Measuring coastal cliff retreat in the Kongsfjorden area, Svalbard, using terrestrial photogrammetry

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Abstract

As part of the international project Arctic Coastal Dynamics, results from two sites for measuring coastal cliff retreat in the Kongsfjorden area in Svalbard (79°N, 13°E) are presented. The two sites were established in August 2002 and revisited in August 2004. Photographs with stereo coverage were taken at distances of 7 and 15 m from the cliff walls with a 60-mm Hasselblad camera mounted on a theodolite. Fixed points were established by drilling bolts into the cliff wall and were then surveyed. These fixed points were used as control points for orientation of the photogrammetric models. Digital photogrammetry applied to scanned photographs of the sites resulted in a detailed digital terrain model (DTM) for each site and year. The coastal cliff retreat rates were found by differencing the DTMs of 2002 and 2004. As a result of the short distance between camera and cliff, the DTM differencing was accurate down to 10 mm at least. The results show a yearly retreat of 2.7 and 3.1 mm. These rates are taken to be significant as most of the retreat takes place within small areas with rates well above the accuracy limits of the technique. The results are analysed and discussed in light of earlier rock-wall retreat studies in the same area.

The shorelines of the Arctic Ocean are about 44 000 km in length according to the World Vector Shoreline (Soluri & Woodson 1990). The international project Arctic Coastal Dynamics (ACD) aims at assessing the rates and magnitudes of erosion and accumulation of Arctic coasts, and to estimate the quantity of sediments derived from coastal erosion (Rachold et al. 2005). As part of the ACD project, the work presented here contributes by obtaining reference data from relative stable bedrock coastal cliffs in the Arctic, which have not been well studied. The investigation sites are in the Kongsfjorden area in the western part of the Svalbard archipelago (Fig. 1).

There are very few data available on coastal cliff retreat rates in Svalbard. Prick (2004) found a rock wall retreat of 1.9 mm y^{-1} in a sandstone and shale rock wall in Longyearbyen using sediment traps. This used to be a coastal cliff but it was cut-off from the sea by road and harbour constructions some 10 years before the monitoring started. Other studies have assessed general rock wall retreat rates in Svalbard ranging from 0 to 1.58 mm y^{-1} (Rapp 1960; André 1997; Berthling 2001). All of these studies are based on estimating the volume of slope deposits and then assessing retreat rates by assuming the time period for which the slope deposits have developed. André (1997) directly measured rock wall retreat in areas where both stable and retreating rock walls are found using lichonometry as a chronological control.

The appearance of the coastal rock walls together with the quantity of angular rock fragments accumulating on the snow- and ice-foot below coastal cliffs during spring show that subaerial mechanical weathering is active and important (O. Liestøl, pers. comm.). In some areas the snow and ice can survive all the way through summer above the high tide, indicating that the removal of material is restricted to heavy storms recurring in the fjords at intervals of several years (Ødegård & Sollid 1993). It has been observed that the ice-foot plays an important role in both removal of weathered material from the base of Arctic coastal cliffs and fracturing the lower part of cliff walls (Nielsen 1979).

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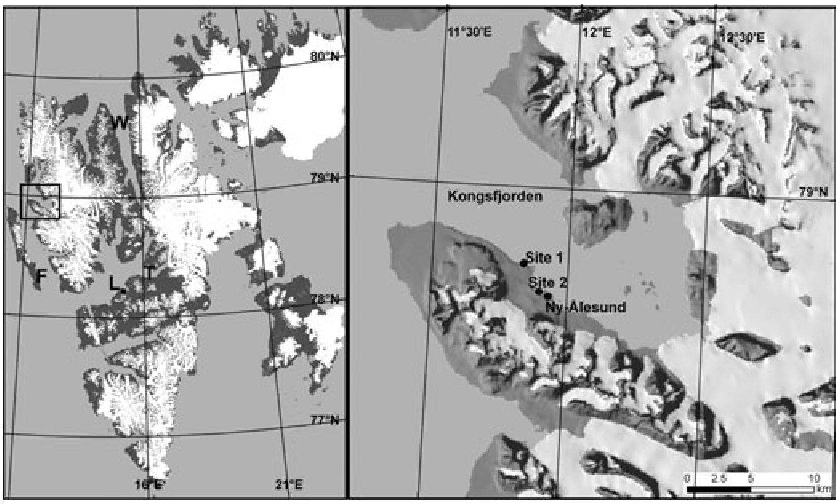

Figure 1 Map of Svalbard and the Kongsfjorden area. The square on the index map represents the research area. L shows the location of Longyearbyen, T and W are the fjords Tempelfjorden and Wijdefjorden, respectively, and F is the island Prins Karls Forland.

Ice-feet and sea ice protect the coastal cliffs in Svalbard fjords from wave energy during most of the year. Submerged strandflat areas along most of the outer western coast also reduce the amount of energy reaching the shores (Ødegård & Sollid 1993). Arctic coastal cliffs are subjected to different types of subaerial and marine weathering processes, and frost weathering has been proposed by Høgbom (1914) and Nansen (1922) to be an important process regarding the formation of the coastal cliffs characteristic of Svalbard fjords. Nansen also suggested that the strandflat forms because of the interaction of frost weathering and marine processes at the base of the cliffs, with frost weathering as the main fracturing agent and marine processes removing the weathered material.

Ødegård & Sollid (1993) investigated the temperature in a coastal cliff near Ny-Ålesund on an hourly basis from August 1987 to August 1988. The steep temperature gradients and available water from snow melting are believed to favour water migration in the fractured dolomitic limestone at <0°C temperatures. Spring and summer snowmelt periods are therefore favourable for crack expansion and rock fracturing. A similar study was performed in Liefdefjorden from May to August 1992 and a similar temperature regime was found (Ødegård et al. 1995). It is suggested that permafrost controls the cliff temperature regime in such a way that the conditions in spring and summer, with a melting snow cover providing sufficient moisture, is favourable to rock breakdown. Ødegård & Sollid (1993) and Ødegård et al. (1995) did not perform any direct measurement of crack expansion or retreat rates in their studies.

As weathered material is removed from the base of the cliff by wave action and sea ice in coastal settings, it is impossible to use the weathered deposits for volumetric calculations of retreat rates. Lichen is very sparse on the faces of the coastal cliffs, thereby also denying lichenometry as an option. The length of the abrasion platform at the sites is 10–15 m, but because of the limited knowledge of the sea level after the Tapes transgression (Forman et al. 1987), and with the possibility of the present sea level occupying a pre-Holocene cliff, it is difficult to calculate an average Holocene retreat rate (Ødegård & Sollid 1993).

Another approach for measuring coastal erosion is remote sensing. Satellite remote sensing and aerial photogrammetry have been successfully used in Arctic coastal change studies (Grosse et al. 2005; Lantuit & Pollard 2005; Mercier & Laffly 2005). Digital photogrammetry, using either terrestrial or aerial photographs, depending on the scale of the feature investigated, has become a valuable tool in geomorphology (Pyle et al. 1997; Chandler 1999; Lane et al. 2000; Baily et al. 2003; Chandler et al. 2003; Lim et al. 2005). Because retreat rates of coastal cliffs in Kongsfjorden are expected to be small, satellite remote sensing and aerial photogrammetry cannot provide the required accuracy for the timescale available. However, terrestrial photogrammetry with camera–object distances of around 10 m can provide the millimetre–centimetre accuracy needed to measure the expected coastal cliff retreat rates. The aim of this study is to quantify the retreat rates of two coastal cliff sites in the Kongsfjorden area using multi-temporal terrestrial photography and digital photogrammetry.

Study area

The Kongsfjorden area is situated on the western coast of Spitsbergen, the largest island of the Svalbard archipelago (Fig. 1). Svalbard is located between 74–81°N and 10–

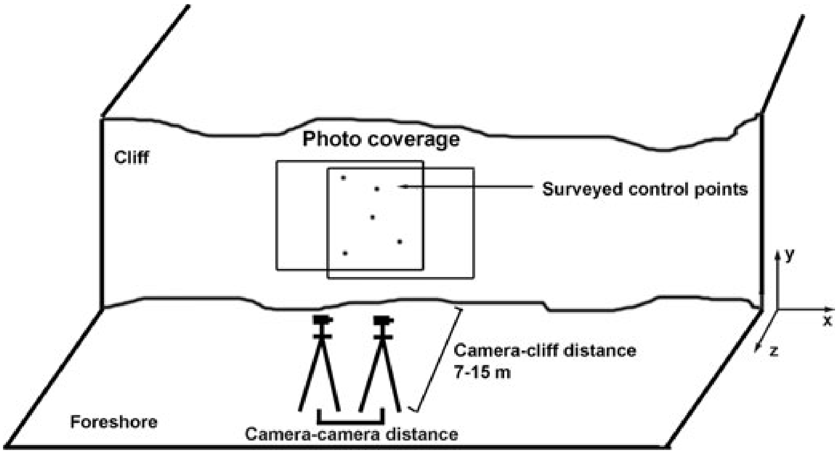

Figure 2 The photograph stations were deployed 7–15 m from the cliff wall and 3.5–7.5 m apart. The photographic coverage is shown on the cliff wall. The investigated area is the area covered by both photographs.

35°E in the North Atlantic. Glaciers of different types cover 60% of the 66 000-km^2 archipelago (Hagen et al. 1993). The mean annual air temperature (MAAT) in Ny-Ålesund is −6°C and the mean annual precipitation 370 mm (Førland & Hanssen-Bauer 2000). The tidal range in Ny-Ålesund is 1.8 m on average; 2.3 m is the maximal tidal range. The average high tide is 0.6 m above mean sea level (Ødegård & Sollid 1993). The area has continuous permafrost with measured depths ranging from 130 to 150 m near the shores of Ny-Ålesund (Orvin 1944; Liestøl 1977). The mean annual ground temperature (MAGT) is believed to be about −5°C based on measurements in a former coal mine (Orvin 1944).

The two sites investigated in this study (Fig. 1) are both close to Ny-Ålesund and consist of low cliffs in bedrock, with unconsolidated material on top, and with sandy and stony beaches in front (Ødegård et al. 1987). Site 2 is located within a small bay and is less exposed than site 1, which is located further out the fjord, with a much longer fetch. The bedrock of both investigated sites is made up of dolomitic limestone of Middle Carboniferous to Early Permian age. The unconsolidated material of 1–2 m in thickness found on the top of the bedrock cliffs are marine deposits of Quaternary age (Hjelle et al. 1999). The dimension of the areas analysed are 2.8 by 3.6 m at site 1 and 2.2 by 2.4 m at site 2. The investigations are limited to the bedrock part of the cliffs.

Coastal geomorphology maps of Svalbard, excluding Nordaustlandet, reveal well-developed coastal cliffs along 27% of the coastline, and another 13% with rocky shores (Etzelmüller et al. 2003). Low vertical cliffs are most frequent in the fjord areas in north-western Spitsbergen. This means that the chosen area is representative of a large portion of the coastline of Svalbard and an even greater portion of the fjord areas. However, one should bear in mind that bedrock properties and marine processes vary greatly within the same coastal type. The percentage of Arctic coasts that are cliffed and rocky is not known, but these coast types comprise three-quarters of the world's coastline (Bird 2000).

Photograph acquisition and digital terrain model (DTM) differencing

Photographs with stereo coverage were acquired with a 60-mm analogue Hasselblad camera at each site in August 2002 and August 2004. The camera–object distances were 15 m at site 1 and 7 m at site 2. The geometry of the camera set-up is shown in Fig. 2. At both sites a bolt was drilled into a bedrock outcrop. The position of the bolt was measured by global positioning system (GPS) and served as a fixed point for reference to global mapping coordinate systems. The positions of the camera stations were also measured using relative GPS and by a theodolite and an electronic distance measurer from the fixed point to tie both to a global and a local reference. At both sites the bolts that were to be used as photogrammetric control points were also drilled into the cliff wall. These fixed points were surveyed from the camera stations and the camera was mounted on top of the theodolite with a special device. This makes it possible to ensure parallel photograph directions.

The photographs where scanned at a resolution of 6.25 μm (4000 dpi) and imported into the Z/I Imagestation digital photogrammetric workstation (DPW) software. The scale of the photographs acquired was 1 : 250 and 1 : 117 for sites 1 and 2, respectively. The scanning resolution therefore gives *xy* resolutions of 1.6 and 0.7 mm for sites 1 and 2, respectively. A local coordinate system was established to simulate aerial photogrammetry, with the *z*-axis is pointing out of the cliff and the *xy* plane vertical behind the cliff wall and also parallel to the photograph base (Fig. 2). All coordinates were also scaled by a magnitude of 100 to simulate reasonable "flying heights". The photograph pairs have been used to create photogrammetric stereo models using the surveyed bolts in the cliff wall as pass points. A high precision DTM was generated for each site using the automatic elevation point collector module in the DPW. The *xy* resolutions of the models created were 2 and 1 cm for sites 1 and 2, respectively. To ensure the high quality of the DTMs, the photogrammetric models from different years at the same site were tied together using the same control points and five additional tie points located in stable parts of the cliff. The retreat rate was simply found by differencing the 2002 and 2004 models using the geographic information system ArcInfo Workstation (ESRI, http://www.esri.com/).

Using terrestrial digital photogrammetry with a similar approach, and evaluating the results, Pyle et al. (1997) infer a DTM accuracy of 12 mm with a 15-m camera–object distance and point out that this accuracy of 1/1000 of the camera–object distance is in the lower end of the accuracies achieved by aerial photogrammetry. This relatively large relative error is attributed to errors in the estimates of ground point positions being much larger relative to the camera–object distance for close-range photogrammetry. Using a digital camera and a 1.6-m camera–object distance, Chandler et al. (2003) found an elevation root mean square (RMS) error of 1. mm, corresponding to 12 parts per 10 000. No direct evaluation of the DTM accuracy was performed in this study, but it is reasonable to believe that they are close to the findings of Pyle et al. (1997). Using the values found by Pyle et al. (1997) the total differentiation error would be 10.6 mm y^{-1} for site 1 and 4.9 mm y^{-1} for site 2.

The RMS values calculated for the combined absolute orientation of the 2002 and 2004 models within the DPW are 3, 4 and 3 mm for *x*, *y* and *z*, respectively at site 1 and 2, 3 and 6 mm at site 2. This means that the accuracy should be 10 mm or better for the yearly retreat values.

Lens distortion and focal length were not known for the camera at the time when the study was performed, but has subsequently been the subject of a Master's thesis (Odberg 2006). Not knowing the exact focal length will lead to an error in the *z* direction and therefore also an error for the retreat. As the same camera was used both times, and the photographing position (to within centimetres) and the photographing direction were also the same, this would not lead to any errors in the calculation of retreat because the errors will be exactly the same for the photographs taken in 2002 and 2004. It would be likewise for the lens distortion, which leads to errors in *x* and *y* as well, but the change of the lens from 2002 and 2004 is insignificant.

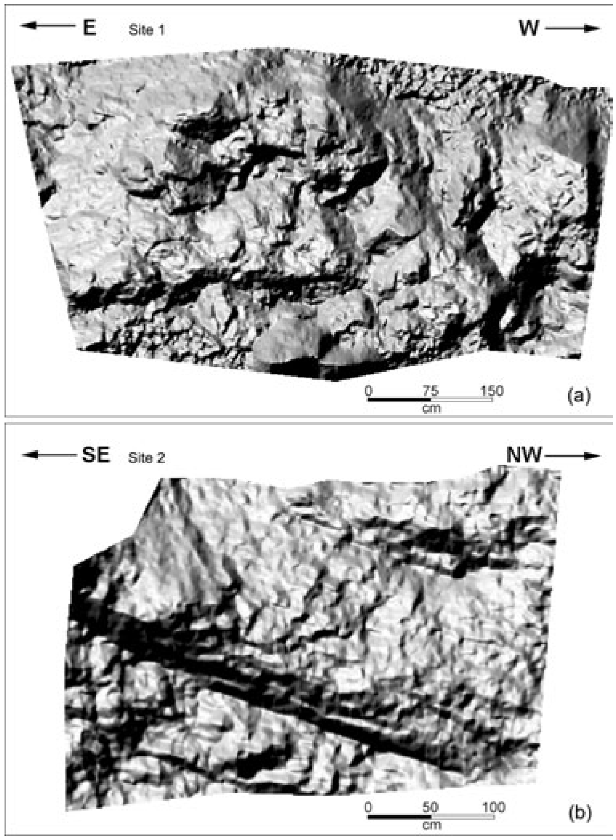

Figure 3 Digital terrain models (DTMs) of (a) site 1 and (b) site 2 from 2004 shown as shadowed relief models.

Coastal cliff retreat rates

The automatically generated 2004 DTMs for sites 1 and 2 are shown in Fig. 3 as shadowed relief models. The differencing of the DTMs reveal an average retreat of 3.1 mm y^{-1} for site 1 and 2.7 mm y^{-1} for site 2 (Fig. 4). The average retreat rate is calculated as the volume difference between the two time periods divided by the investigated area of the cliff. At site 1 parts of the cliff wall was hidden behind boulders, and these areas were excluded from the retreat rate calculation. Both difference models show retreat occurring in spots, with maximum retreat rates of 125.0 and 42.0 mm y^{-1} for sites 1 and 2, respectively. The other retreat spots at both sites 1 and 2 are in areas where the cliff is quite planar, and therefore show flaking rather than small rockfalls (Fig. 5). Orthophotographs of site 1 from 2002 and 2004 show a loss of material in front of the cliffs between the two acquisitions. The volume of the removed boulders along the 6.5 m distance with stereo coverage is estimated to be about 0.6 m^3 based on photogrammetric stereo measurements. As the boulders are located in front of the cliff it is

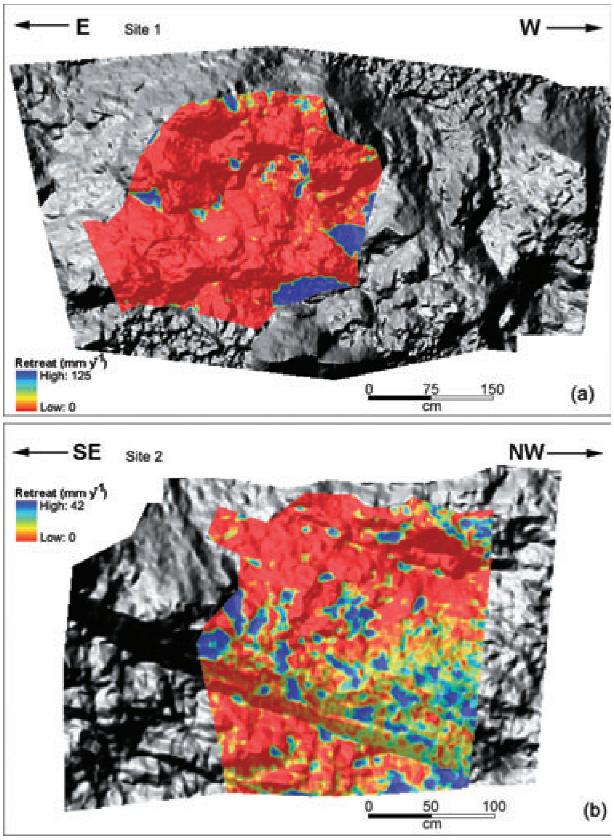

Figure 4 Retreat rates from (a) site 1 and (b) site 2 draped over the 2004 relief models.

not possible to measure them using DTM differencing, and this area is therefore excluded from the DTM differencing presented in Fig. 4. The blocky material that has been removed from the beach at site 1 is also marked in Fig. 5. There was no blocky material in front of site 2, and therefore only the retreat rates of the cliff itself were calculated (Fig. 6).

Discussion

DTM differencing accuracy

Looking at either RMS values from the orientation of the model or using the values computed using either Chandler et al. (2003) or Pyle et al. (1997), the accuracy of the applied method is 10 mm or better for yearly retreat rates at both sites.

As an additional check of the accuracy, semivariograms were made for the retreat rate grids. In these grids all points with retreat rates above 10 mm y^{-1} were left out. Semivariograms are used in geostatistics to evaluate spatial dependency in data sets (Burrough 1990) and are plots of the semivariance as a function of distance. The difference between the nugget (a measure for variance caused by noise in the data) and the sill (a measure for the variance level at the distance where the spatial dependence ceases) can be taken as an indicator for the overall spatial dependency in the data. At both sites there was a relatively small difference between the sill and the

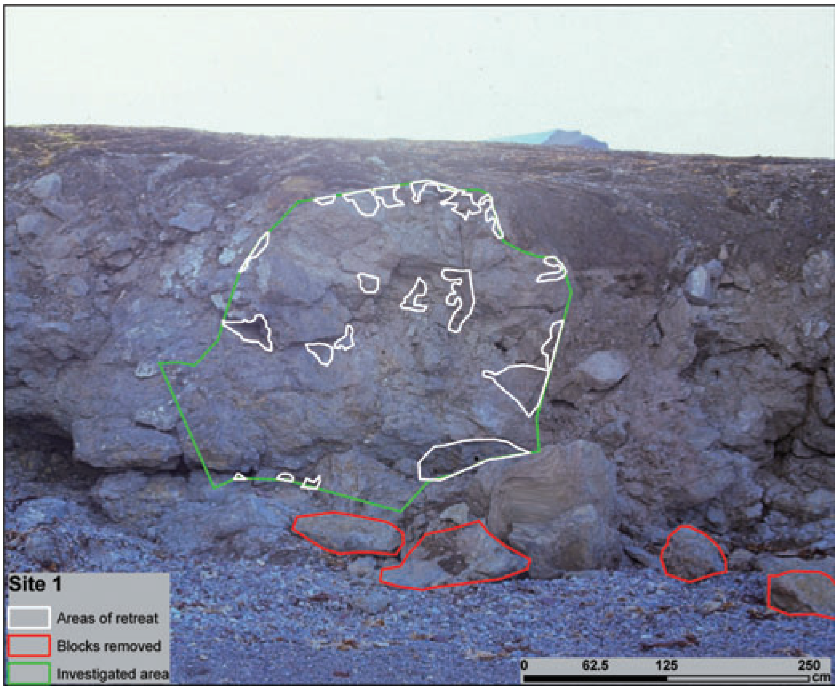

Figure 5 Orthophotograph of site 1 in 2004 showing areas of retreat and block removal.

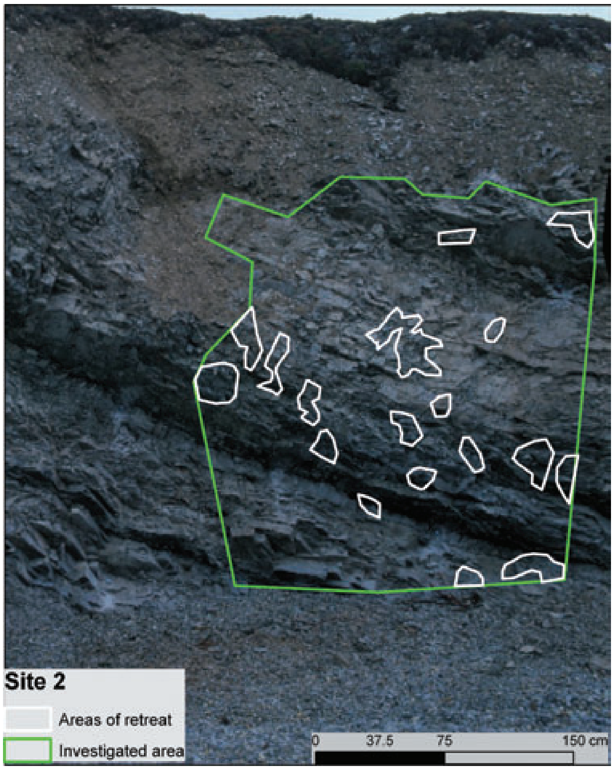

Figure 6 Orthophotograph of site 2 in 2004 showing areas of retreat.

nugget values, namely 4% for site 1 and 20% for site 2, meaning that there is only a small spatial dependency in the data set for values below the believed accuracy, and that the retreat rates should be valid as volume measures and not only as point measures. Hence, no spatial trends in the data sets were found.

It is worth noting that the semivariograms and the RMS values from the orientation show that the data set from site 1 is more accurate than that from site 2, even though site 1 has twice the camera–object distance compared with site 2. This might be a result of there being fewer fixed points used for orientation at site 2, and hence a less accurate orientation of the models.

As noted earlier, most of the retreat detected in this study takes place in concentrated and rather small areas and with a retreat rate greater than the accuracy, indicating that the overall retreat rates are significant.

Retreat rates

Compared with the findings of Rapp (1960), André (1997), Berthling (2001) and Prick (2004), the results from this study show somewhat higher retreat rates. André (1997) found retreat rates of up to 1.58 mm y^{-1}, but attributes only a small portion of these rates to currently active frost shattering, namely 0.07 mm y^{-1} in average for amphibolite in Wijdefjorden, and 0.16 mm y^{-1} for quartzite in Kongsfjorden. Rapp (1960) reported a rock wall retreat rate of 0.02–0.20 mm y^{-1} for the sand and limestone in Tempelfjorden, and 0.50 mm y^{-1} for a nunatak in the same area. Berthling (2001) reported rock wall retreat rates of 0.3–0.6 mm y^{-1} based on volume and age estimates of rock glaciers on Prins Karls Forland in an area of quartzite bedrock. None of these localities are exposed to marine processes and are therefore not directly comparable with the results from this study. Prick (2004) reports a rate of 1.9 mm y^{-1} for a sandstone and shale cliff wall in Longyearbyen, which is the most similar site compared with the ones we investigated in terms of process and bedrock composition. The differences between the results found in this study and the earlier works of Rapp (1960), André (1997) and Berthling (2001) can be attributed to differences in the effectiveness of the rock wall retreat processes involved compared with coastal processes.

The smaller retreat rate found by Prick (2004) may be explained by differences in bedrock. Her study focused on bedrock that is somewhat less susceptible to weathering. According to Sunamura (1992), however, cliffs consisting of shale and sandstone should be more susceptible to coastal erosion than limestone. The site investigated by Prick (2004) has been protected from these processes for a decade, whereas the locations used in this study are currently influenced by marine processes.

Marine cliffs in general show a variety of erosion rates caused by lithology, from several metres per year for regolith, to 4 mm y^{-1} and upwards for rocks of medium to hard rock cliffs unaffected by erosion (Young & Saunders 1986). Sunamura (1992) lists worldwide linear cliff recession rates and found the following average rates: 1 mm y^{-1} for granite, 1–10 mm y^{-1} for limestone and 1 cm y^{-1} for shale. Cold regions exhibit higher retreat rates and Allard & Tremblay (1983) found erosion rates in the order of 10 mm y^{-1} for a basaltic bedrock coast by Hudson Bay in northern Quebec, Canada. They attribute this to the joint actions of waves, sea ice and frost shattering. It is reasonable to believe that chemical weathering is more active in the coastal zone compared with areas not influenced by the sea. As carbon dioxide is more soluble at colder temperatures one should expect higher rates of chemical erosion in Arctic marine environments (Williams 1949). At a non-coastal locality, chemical erosion rates of 2 mm per thousand years have been found, whereas rates in marine polar areas may be at least two magnitudes greater (Corbel 1959). Therefore, chemical weathering accounts for a negligible portion of the coastal cliff retreat rates measured in this study.

It is important to bear in mind that the measurements that form the base of this study were performed only at two selected localities and on only a few metres of coastline. As the processes governing coastal cliff retreat probably vary considerably both spatially and temporally, because of variations in sea-ice cover, snow cover, bedrock and existence of the ice-foot, as well as with wave activity and storminess, the retreat rates will also show a huge variation. Earlier studies for instance show a considerable spatial and temporal variation in sea-ice and ice-foot conditions in the Kongsfjorden area (Wiseman et al. 1981) and other places in Svalbard (Feyling-Hansen 1953). Weather data from the meteorological station in Ny-Ålesund show that the temperature, precipitation and wind in the investigated period from August 2002 to August 2004 did not differ largely from the general climate deduced from meteorological observations undertaken by the Norwegian Meteorological Institute since 1974 (data accessed at http://eklima.met.no for station no. 99910). The greatest deviations from the general climate are found for temperature in late 2002, showing temperatures of 4.6 and 5.4°C above the mean temperatures for November and December, respectively, although the temperatures remained well below 0°C. These months also show higher values for precipitation, meaning more snowfall. Whether this led to either a greater snow thickness or longer snow cover duration in the following spring at the investigated sites is unknown. There are no observations of sea-ice distribution available. To assess reliable retreat rates a long-term programme, preferably also including more sites, should be undertaken. Monitoring of temperature, snow, sea-ice cover and wind at the investigated sites would also be a requirement.

Traditional geomorphologic estimates of coastal retreat rates at a scale of either millimetres or centimetres per year are based on a longer period of time than two years, and the uncertainty of those are mainly caused by uncertainties of the time horizon (i.e. dating). The advantage of using volume-/time-based retreat rates is that the year-to-year variation in the processes governing weathering and coastal processes is better dealt with. As noted earlier, the uncertainty of the sea level development since the Tapes transgression in the investigated area makes it difficult to estimate the Holocene retreat rate using these traditional methods (Forman et al. 1987). However, terrestrial photogrammetry makes is possible to perform spatially detailed studies of retreat rates and to map more short-term temporal variations.

Conclusion

The method of close-up digital terrestrial photogrammetry seems suitable for creating accurate DTMs of coastal cliffs and for calculating retreat rates on the order of millimetres–centimetres. Differencing of multi-temporal DTMs reveal retreat rates of 3.1 and 2.7 mm y^{-1} for two costal cliff locations in the Kongsfjorden area in western Spitsbergen, Svalbard. The retreat occurs in spots and the processes involved seem to be both flaking and small rock falls. Compared with rock wall retreat rates found elsewhere in Svalbard, the rates are quite high. This could be because other investigations were performed in non-coastal environments or because there were other natural processes involved. Two years is too short a time interval for investigating coastal cliff retreat rates. Nevertheless, the retreat rates found are within the range of worldwide averages for limestone cliffs. Removal of weathered material at the base of the coastal cliffs is considered to be important in the retreat process, and is documented through the multi-temporal photography obtained at one of the sites.

Acknowledgements

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