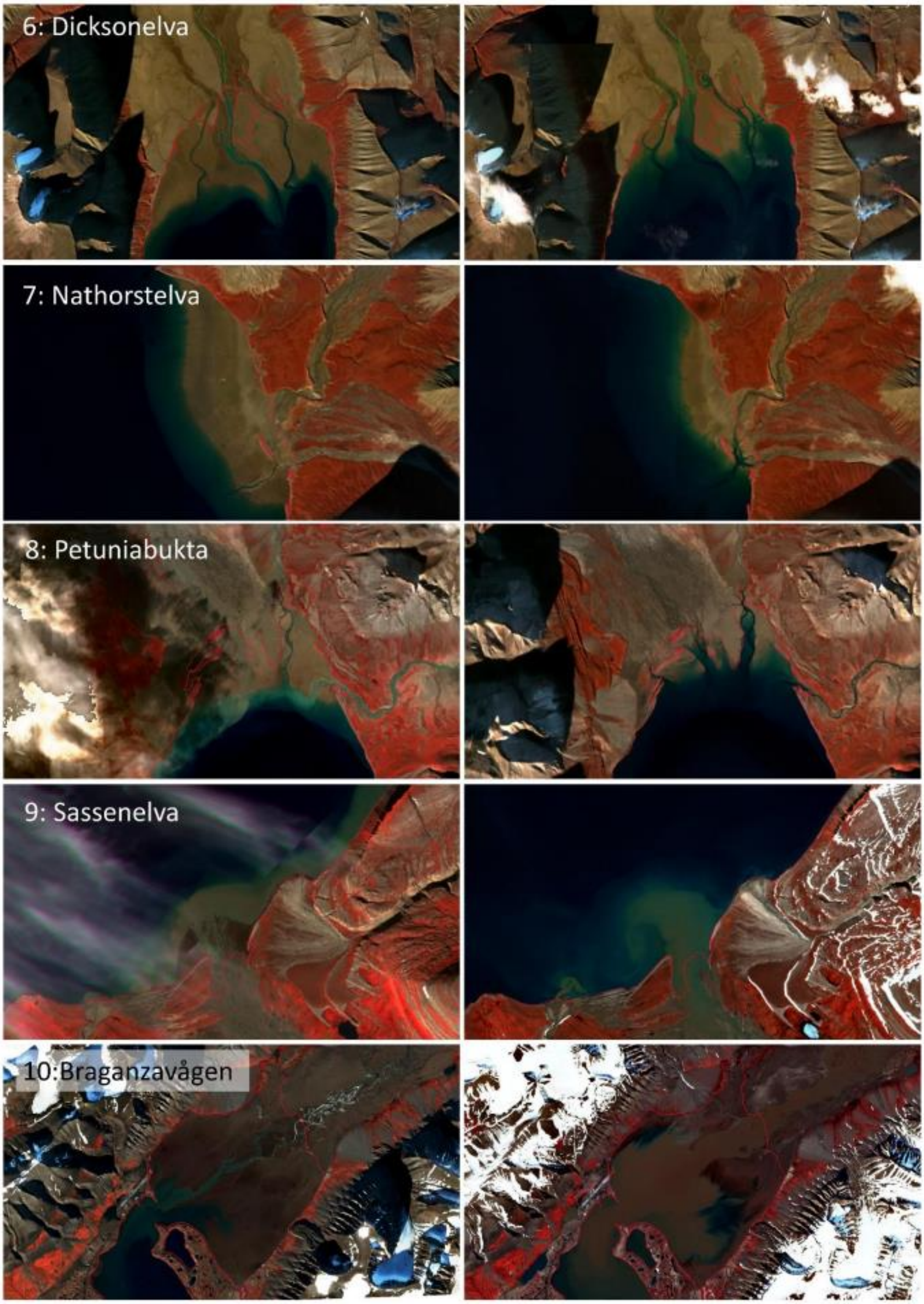

Figure 2 - continued

Methods

Sentinel-2 satellite images were used to map ten delta systems of the Svalbard archipelago during the 2021 summer season. These publicly available images were acquired from the Sentinel Hub EO Browser. For the purpose of this study images with cloud cover less than 30% were filtered out. Such approach resulted in the dataset of 14-31 images for each locality depending on the location of the delta and atmospheric conditions. There were originally two more locations, but these were excluded from the analysis due to insufficient number of cloudless images.

The false coloured images (bands 8, 4, 3) were downloaded as a geoTiff images which were already georeferenced and thus easy to process in the QGIS 3.22 software. The areal extent of the deltas above actual sea level was delimited manually for each image. The polygon was limited by the actual land/sea boundary and the coastline as delimited on the map of Norwegian Polar Institute (2011). In such a way an areal extent of the subaerial delta surface was calculated (Figure 3). Some of the deltas extended its inundated area towards inland even behind the mapped coastline.

The hourly tide observations attributed to Longyearbyen site were downloaded from the Norwegian Hydrographic Service. It was not possible to obtain data for all the delta locations separately. Based on previous investigations (Kowalik et al. 2015) it is however considered that the tides at Isfjorden and Van Mijenfjorden are not very different. This covers the location of 8 of 10 delta systems investigated. For the two deltas located out of the Isfjorden and Van Mijenfjorden precise tide estimation cannot be easily provided.

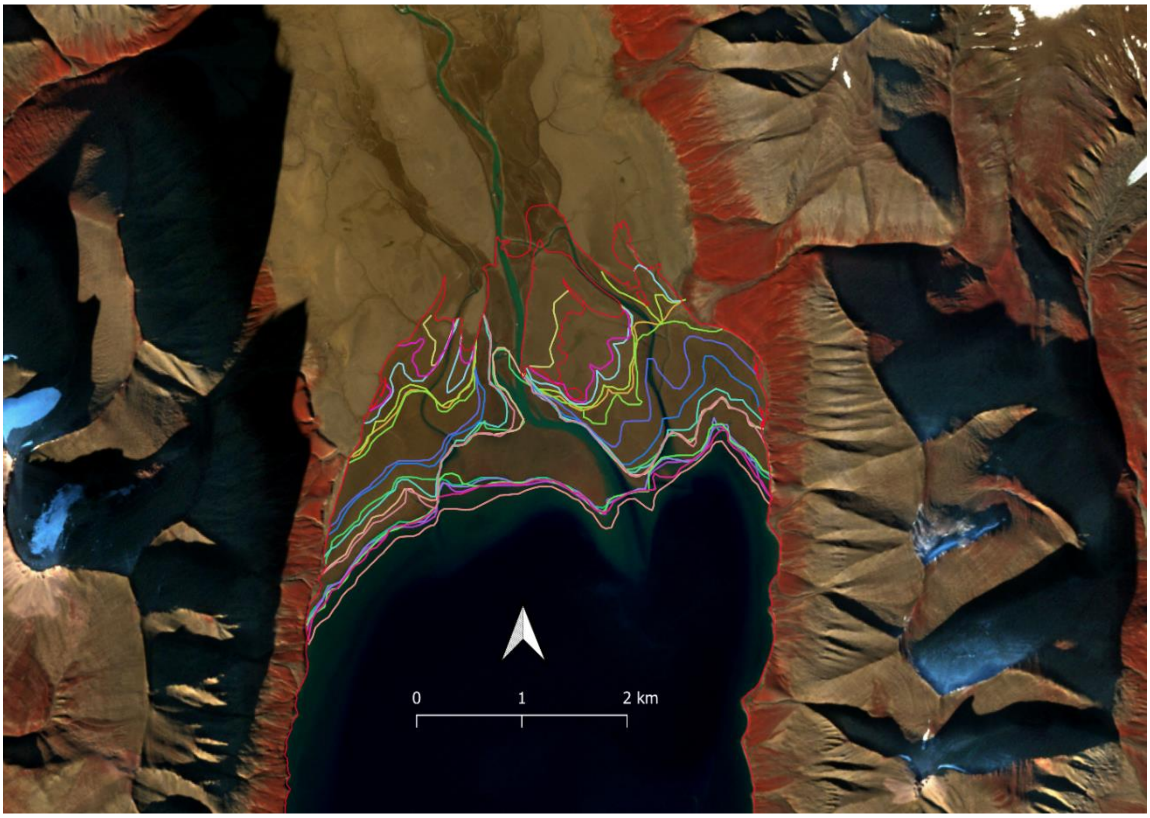

Figure 3 – example of delta areal extent delimitation in case of Dicksonelva – the coloured lines represent the actual delta extent limits as derived from different Sentinel-2 images; the red line stands for the NPI coastline; Sentinel-2 false colour image from 13 September 2021 as a background.

For the tidal channels, creeks and island stability tests in Mudderbukta NPI aerial photos from 1969, 1990 and 2011 were used. Georeferencing of the aerial photos and manual vectorisation of the channels, creeks and islands located within tidal flat in the fjord head delta, was carried out in QGIS 3.22 software. Maps were designed in ArcMap 10.7, where the changes over a period of more than 40 years are shown by overlapping the same areas from different years.

Results

Deltas areal extent

The maximum areal extent difference between the minimum and maximum extent recorded of the ten deltas studied varied from 1.5 km2 in case of Petuniabukta site up to the maximum in case of Braganzavågen delta (110.6 km2). It is however necessary to point out that the case of Braganzavågen delta is an extreme outlier, the second largest delta extent in the dataset are Kaldbukta and Dicksonelva (both with 6.3 km2). The areal extent variability is demonstrated in Figure 4, where the probability of exceeding certain area is plotted in Y axis. Note that the Braganzavågen delta upper limit is far out of the limit of the figure (up to 110 km2). Besides Braganzavågen, the maximum fluctuation of delta area is found in case of Kaldbukta and Dicksonelva, whereas the minimum fluctuation was recorded in Petuniabukta and Bockfjorden.

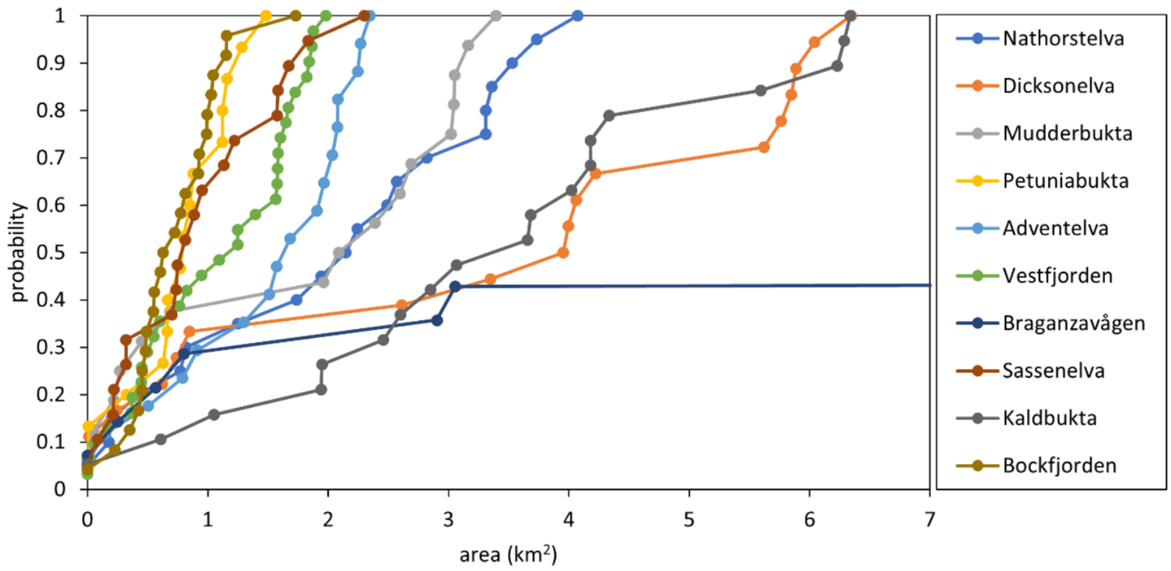

Figure 4 – variability of the delta areal extent for all the deltas studied

Delta shoreline position

The actual delta shoreline position (i.e. the actual sea/land boundary) has a similar pattern as the delta areal extent described above. The abrupt shift described in case of areal extent is apparent only in case of Van Mijenfjorden and also Vestfjorden. Such shifts in the position of sea/land boundary is affected by the topography of the delta system, position of river channels and general topography of the coastal area.

An interesting feature can be observed in case of Sassenelva, Kaldbukta and Bockfjorden where the inland parts of the coastal zone were inundated during the high tide events. This might be however affected by the methodology of the coastline delimitation on the official maps of the Norwegian Polar Institute. The detailed shape of the curves presented in Figure 5 may be also affected by the exact positioning of the centreline in the axis of the delta system.

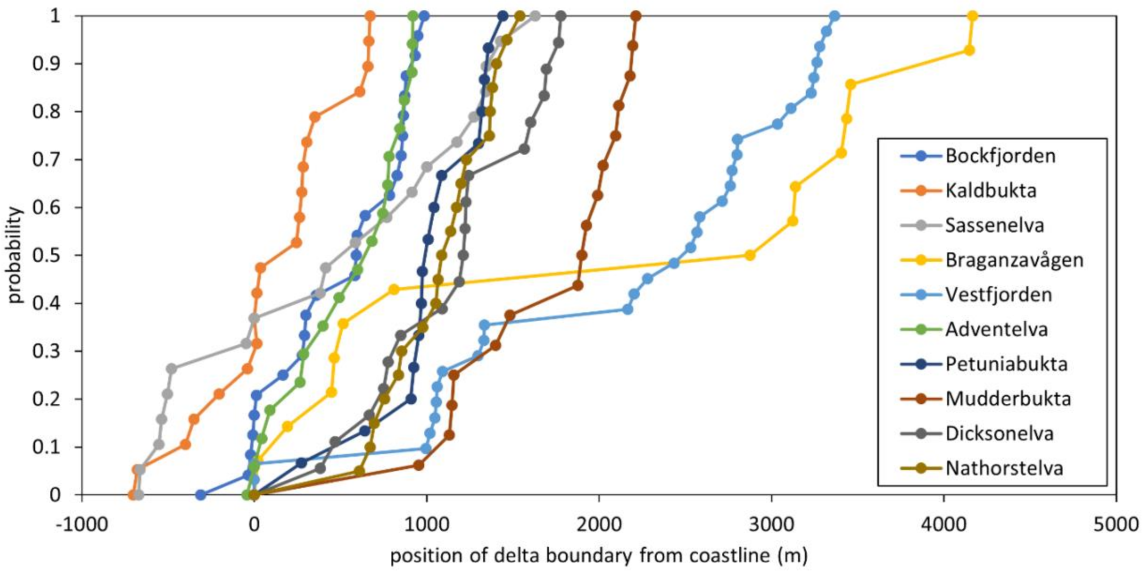

Figure 5 – variability of the actual coastline positions along the centreline

Delta areal extent and water level relationship

The relationship between the delta areal extent and water level in the moment of area delimitation can give us a useful hint on the slope of the delta which is relatively difficult to quantify from bathymetry mapping or remote sensing techniques. As the range between low and high tide is just about 1.5 m, this is on the edge of the accuracy of both classical methods. Moreover the bathymetry is difficult to map due to the very shallow environment usually inaccessible for boats and for the temporal variability of the depth as the tide is advancing/retreating.

In general the water level measurements from Longyearbyen (1.4.2021 – 30.9.2021) covers the range from -126.6 cm to 103.3 cm. The images used in this study covers the range from -97.5 cm to 39.5 cm which corresponds to the relative coverage 1.6 % – 89.9 % of the whole water level record. The big differences between the absolute maximum and minimum water level arise from a few measured extremes affected by storm surges and similar events.

Similarities and also important differences can be observed when comparing the individual deltas (Figure 6). A common feature that can be observed almost in all study sites is the abrupt shift of the delta surface elevation in the water level interval between -50 cm and 0 cm. Such pattern is visible in case of Adventelva, Petuniabukta, Dicksonelva, Sassenelva, Nathorstelva, Mudderbukta and especially the largest delta in Van Mijenfjorden. The remaining three deltas (Bockfjorden, Kaldbukta, Vestfjorden) seemed to have more homogeneous profile with only minor shift within this water level interval.

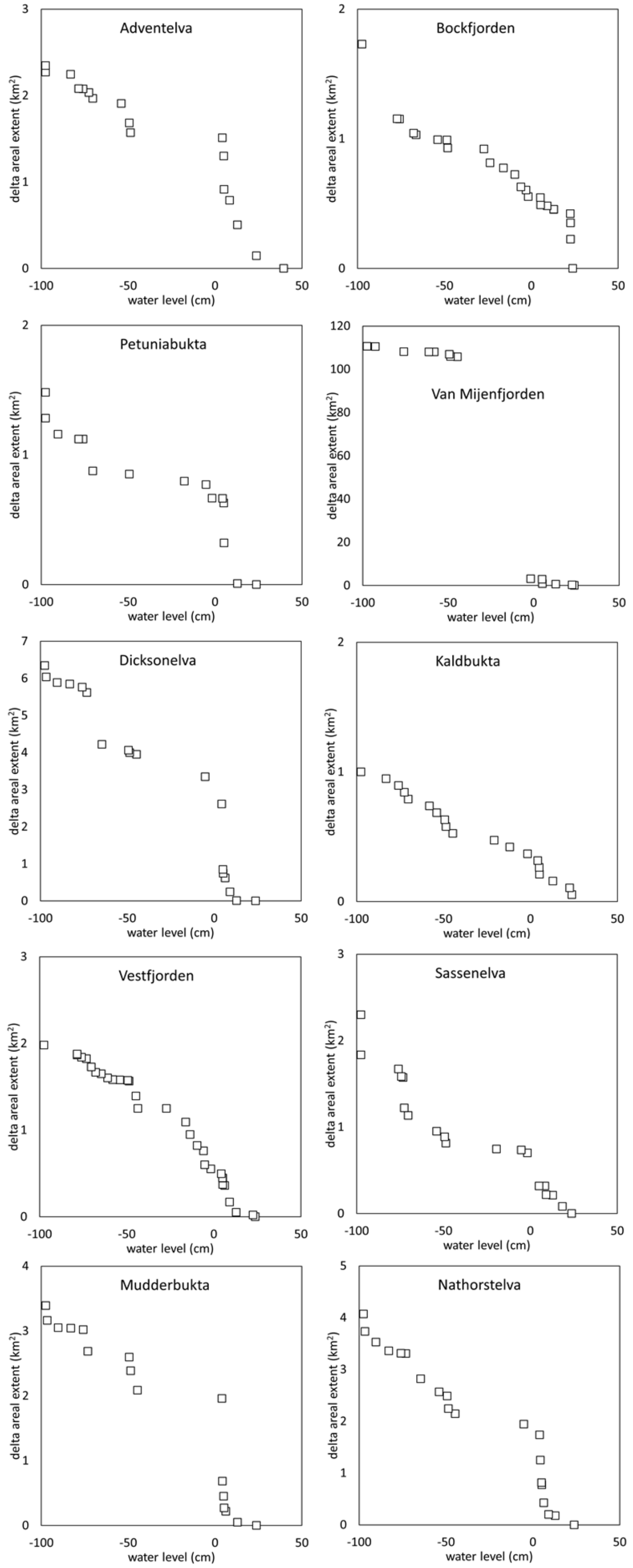

Figure 6 – water level and delta areal extent for the ten deltas studied (note different scales on y axis)

Interpretation and Discussion

Based on the morphology of the deltas revealed from remote sensing data we can distinguish two basic types of delta coastline evolution in relation to the tidal phase (Figure 6). These two types differ in terms of their development dynamics as revealed from the above mentioned relationship.

Stepped coastline development

This type is characteristic for deltas of Adventelva, Petuniabukta, Dicksonelva, Nathorstelva, Mudderbukta and Sassenelva. The subaerial delta extent between the maximum high tide and approximately 0 cm tide level accounts for about 50% of its total areal change. The next 50 cm of drop in water level is not expressed in any important change of the areal extent. Further decrease in water level towards the ebb tide is accompanied by more important areal changes when the coastline moves towards the sea basin and the areal extent of exposed subaerial surfaces reaches its maximum.

This stepped coastline development can be mostly found in the fjord-head deltas fed by the large river systems with spatially important catchment area. Sassenelva delta included in this group can be considered as fjord-head delta as well even though it is not positioned directly in the fjord head. The other characteristics are however fulfilled – large fluvial system of Sassendalen with high runoff and large catchment area. From the topography of the area it is obvious that Sassendalen once used to be a fjord system shaped by glacier and river processes recently being connected to the Templefjord.

Three morphologic components can be distinguished in most of the deltas: proximal tidal flat, fluvial channels, and distal tidal flat. Proximal tidal flat corresponds to the channel belts of the rivers feeding the delta system. It is inundated only during the high tide (0-50cm). Distal tidal flat is relatively large zone between the fluvial distribution channels and zone in contact with sea during the ebb tide. This zone is exposed right before the culmination of ebb tide. Inundation/exposure of both sectors is connected with important changes in areal extent of these landforms. Sea water is migrating over the delta surface in the fluvial/tidal channels. Water level change in the channels itself is not accompanied by any important change in the coastline position despite the water level change accounts for about 30% of the water level interval. The stepped coastline development is therefore driven by the delta morphology. The interval between +50-0 cm is connected with the upper intertidal zone, 0- -50 cm interval impacts the fluvial/tidal channels and the ebb tide interval (-50 - -100 cm) is connected to the inundation/exposure of lower intertidal zone.

The extreme case of the stepped coastline development is the Braganzavågen delta. This delta is specific by its extremely long proximal tidal flat which is identical to the multichannel belt of the feeder river system and goes far inland to the Kjellströmdalen while gradually narrowing. Proximal tidal flat is transforming into vast distal tidal flat. The subaerial delta surface along the maximum high tide shoreline position does not react significantly to the changes of the water level, because the sea fluctuation happens only in the narrow part of the proximal tidal flat far from the marine basin. The change of the water level in the interval 0 - -50 cm is characterised by large shift in the areal extent up to 100 km^2 which is related to the exposure of a very flat and shallow outlet of the feeder river and connected distal tidal flat. The further drop in the water level towards the ebb tide is not accompanied by any important changes in the areal extent because most of the water level drop occurs in the incised tidal channel on the farthest part of the tidal flat.

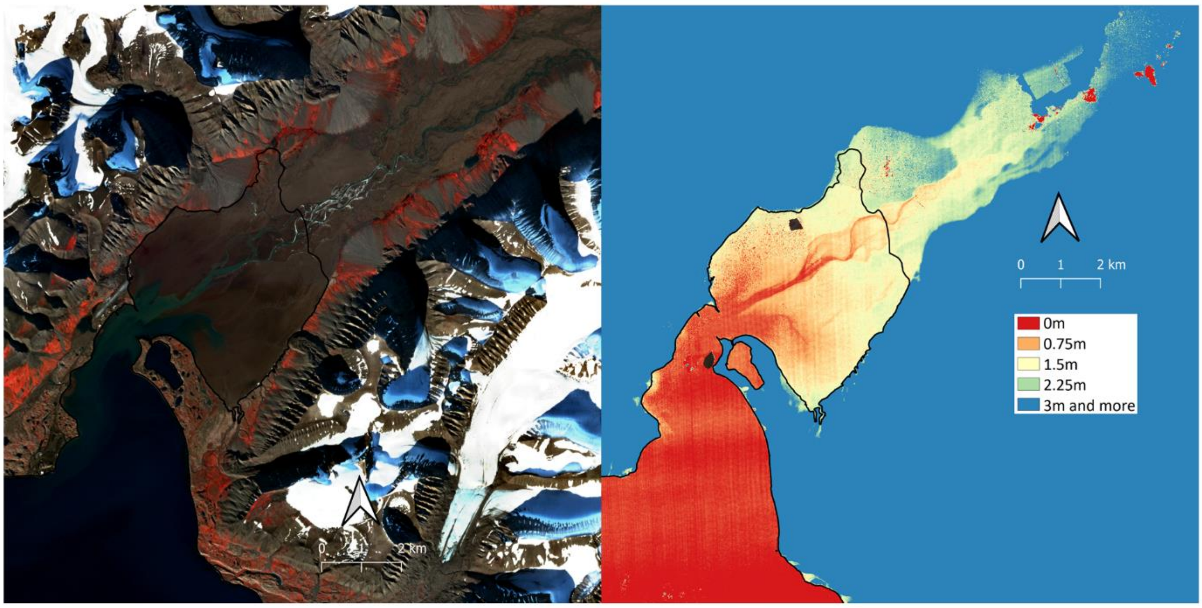

Figure 7 – false colour Sentinel-2 image (13.09.2021) and ArcticDEM strip from 31.05.2017 (Porter et al. 2018) covering the Braganzavågen site; the black line indicates coastline as defined by NPI;

Continual coastline development

Kaltbukta delta can be considered as a perfect example of this type. Coastline development throughout the whole water level range is gradual without any significant abrupt changes in the subaerial surface area. The continual coastline development correlates with slightly convex longitudinal profile of coast in Kaldbukta. The whole delta plain declines slightly towards the marine basin. Therefore the coastline position is changing gradually as well without morphologically determined steps. Kaldbukta delta is a side fjord delta, thus having completely different position in comparison with the previous type – stepped coastline development deltas.

Unlike Kaldbukta, Vestfjorden and Bockfjorden deltas can be considered as fjord head deltas. Despite that, there are no signs of the stepped coastline development, but only a slight variation of such development. The curve in case of Vestfjorden is more similar to that of a continuous development type. Vesfjorden and Bockfjorden are narrow and short fjords with important sources of available clastic material (proglacial outwash plains of valley glaciers, alluvial and colluvial fans). The intensive aggradation regime dominating in both fjords is the main reason for different coastline development. The tide fluctuation on Vestfjorden delta is limited only to a channel belt of feeder river with stable slope corresponding to the slope of the channel belt. Consequently, the curve of areal changes and tidal phase relationship is gradual. Development of a wide tidal flat is limited by aggrading alluvial and colluvial fan deposits on both sides of the channel belt. As a result, large part of the delta plain is subaerial.

Changes of coastline in Bockfjorden delta are limited to the coastal area parallel to the general coastline. Two secondary feeder streams flow on the edge of the delta plain and fjord slopes. The main feeder stream flows in the axial part of the delta. Aggradation of sediments is the most intensive in the eastern part of the delta where a flat outwash fan is slowly aggrading. The outwash fan works as a shallow tidal flat but mostly with the surface above water level as a result of aggradation regime. Only the high tide level is affecting this zone. Channel belt of the main feeder river has a deeper erosion base in comparison to the other streams. This results in exposing the surface gradually only during the ebb tide water level and inundated during the initial phase of high tide. Therefore the relationship between areal extent and water level indicates abrupt shift during the high tide (~1/4 of the whole delta tidal flat). The further decline in areal extent is mostly gradual. It is likely that the ongoing aggradation on the secondary feeder streams will block the transgression of the tide to the lateral parts of the delta. Tidal fluctuation will then be limited only to the channel belt of the axial feeder river, which will result in the morphology of the delta and its subaerial areal extent development to be very similar to that one of Vestfjorden.

Long-term trends and delta features stability

The comparison of shape and position of the main elements of Mudderbukta fjord head delta system (tidal channels, tidal creeks, tidal islands) using images from 1969-1990 and 2011 demonstrated a high level of stability of their morphology. This is particularly evident when comparing the channels and creeks in fig. 8B and fig. 8C. For more than 40 years the channels preserve their shape and curvature. A noticeable difference concerns the narrowing of the channel in fig. 8B, and thus the disappearance of the small island in the NW part of the channel (visible in 8B). In figure 8C, the narrowing of the channel occurred to such an extent that vectorization of the two banks was impossible, so the channel was represented as a line. The main change noticeable both in case of tidal channels and creeks was their steady elongation. Sometimes, through elongation, creeks merge with each other. Such a case was detected in the central eastern part of fig. 8C, where creeks from 1990 in 2011 merged together.

Islands located on tidal flats showed a tendency to change. Figure 8D shows how the merger of the two islands seen in 1969 and 1990 in 2011 results in the formation of a single island. Despite this, the shape of the island itself did not change much.

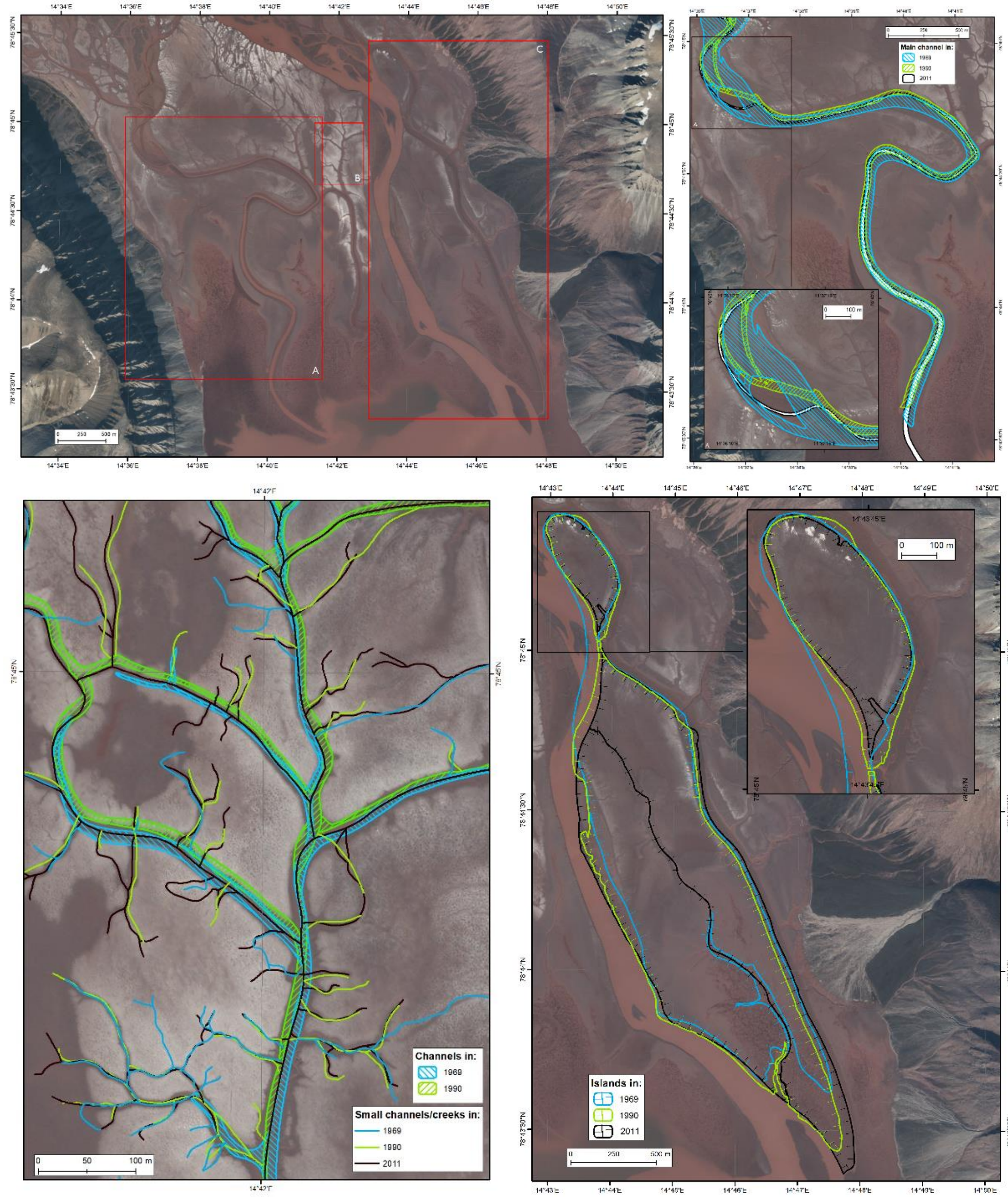

Figure 8 – overview of Mudderbukta delta system (NPI orthophotomap from 2011 in the background) illustrating evolution of channels, creeks and islands between 1969, 1990 and 2011(A)

The long-term trend in the progradation/erosion of the deltas can be assessed using historic aerial images combined with recent satellite imagery as shown e.g. in Bendixen et al. (2017) for Greenland. The dominant progradation trend in case of Greenland is mainly driven by changes detected in the tidal-dominated fjord head deltas. However, the large variability of the actual sea/land position makes such comparison difficult and highly uncertain. The dependency of the areal extent on the actual tidal phase is crucial given the large amplitude of possible shoreline positions. This phenomenon is illustrated in figure 9, where the seemingly progradation trend is put in the context of the amplitude of all recorded shoreline positions during 2021 summer season. The first three values are within the amplitude recorded in 2021, the last one from 2010 is outside the recorded amplitude very likely corresponding to the extreme ebb tide and consequent substantial extent of subaerial delta zone.

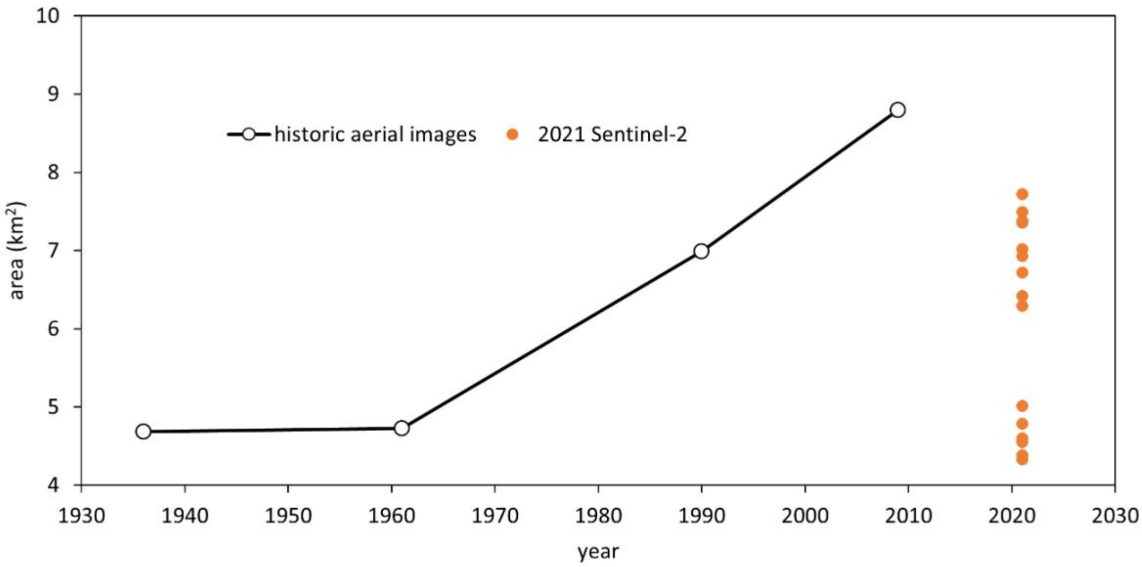

Figure 9 – areal extent of delta in Mudderbukta derived from historic aerial images compared with the areal extent variability derived from 2021 Sentinel-2 images

Controlling factors of the coastline development

All the deltas studied are coarse grain deltas fed by seasonal braided streams with different level of sinuosity. According to their position within the fjord system, these are shallow water deltas without a pronounced deep-water gilbert type delta features and a feeder systems of neither type B or C as defined by Postma (1990). Based on the classification of Nemec a Steel (1988) we can distinguish the fjord-head deltas in the wide open fjords (Mudderbukta, Dicksonelva, Nathorstelva, Petuniabukta, Sassenelva, Braganzavågen) braidplain deltas, fjord-head deltas in narrow fjords (Bockfjorden and Vestfjorden) confined fan deltas. Kaldbukta side fjord delta can be defined as a fan delta complex. The differences are however apparent mostly in the delta's morphology (plain vs. fan shape) and in the number of feeder streams.

The main controlling factors of the delta development in general are tectonics and climate complemented by morphology of the source area and depositional basin (Postma 1990). The deltas described in the study are all situated in the area of continuous glacioisostatic uplift following the postglacial ice mass lost (Kierulf et al. 2022). The morphology and regime of the Svalbard deltas are thus driven mainly by distinct characteristics of the source area and depositional basins. These factors are also controlling the general coastline development. Stepped coastline with large tidal flats originates in large flat and consequently rather shallow basins (fjord-heads). These basins are fed by large amount of material from vast source areas. Morphologic predispositions can be enhanced by locally exceptional conditions. Braganzavågen delta is a perfect example of this process. The very flat surface of the delta may be a result of reported damming of the fjord head by glacier surge of Paulabreen around 600 BP (Lyså et al. 2018). The remnants of the lateral moraine damming the lake are still apparent on the aerial images and DEM and form a present day barrier to between the fjord and the Braganzavågen tidal system creating an unusually efficient sediment trap in Braganzavågen (Figure 7). Modern Braganzavågen delta is prograding across the very shallow floor of the former ice-dammed lake. Continuous coastline originates in vast, but at the same time rather deep depocenters. The areal extent of the source areas (Kaldbukta delta is fed by rivers with catchment size of approximately 970 km2) is just a secondary controlling factor in this case. Accommodation space of the deposition basin is so large, that the inflow of the clastic material is not important enough to substantially fill this space by aggradation of bottom sediments despite the source area being so large.

Landsystem development prediction

It is possible to estimate the future development of the studied environment based on the above-mentioned source areas/depositional basins interconnections. Head fjord deltas with stepped coastline development (i.e. with large tidal flats) develop mainly in the areas of large catchments (e.g. central part of Spitsbergen Island). The valleys heading towards the sea are often glacier-free or only partially occupied by minor glacier snout of ice caps or individual valley glacier. In some cases terminoglacial lakes dammed by ice-cored latero-frontal moraines from the LIA maximum glacier areal extent can be found between the glacier front and coastline. The spatial pattern of the valley heads is rather uniform – there is an axial river channel with series of secondary braided channels flowing into the fjord. Deltas in such glacier-free valleys will possibly show less progradation. On contrary, deltas in the glacier-occupied valleys have larger progradation potential. The most complicated scenario of a future development can be expected in case of valleys with ice cored moraine dammed lakes. Progradation of delta systems can be expected here as a result of abrupt glacier lake outburst floods. Rapid degradation of these lakes and temporally increased runoff accompanied by enhanced sediment transport rate from land to sea may cause short-term progradation of deltas. Example of such behaviour was observed in case of rapid degradation of ice-dammed lake at Nordenkioldbreen front (Nehyba et al. 2017).

It seems obvious that all the controlling processes (specially glacioisostatic uplift) are favourable to continuation of the delta plains growing in their areal extent, i.e. we will probably observe increasing importance of these tidal environments. Only in the deltas proximal zone the permanent terrestrial environment will form as a result of the continuous aggradation of sediments until these rise above the maximum high tide level. The complete shift towards a terrestrial environment will be faster in smaller fjord (Vestfjorden and Bockfjorden) as a result of aggradation being more important than progradation. Areal extent of lateral coasts of large and deep fjords will not increase significantly. Such changes will however result in direct shift to terrestrial environment because of the fan shaped deltas is limiting the width of tidal flat to a very narrow zone. The coastline development analysis shows that the central Spitsbergen will undergo important increase of the tidal zone. On contrary, the outer zone of Spitsbergen where the large fjords are located will experience formation of narrow but rather long discontinuous terrestrial zones. The rate of tidal flat and land areal extent increase will be affected by intensity of deglaciation and continuing uplift of the island. The enhanced deglaciation caused by climate change forcings may lead to a rapid increase of terrestrial environment areal extent. This process will later slown down after the complete meltdown of the cryosphere. Deglaciation will result in decrease of available water stored in the glacier (thus also the runoff), but also the distance between source areas and deposition basin will significantly increase. The continuous ceasing of the basal erosion can be expected despite the uplift will probably continue for longer time. The basal erosion, as a main contributor to the sediment input to the side-fjord deltas, will gradually cease.

Context within the Svalbard archipelago and the Arctic

The studies on the development of coastal environment in Svalbard are rather frequent. Most of them focused on the evolution of the most dynamic processes of the coastline such as erosion/progradation of beaches or accumulation shapes. These processes are frequently monitored because they often affect marine traffic transportation facilities, industrial infrastructure (Jaskólski 2021) or put the historic heritage sites into danger (Nicu et al. 2021). The coastline changes recorded in these studies ranges from 0.14 to 0.77 m/year (Nicu et al. 2021), 0.16 m/year (Bourriquen et al. 2018), 0.96 m/year (Strzelecki et al. 2018), 0.94 m/year (Kavan 2020a), 0.33 to 3.6 m/year (Sessford et al. 2015), 3 m/year (Mercier and Laffly 2005), the highest progradation rate of 20 m/year was recorded in Southern Svalbard (Ziaja et al. 2009) even though this calculated value is disputable regarding the geomorphologic settings of the locality. Such changes on a decadal timescale usually mean the absolute shift of the coastline in the order of tens to hundreds of meters. Such changes are very well derived from comparison of the historic aerial images and present observations. In case of erosion of old marine terraces or progradation of beach complexes the influence of tidal phase is not so important, because the near shore marine environment is relatively deep. The other case is when comparing coastline positions in a very shallow environment such as the tide-dominated fjord head deltas where the fluctuation of actual shoreline position is dependent on tidal phase and may be larger than the detected changes. The magnitude of change in the shoreline position can be few hundreds of meters up to few kilometres in the most extremes cases as demonstrated in this study. In such light it is obvious that outcomes of certain studies may be biased by this phenomenon. Bendixen et al. (2017) reported rapid progradation of deltas in Greenland. However almost 50% of deltas studied involved restricted tide-dominated shallow delta systems in the heads of the fjords. This implies possible large uncertainties in calculated shifts in shoreline positions despite the trend being very likely correctly estimated. The difficulty to correctly locate the position of the delta margin was also noted by Jensen et al. (2016) in Dicksonfjorden, what was one of main inspirations to run this study.

Conclusions

Analysis of a set of remotely sensed images revealed a high variability in the actual position of a shoreline in a shallow depositional environments of Svalbard deltas. The actual position of the delta shoreline may vary in the order of hundreds of meters up to few kilometres in the most extreme cases (the recorded amplitude ranges from 930 m to 4140 m) despite the moderate tidal amplitude of up to 1.5 m. The high variability of parameters derived from remote sensing data can significantly affect the long-term studies on delta system development when using single historic photographs for example.

This may be true especially for similar shallow water environments where the dependency of the areal extent/position of shoreline on actual tidal phase is crucial.

The set of remote sensing images with derived parameters such as delta areal extent and position of actual shoreline can give us a useful hint on the delta system topography and processes that shape it. All delta systems that show signs of very shallow depositional environment are located in the inner fjords of the archipelago. No similar deltas were found close to the open sea along western or eastern coasts. We argue that the reason for this are the stable morphodynamic conditions with no significant storm impacts, slow offshore currents, and abundant sediment supply from deglaciating valleys. The prolonged sea ice duration is another factor that helps to protect the deposited sediments by reducing the erosion and restricting the sediment transport by wave actions and offshore currents. Together with continuous glacioisostatic uplift, which controls the stability of tidal channels and creeks network, it makes such environment ideal for evolution of these vast and shallow deltas.

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