Advancing Arctic coastal erosion measurement and monitoring through UAV-SfM and object-based image analysis

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Abstract

Arctic coasts are vast, representing 30-34% of Earth's coastline and exhibit some of the highest rates of erosion in the World due to the presence of permafrost. Rates of erosion are expected to increase with warming air and water temperatures, reductions in Arctic sea ice extent and duration, sea level rise, and increased storm severity and frequency. Erosion of Arctic coasts can lead to rapid land loss threatening habitat, archaeologically significant sites, modern infrastructure, and communities. Rapid erosion and permafrost degradation also leads to the liberation of previously frozen sediment and organic carbon into the nearshore zone which affects marine ecosystems and contributes to ocean acidification. Further, the release of organic carbon from frozen sediment contribute to global greenhouse gas release which are not well understood nor included in current Earth System Models. This thesis focuses on the use of emerging technologies to further our understanding of Arctic coastal processes, specifically, volumetric erosion, and broad scale delineation of multiple shoreline proxies for monitoring and quantification of erosion. UAV-SfM provides aerial and DSM imagery at unprecedented spatial and temporal resolution that provides perspectives and quantitative measures that are unachievable using conventional methods while image classifications derived from OBIA, or GEOBIA, provide opportunities to systematically create boundary features (i.e. shoreline proxies) at a broad scale. Overall, this doctoral research develops and evaluates techniques that enhance our ability to make quantitative measures of Arctic coastal erosion, both planimetric and volumetric, that have implications locally, regionally, and globally.

Research Objectives

The overall objective of this doctoral research is to advance the measurement of Arctic coastal erosion by focusing on two emerging technologies:

1. UAV-SfM and 2. GEOBIA (OBIA).

Within these areas of focus, there are three major themes and lines of investigation relevant to the measurement of Arctic coastal erosion:

1. Multi-coastal proxy analysis
2. Planimetric and volumetric quantification
3. OBIA feature extraction

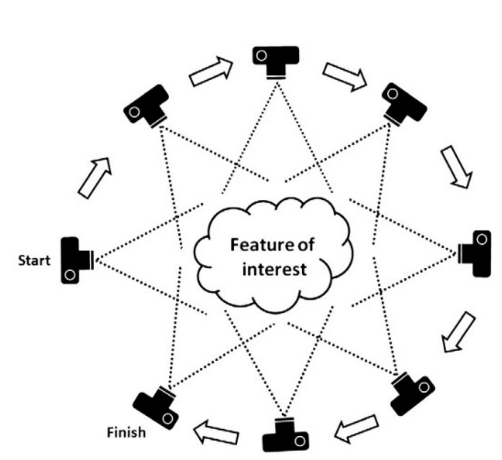
The development of these emerging technologies creates new opportunities to advance our understanding of and ability to measure Arctic coastal processes across scales, however, the practical implementation requires evaluation and assessment of the inherent challenges.

UAV-SfM

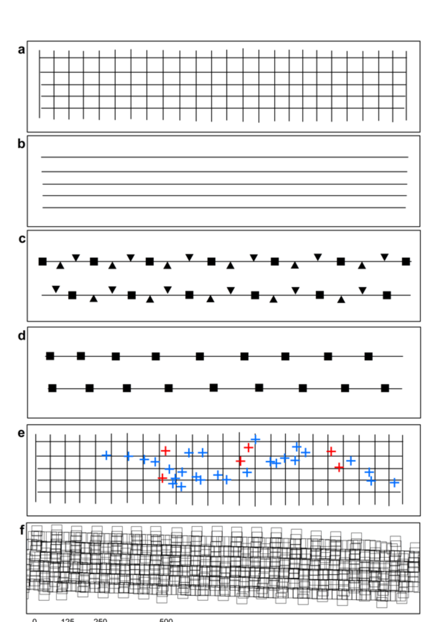
Uninhabited Aerial Vehicles (UAVs) combined with Structure-from-Motion (SfM) (left) are democratizing the collection of high-quality two- and three-dimension data in a variety of industries but in particular in the geosciences. UAV-SfM offer a flexible, cost-effective alternative to existing techniques that can offer truly 3D information when coupled with ground control points (GCPs) which can contend with the spatial accuracy of other digital survey methods.

This research makes contributions towards the measurement of Arctic coastal erosion by investigating the emerging technology that is not well-developed in this space. Specifically, data products derived from Uninhabited Aerial Vehicles (UAVs) combined with Structure-from-Motion (SfM) (overlapping images) are used to investigate Arctic coastal processes at high spatial and temporal resolution to better understand the volumetric consequences of Arctic coastal erosion as a contribution towards better constraining the amount of release of OC from permafrost coasts.

Further, the affordability of consumer UAV, the ease of UAV operation, and user friendly SfM software has unfortunately contributed to a lack of understanding of the parameters, workflow and underlying sources of error involved in close-range SfM. As part of this work, we conducted an analysis that highlights the influence of different data collection strategies and provide Arctic coastal erosion researchers with recommendations to mitigate systematic errors that can influence reported results, particularly in 3D-based analysis.



(Westoby et al., 2012)



a) Cross hatch/Perpendicular flight lines

b) Parallel flight lines

c) Nadir (square) and Oblique images (triangle)

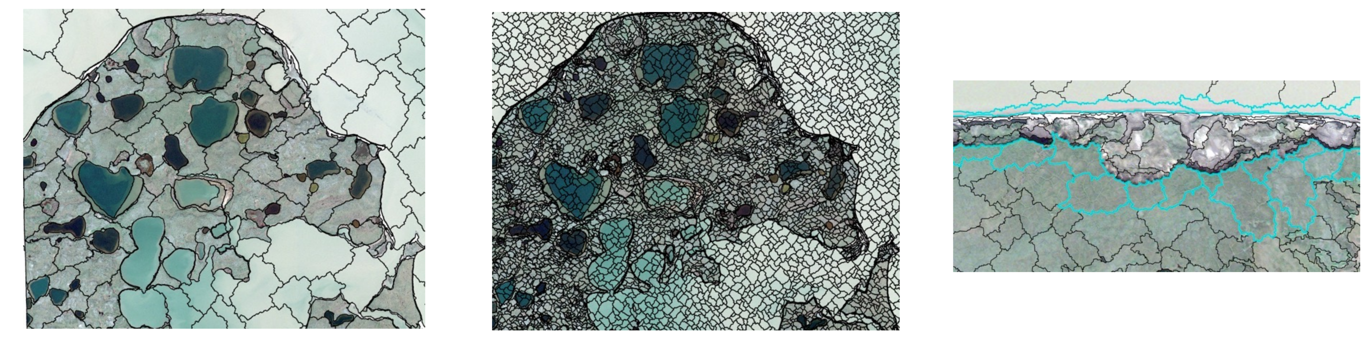
d) Nadir images

e) Target locations
Red - GCP
Blue - Independent check points

f) Image block

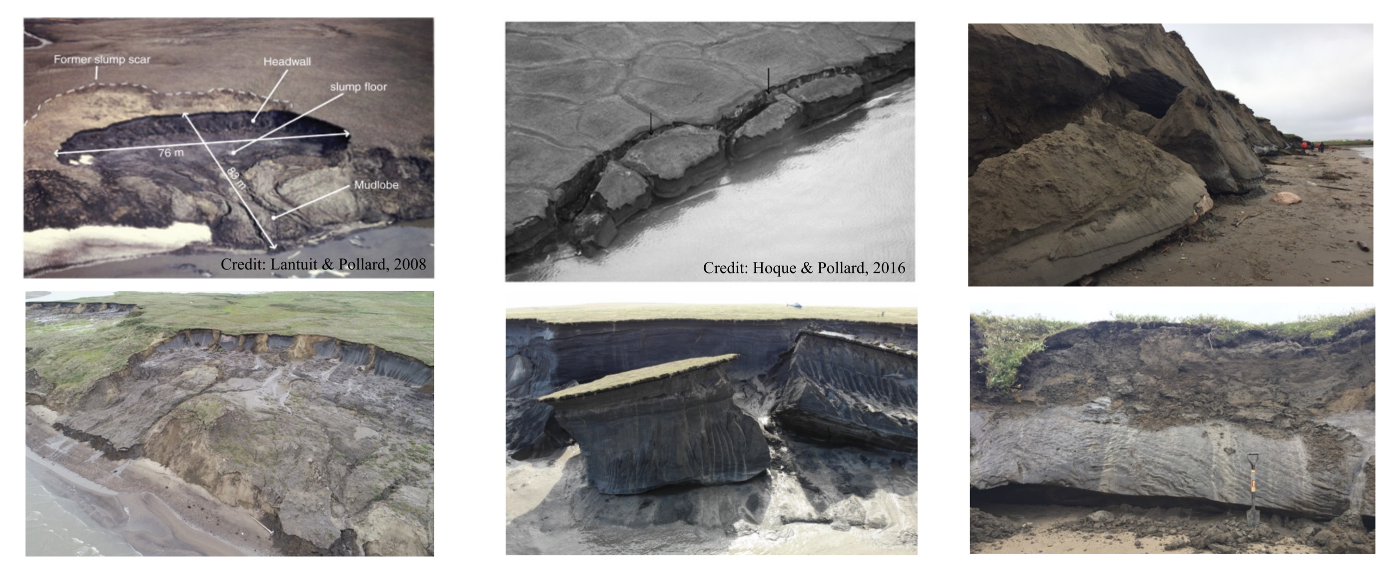
Object-based image analysis (OBIA)

OBIA, or GEOBIA, refers to an object-based approach in the analysis of Earth observation remote sensing imagery. More specifically, it is a sub-discipline of Geographic Information Science (GIScience) devoted to developing automated methods to partition remote sensing imagery into meaningful image-objects, and assessing their characteristic through spatial scale, spectral and temporal scales, so as to generate new geographic information in GIS-ready format. OBIA is an alternative to the pixel-based paradigm traditionally used in satellite imagery and is based on the concept of using image objects instead of pixels as the basic units (primitives) to extract spatial information that is implicit in RS imagery while integrating better with vector-based GIS.



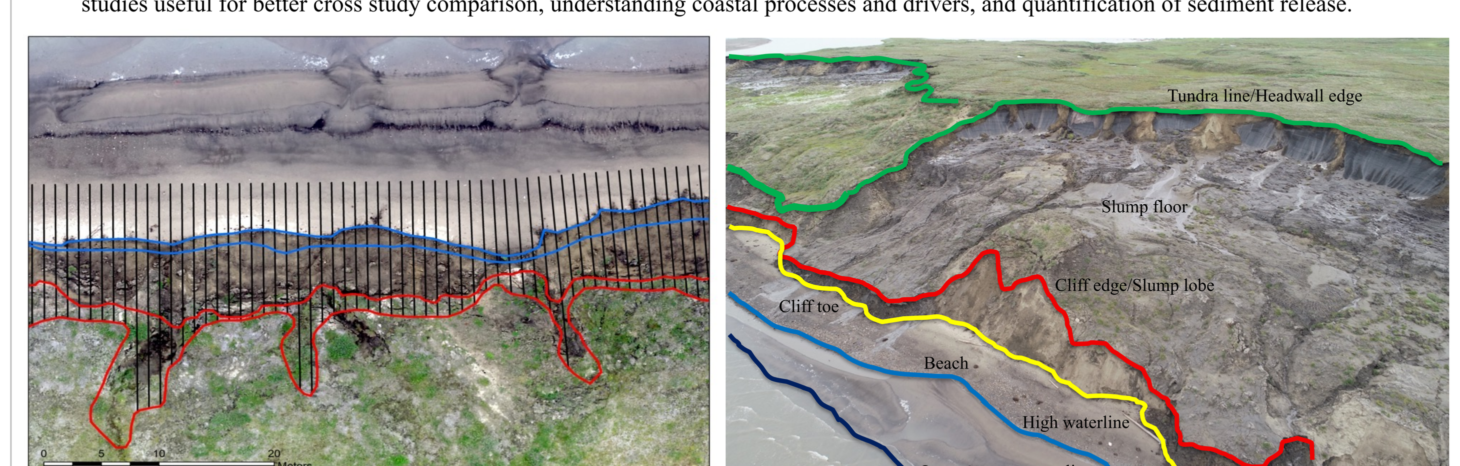
Arctic Coasts

Arctic coasts are especially vulnerable to climate change due to the presence of underlying permafrost and ice, which leads to unique coastal processes and environments like retrogressive thaw slumps (RTS) (left) and block failures (middle). These features, specifically, are a source of rapid and continuous, in the case of RTS, sediment release that is not well quantified at an Arctic wide scale. However, rapid erosion is common outside of these environments where wave action (from storms in the case of the right images) leads to niche development and exposes underlying massive ice.



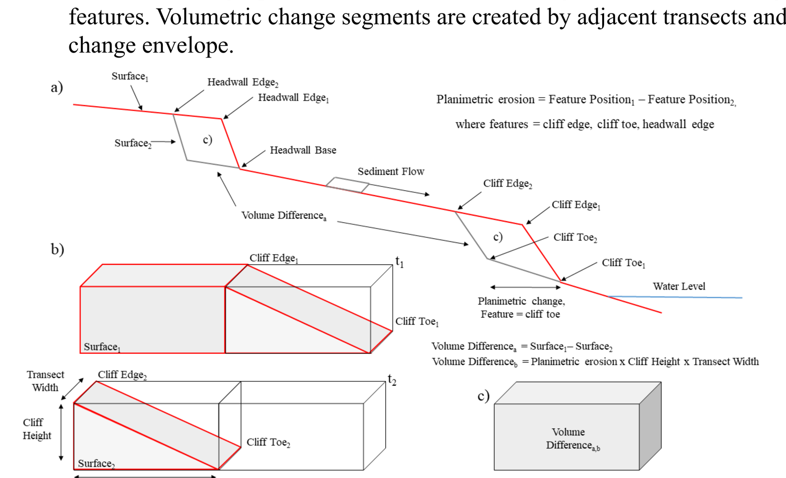
Multi-coastal proxy analysis

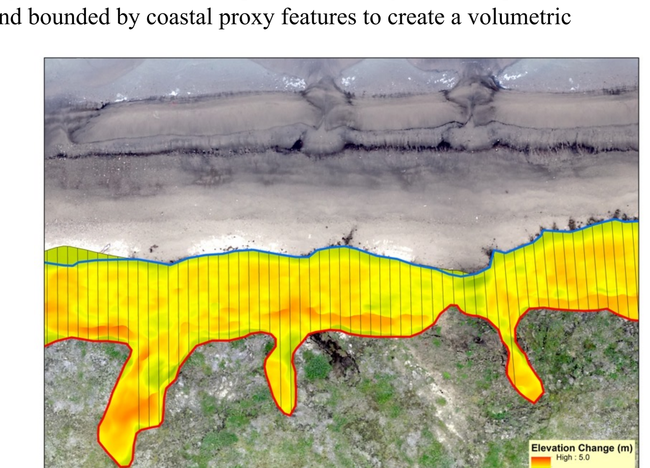
Traditionally, erosion studies of Arctic coasts have used a single coastline proxy (i.e. waterline or vegetation line) to track changes identified from aerial or satellite imagery. This makes cross study comparisons difficult and doesn't account for the complexity of changing Arctic coasts where in the case of coastal retrogressive thaw slumps (right) there are multiple independently changing features that contribute to sediment release. Often the proxy was dictated by the quality of available data but with the increasing ubiquity of very high resolution UAM-SfM and satellite imagery, multiple distinct features are visible across the datasets. As a result, this work proposes and demonstrates the identification and change analysis of multiple coastal proxies (left). This approach enhances Arctic coastal erosion studies useful for better cross study comparison, understanding coastal processes and drivers, and quantification of sediment release.



Planimetric and volumetric quantification

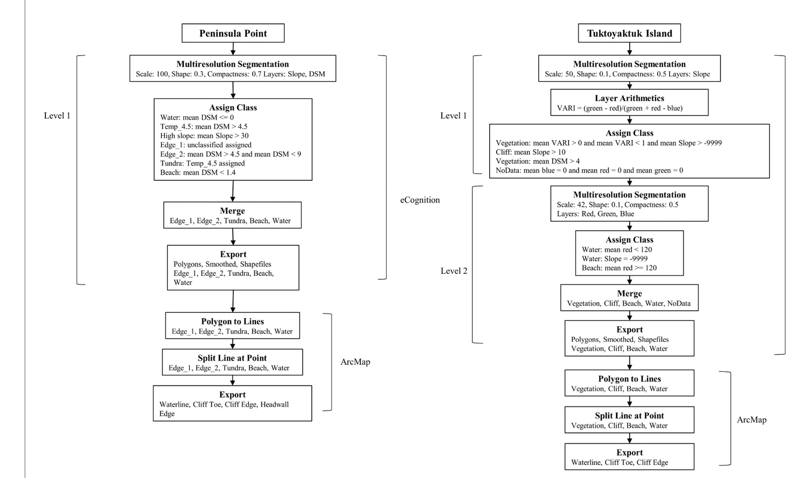
The increasing availability of 3D information through UAV-SfM, LiDAR surveys, and ArcticDEM creates further opportunities to enhance Arctic coastal erosion studies and understanding. The development of this theme focuses on leveraging multiple coastal features to constrain the volumetric analysis to morphological changing features only to avoid conflating with systematic errors between datasets which was identified as a limitation of current methods in the literature. In addition, the demonstrated approach enables the direct comparison between planimetric and volumetric measurements that will be useful in determining relationships for broad scale volumetric change quantification. Planimetric changes are measured along transects that includes positional changes of multiple features. Volumetric change segments are created by adjacent transects and bounded by coastal proxy features to create a volumetric change envelope.

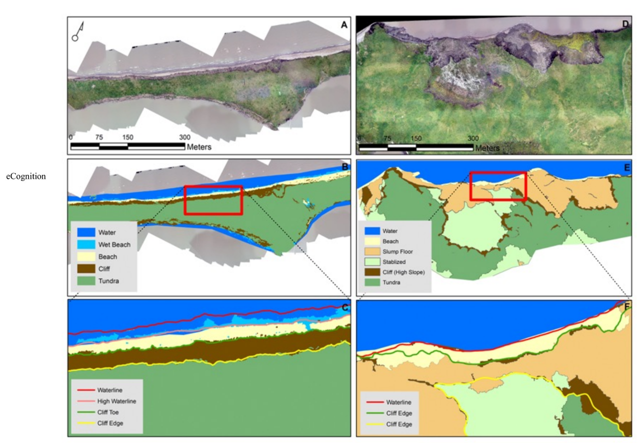




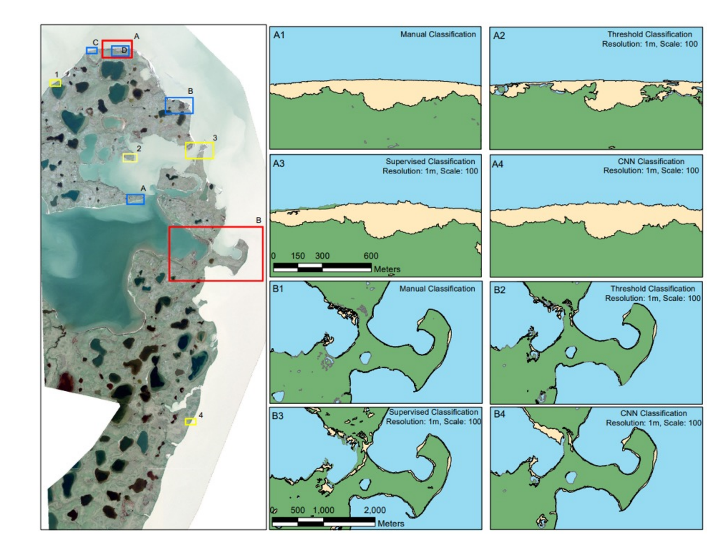
OBIA feature extraction

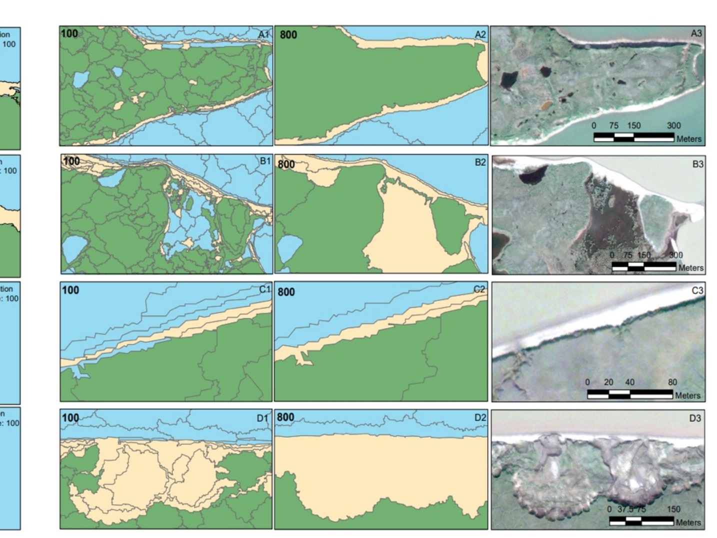
Object-based image analysis using eCognition software was first implemented on UAV-SfM datasets and later VHR Pleiades satellite imagery. Two sites, Tuktoyaktuk Island (A) and Peninsula Point (B) in the Northwest Territories are representative coastal environments of the Arctic; a RTS and a cliff. The feature extraction workflow (left) varied between sites to accommodate the site differences but generally involved created an image segmentation and assigning image objects to a class based on object parameters. This process vectorized the raster imagery for use in a GIS, from which feature extraction could be conducted by assigning meaning to boundary lines. The waterline, cliff toe, and cliff edge (i.e. multi-proxy analysis) were evaluated against manually identified reference features. The waterline produced poor results due to the inaccuracies associated with UAV-SfM reconstruction of the water surface. Cliff toe and cliff edge features were extracted with high accuracy particularly along high contrast features (A). The polycyclic nature of RTS present challenges due to the land cover variability. Nevertheless, utilizing the slope derivative was especially useful in identifying edges, which generally denote a cliff edge or headwall edge (tundra line).



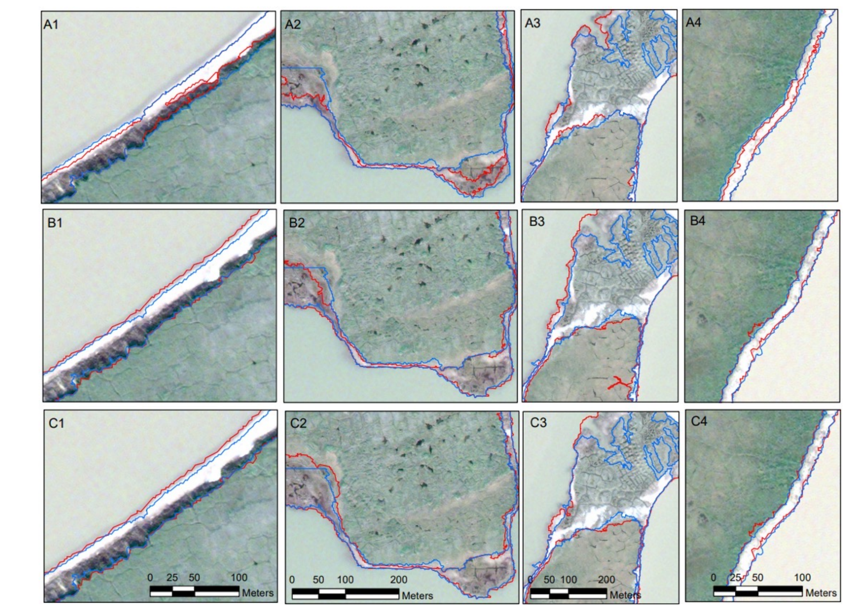


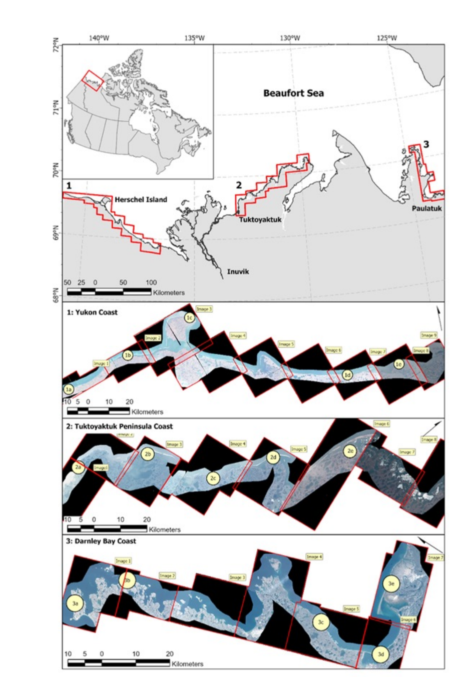
While the above OBIA provided useful data products for analysis, it is best suited for high temporal analysis along small sections of the coasts. In addition, it provides useful information for scaling up to larger areas. For example, a limitation of OBIA using UAV-SfM derived imagery is the lack of the near infrared (NIR) band and dedicated image bands because of the consumer grade sensors common on these platforms. Satellite imagery covers a larger areas and dedicated channels which enable better identification of water and vegetation through NDVI and NDWI. This analysis of a single satellite scene covering close to 100 km of coastline involved testing multiple classifications methods (threshold based, supervised, and deep learning CNN) on multiple image resolutions (left). Classifications were evaluated using confusion matrices and found to be at least 90% and up to 95% accurate for the highest resolutions (0.6, 1.0, and 2.5 m/pixel). Accuracies decreased at a resolution of 5m/pixel or greater. The deep learning CNN classifier provided the best classification results. In addition, because the image objects created during the segmentation process provide the backbone of the analysis, testing of the segmentation scale was conducted to understand the implications of over and under segmentation and to find the preferred segmentation scale for this dataset.





Similar to the feature extraction process first developed using UAV-SfM datasets, coastal proxy lines (tundra line and waterline) were extracted in a GIS using the vector-based classifications (left) where the blue line represents the reference features and red represents the OBIA extracted features. The waterline and tundra line, when the tundra line has a well-defined edge (i.e. a cliff edge), were extracted with accuracies comparable to what can be achieved by human interpretation, suggesting this approach can be systematized to aid in the production of multiple coastal proxy features. As a result, the developed methods were further refined and scaled up (right) to simulate a broad-scale Arctic coastal analysis program that includes additional coastal types and environments. A new classification scheme, using sub-classes, was created to account for broad scale variabilities that was generalized to create the vector-based classifications from which the features could be extracted. Shadows (due to low imaging angle) and turbid waters were data limitations that contributed to misclassification and subsequent poor feature extraction. Cloud cover and ice also introduce complexity that requires additional attention. Overall, however, the developed methods continued to perform well where well-defined features were present, taking advantage of OBIA's ability to mimic human interpretation. The analysis performed particularly well along erosional coastal types, as opposed to depositional coastal types that tended to have fuzzy boundary features that are even subjectively identified using traditional methods. This is important because of the need to better constrain the sediment release from Arctic coasts due to the presence of OC where the largest impact results from erosional coasts. This provides promising opportunities to integrate the methods of this work into future monitoring programs to measure broad-scale erosion in the Arctic.





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