**Modeling Glacier Dynamics and Sea Level Rise for Future Projections in the Gulf of Alaska**

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**Abstract**

**Introduction**

Glaciers play a crucial role in the Earth's climate system and significantly contribute to global sea level rise. Recent studies have highlighted the alarming rate of glacier mass loss worldwide, with substantial implications for sea level rise, freshwater resources, and regional hydrology. The Intergovernmental Panel on Climate Change (IPCC) has projected a likely global mean sea level rise of between 0.43 m and 0.84 m by 2100 under a high emission scenario (RCP 8.5) (IPCC, 2021) [2]. This rise poses significant threats to coastal communities, infrastructure, and ecosystems worldwide.

From 2019 to 2023, global glaciers experienced a significant mass loss of approximately −331.68 ± 59.07 Gt/yr, contributing to a sea level rise of 0.916 ± 0.163 mm/yr [1]. Notably, Alaska emerged as the foremost contributor to global glacier mass change, with a substantial mass balance loss of approximately −57.11 ± 7.68 Gt/yr [1]. This deceleration in mass loss contrasts with the accelerated mass loss observed in other regions, such as the southern Canadian Arctic and the southern Greenland Periphery. The Gulf of Alaska (GOA) stands as an ideal research site because it contains diverse terrain features together with both heavy rainfall and significant ice coverage, which is visualized in Figure 1 [4].

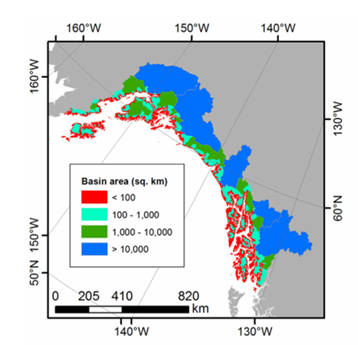


Figure 1. Map of the individual coastal watersheds in the GOA, color-coded by area.

To understand and quantify changes in glacier mass, four main methods are commonly used: glaciological, digital elevation model (DEM) differencing, altimetry, and gravimetry. Repeat observations from optical and radar DEMs provide detailed glacier elevation data at high temporal and spatial resolution. The IPCC’s sixth assessment report (AR6) complemented glaciological observations with global glacier mass balance from DEM differencing, using results from gravimetry for evaluation [2]. Furthermore, a broad range of mass balance estimates exists within the literature, emphasizing the challenges inherent in accurately measuring and modeling glacier dynamics, the major runoff sequences for GOA is shown in Figure 2 [6].

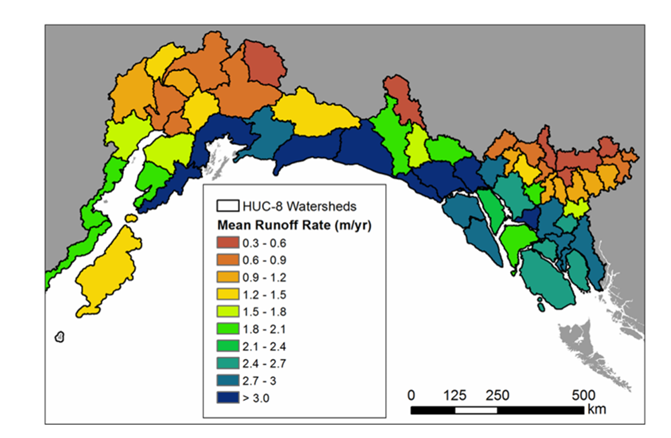


Figure 2. .Map of mean annual runoff rate (in m yr21)

The Kenai Peninsula in south-central Alaska has experienced significant glacier mass loss, with a 12% area shrinkage between 1986 and 2016. The region-wide mass-balance rate between 2005 and 2014 was −0.94 ± 0.12 m w.e. a−1, indicating an acceleration in glacier mass loss.[3] This region's glaciers contribute significantly to global sea level rise and freshwater input into the Gulf of Alaska. The current state of GOA glaciers reflects a complex interaction of various factors. While globally, glacier mass loss is accelerating [1], with Alaska playing a substantial role for whose a historical trend pattern is plotted for the 4 Major Glaciers of Alaska in Figure 3 [10].

A graph of different colored lines

Description automatically generated

Figure 3. Mass balance trends of Alaskan glaciers (1952-2023)

This research aims to develop a robust pipeline for processing images, extracting meaningful features, generating datasets, analyzing data, and deploying models to study glacier mass balance changes. The research begins with extracting frames from glacier timelapse and segmented into 300 individual frames, which then undergo image processing to enhance quality and identify key features through segmentation. 9 Statistical features are derived from these processed frames, complementing data acquired from existing research, including geographical facts about the glaciers. The dataset represents the glacier's characteristics over the 36-year period, with each row corresponding to a specific year from 1986 to 2021. This combined dataset is then pre-processed, analyzed, and normalized to prepare it for modeling.

Following image processing, the extracted features are used to generate datasets for training and testing machine learning models. Data analytics is performed to gain insights into the datasets and prepare them for model training. Different machine learning models, including ensemble models, Long Short-Term Memory (LSTM) networks, and Recurrent Neural Networks (RNNs), are tested to evaluate their performance and suitability for the given task. The best-performing models are then prepared for deployment.

The results from these two models were then ensembled to obtain optimized forecasts for the years 2022 to 2026. Additionally, linear regression is utilized to establish a relationship between the extracted statistical features and real-world glacier trends. estimate the glacier's mass balance and sea level contribution, which are crucial indicators of the glacier's health and the region's environmental changes.

This comprehensive workflow showcases the integration of image processing, machine learning, and data analytics to solve complex problems effectively. By providing a detailed methodology for developing and deploying machine learning models for image processing tasks, this research aims to contribute to the field and serve as a valuable reference for future studies and applications in related domains.

**Literature Study**

Recent studies highlight the alarming rate of glacier mass loss, significantly contributing to global sea level rise. From 2019 to 2023, global glaciers lost approximately −331.68 ± 59.07 Gt/yr, equating to a sea level rise of 0.916 ± 0.163 mm/yr. Alaska was the foremost contributor, with a mass balance loss of −57.11 ± 7.68 Gt/yr [1].

Four main methods are used to quantify glacier mass changes: glaciological, digital elevation model (DEM) differencing, altimetry, and gravimetry. The IPCC’s sixth assessment report (AR6) complemented glaciological observations with global glacier mass balance from DEM differencing, using gravimetry for evaluation [1].

Alaska has been a significant focus due to its substantial contribution to global sea level rise. The region-wide mass-balance rate between 2005 and 2014 was −0.94 ± 0.12 m w.e. a−1, indicating an acceleration in glacier mass loss. Alaskan glaciers account for approximately 12% of the total global glacierized area, excluding the Greenland and Antarctica ice sheets [3].

The Kenai Peninsula experienced a 12% area shrinkage between 1986 and 2016. The region-wide mass-balance rate between 2005 and 2014 was −0.94 ± 0.12 m w.e. a−1, indicating an acceleration in glacier mass loss [3]. The glaciers have experienced widespread recession since the Little Ice Age [7].

Glacier mass loss in Alaska impacts global sea level rise and freshwater resources. Annual runoff is partitioned into 63% snowmelt, 17% glacier ice melt, and 20% rainfall. Glacier runoff was 38% of the total seasonal runoff [4].

Climate models predict that the Gulf of Alaska (GOA) will become warmer and wetter, leading to significant reductions in snowpack and glacier extent. For RCP 4.5, reductions in glacier volume and area resulted in a 30% decrease in annual glacier runoff between 2003–2022 and 2080–2099 [6].

Ice flow plays a fundamental role in glacier dynamics and hazards. In Alaska, glacier speeds are 50% greater in spring than the annual mean. Lake-terminating and tidewater glaciers flow faster than land-terminating glaciers. Glacier Lake Outburst Floods (GLOFs) can cause significant speed-ups in glacier flow [7].

**Methodology**

The workflow structure and implementations of the study have been mentioned below in the sections discussed in the sections ahead. The procedure starts with the extraction of frames from glacial timelapse, followed by the segmentation into 300 distinct frames, which subsequently undergo image processing to improve quality and discover essential elements using segmentation. Statistical characteristics are extracted from these processed frames, augmenting data obtained from prior studies, including geographical information on the glaciers. The integrated dataset is subsequently pre-processed, analysed, and normalised to facilitate modelling. Two hybrid models, a Long Short-Term Memory (LSTM) network and a Recurrent Neural Network (RNN), are trained and their outputs ensembled for improved prediction. The results from these two models are then ensembled to obtain optimized forecasts for the years 2022 to 2026. Additionally, linear regression is utilized to establish a relationship between the extracted statistical features and real-world glacier trends, estimating the glacier's mass balance and sea level contribution. The proposed architecture is described in Figure 4.

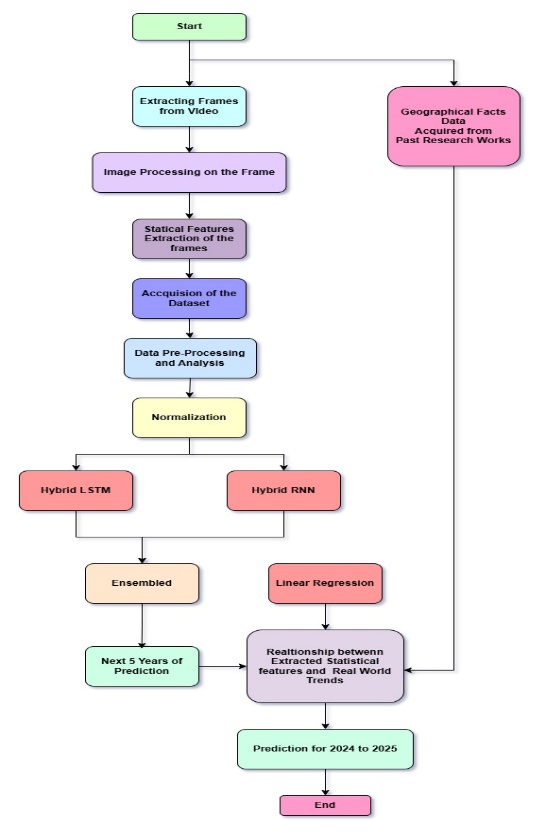


Figure 4. Workflow Algorithm of the Proposition