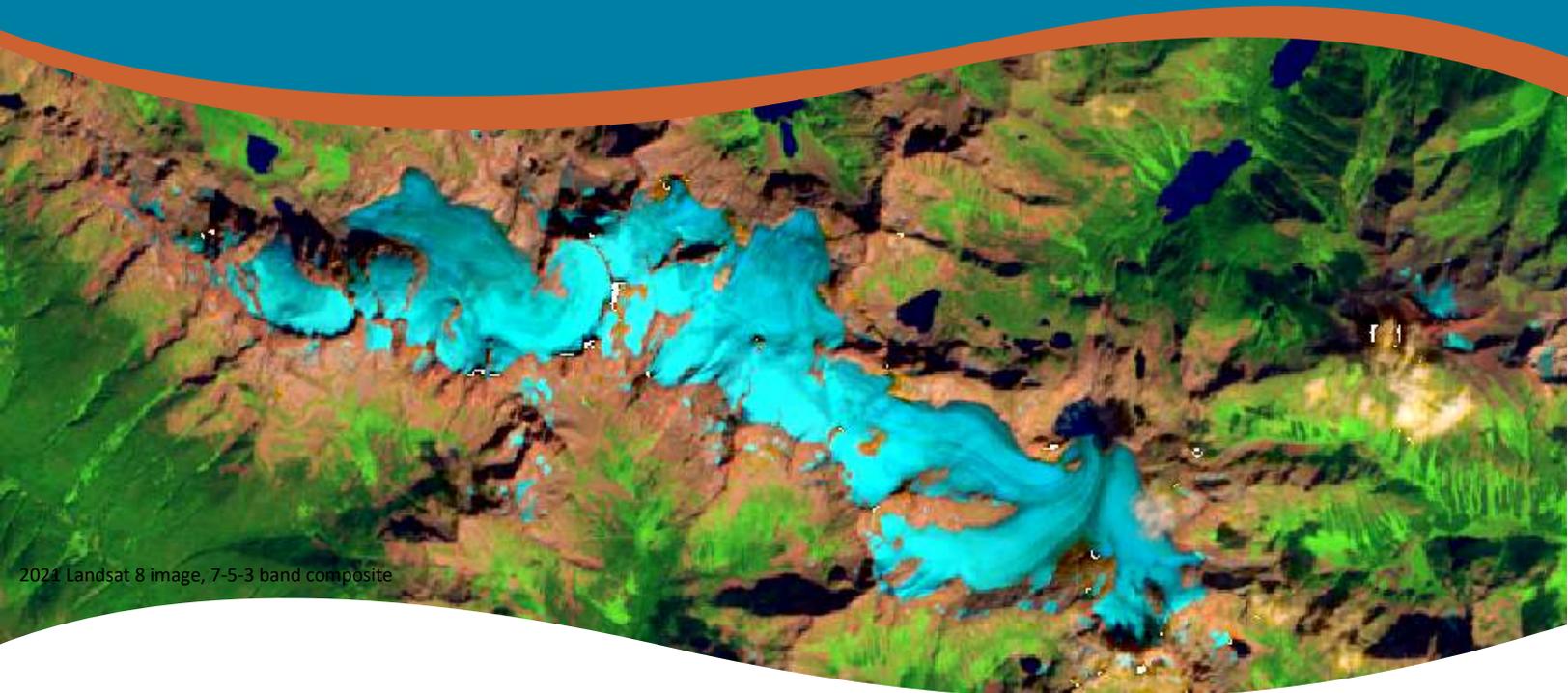


# Kanaka Bar Glacier Analysis Phase 1 – Glacier Recession Estimates



2021 Landsat 8 image, 7-5-3 band composite

## Prepared For

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21P0475  
Version: 1  
November 2021



**Down to Earth Biology**

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## EXECUTIVE SUMMARY

EDI Environmental Dynamics Inc. (EDI) was retained by the Kanaka Bar Indian Band to determine the decline rate and projected year of disappearance of glaciers within the Kwoiek watershed located approximately 15 km south of Lytton, BC. Glaciers in this study area include the Chochiwa, Kwoiek, Rutledge (outside of the Kwoiek watershed), and an Unnamed glacier (northwest of Antimony Lake). These glaciers currently provide meltwater runoff that supports Kanaka Bar Indian Band's hydropower facility, provide runoff to streams/rivers supporting fish habitat including salmon habitat and are culturally important to the Kanaka Bar Indian Band.

A desktop study was undertaken primarily to assess the observed changes in glacier areas, volumes, terminus positions, the projected dates of disappearance, and the projected climate conditions under which this would occur. Glacier extents from 1951, 1985, 2005, and 2021 were determined from air photos, Landsat satellite imagery and the Randolph Glacier Inventory to determine the rate of glacier decline over the past half-century, and to determine the accuracy of the Clark et al. (2015) on its first 10 years of projection. The analysis used glacier projection data for the period of 2010 to 2100 from a BC wide glacier modelling project by Clark et al. (2015) for three Representative Concentration Pathways (RCP2.5, 4.5 and 8.5). Several additional open-source datasets were used to validate climate and glacier model performance over the period of 2011–2021. Projections of air temperature and precipitation from six Global Circulation Models of the Coupled Model Intercomparison Project Phase 5 (CMIP5) experiment were used as climate forcing data in the Clark et al. (2015) projection data and were compared with ERA5-Land reanalysis data to validate the forcing datasets that drive the glacier modelling.

For the period of 1951 to present, glaciers in the Kwoiek watershed experienced terminus retreats of at least 550 m (Kwoiek and Unnamed glaciers),  $987 \pm 73$  m (Chochiwa Glacier) and up to  $1575 \pm 73$  m (Rutledge Glacier). The rates of retreat varied during this time period and by glacier; however, all glaciers have been experiencing retreat since 1951. A slower period of retreat was observed between 1985–2005 compared to surrounding periods for most glaciers. In tandem with terminus retreat, glacier extents decreased for all glaciers by 31% to 37% for Chochiwa, Kwoiek, and Rutledge glaciers and 52% for Unnamed glacier during the 1951 to 2021 period.

Validation of the glacier modelling data from Clark et al. (2015) and the CMIP5 projection datasets was completed by comparing projection model outputs over the period of 2010 to 2021 with observational and reanalysis datasets, respectively. Glacier model output was validated by comparing modelled glacier extents at 2021 with extents mapped from Landsat 8 imagery and rates of volume change from 2010 to 2020 using rates from Hugonnet et al. (2021). The validation found that the model output potentially misrepresents glacier areas in the early years of the glacier model but represents the rate of volume change in all glaciers except Chochiwa Glacier, where it underestimates the rate of volume loss. Validation of the CMIP5 air temperature and precipitation forcing datasets was conducted by comparing the climate projection data with ERA5-LAND gridded reanalysis, and high-resolution PRISM gridded 30-year climatology datasets at overlapping grid cell location at the centre of the Kwoiek watershed. This exercise found that the CMIP5 projection data underestimate the effects of topography on temperature and precipitation with ERA5-Land presenting



temperatures  $-1.46 \pm 0.67$  °C below, and precipitation by  $567 \pm 183.43$  mm above the projection dataset. The CMIP5 data do match more closely with the range of the PRISM 30-year normals, which suggest that the model data tracks more accurately with long-term trends.

Model data of the glaciers into 2100 show consistent decline into the latter part of the century, with the rates and glacier termination dates varying by RCP emissions scenarios. Total volume loss estimates by the end of the modelling period were 832,000,000 m<sup>3</sup> for Chochiwa Glacier; 477,000,000 m<sup>3</sup> for Kwoiek Glacier; 400,000,000 m<sup>3</sup> for Rutledge Glacier; and 34,000,000 m<sup>3</sup> for Unnamed glacier. The Unnamed glacier disappears in all modelling scenarios as early as 2035 under RCPs 4.5 and 8.5, and as late as 2087 under RCP2.6. For the larger glaciers, disappearance occurs under the two higher emissions scenarios occurring around  $2087 \pm 14$  years and  $2088 \pm 15$  years for Chochiwa and Rutledge glaciers under RCP4.5, and  $2072 \pm 7$  years,  $2083 \pm 7$  years and  $2072 \pm 8$  years for Chochiwa, Kwoiek, and Rutledge glaciers under RCP8.5.

Overall, the model uncertainties indicate that the glacier data may overestimate the rates of decline going into the end of the century; however, the data do provide reliable timeframes from which further analysis can be completed and help support future environmental policy decisions.

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## ACRONYMS AND ABBREVIATIONS

Acronym/Abbreviation	Definition
BEC	Biogeoclimatic Ecosystem Classification
CMIP5	Coupled Model Intercomparison Project Phase 5
DPI	Dots Per Inch
EDI	EDI Environmental Dynamics Inc.
GCM	Global Circulation Model
GCP	Ground Control Point
PCIC	Pacific Climate Impacts Consortium
PRISM	Parameter-elevation Regressions on Independent Slopes Model
RCP	Representative Concentration Pathway
RGI	Randolph Glacier Inventory
RGM	Regional Glaciation Model

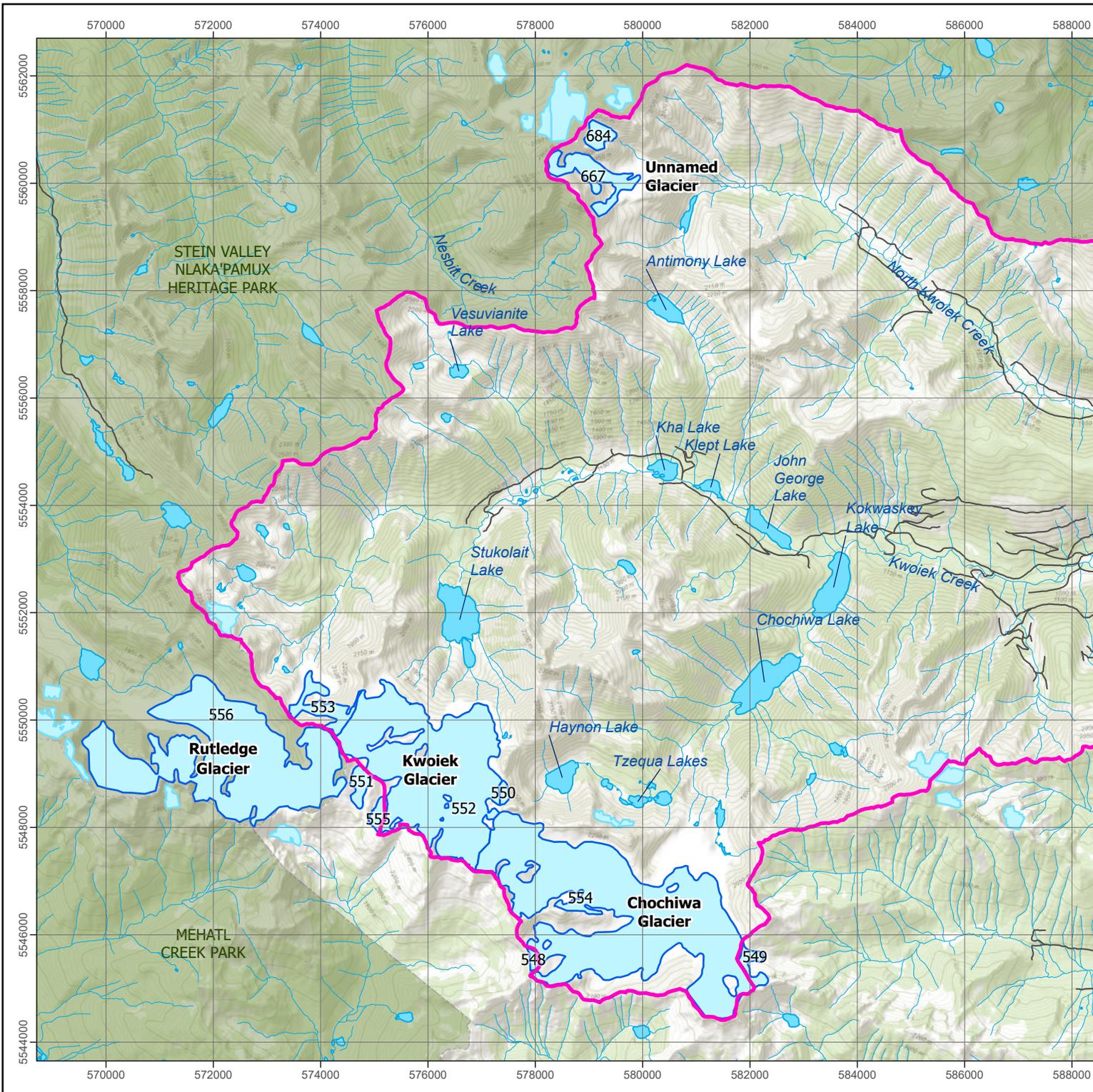


## 1 INTRODUCTION

The Kanaka Bar glacier analysis was undertaken as part of Kanaka Bar’s Cumulative Effects Initiative. The glaciers in the Kanaka Bar Band territory are not only an important source of water for locals and the surrounding environment, but also support the Kanaka Bar’s hydroelectric project, a key economic driver. Over time, local community members have witnessed glacial retreat from climate change effects and have expressed concerns of what the future ecological and economical impacts will be as glaciers continue to retreat. To document glacier recession rates and assess potential effects to the watershed/territory, Environmental Dynamics Inc. (EDI) and the Kanaka Bar Band have structured an approach into three phases:

- Phase 1 – Glacier Recession Estimates.
- Phase 2 – Hydrological Impacts of Reduced Glacier Melt.
- Phase 3 – Receding Glaciers Impacts on Water Temperature in Kwoiek’s Lake and Creek Systems, the Fraser River and on Salmon Lifecycles and Habitat, and Impacts on Forest Composition and BEC Zones in the Kanaka Bar Band Territory.

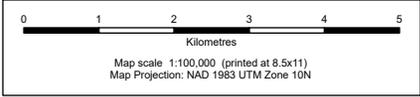
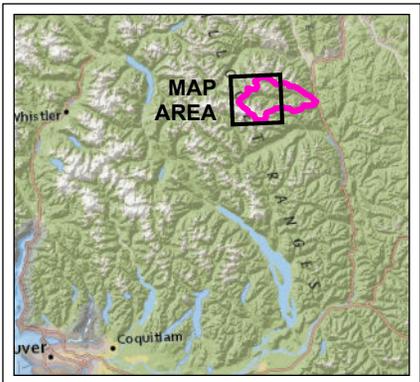
This report focuses on Phase 1 of the glacier analysis to model how fast glaciers are receding and predict the disappearance dates. The analysis includes four main glaciers: Chochiwa, Kwoiek, Rutledge (outside of the Kwoiek watershed), and an unnamed glacier (northwest of Antimony Lake; Map 1). Observed glacier terminus retreat and area change between 1951 and 2021 are presented along with projected glacier area and ice volume changes between 2010 and 2100.



### Kanaka Bar Glacier Analysis Glaciers of Interests

#### Legend

- Road
- Watercourse
- Waterbody
- Glacier
- Glacier of Interest (with Randolph Glacier Inventory number)
- Kwoiek Watershed
- Parks



**Data Sources**

- 2021 glacier extents. Digitized by EDI from a Landsat 8 image from Sept 2, 2021.
- Watercourses, Waterbodies, Watersheds: Freshwater Atlas. Government of British Columbia
- Parks and Roads: Government of British Columbia
- Inset Basemap: National Geographic World Map; National Geographic, Esri, Garmin, HERE, UNEP-WCMC, USGS, NASA, ESA, METI, NRCAN, GEBCO, NOAA, increment P Corp.
- Main Basemap: Canada Hillshade: Sources: NRCan, Esri Canada, and Canadian Community Maps contributors.
- Main Basemap: World Hillshade: Esri, NASA, USGS

**Disclaimer**  
EDI Environmental Dynamics Inc. has made every effort to ensure this map is free of errors. Data has been derived from a variety of digital sources and, as such, EDI does not warrant the accuracy, completeness, or reliability of this map or its data.

Drawn: CT	Checked: RB / MAM	Map 1	Date: 2021-11-02
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## 2 METHODS

### 2.1 CLIMATE DATA

Climate projection datasets from the Coupled Model Intercomparison Project Phase 5 (CMIP5) for several of the Representative Concentration Pathways (RCPs) (Table 1) used in Clarke et al. (2015) were acquired from Pacific Climate Impacts Consortium (PCIC) for RCP2.6, RCP4.5 and RCP8.5. RCPs project solar radiative forcings resulting from different emissions concentrations (greenhouse gases and aerosols) and land covers/uses (Moss et al. 2010).

RCPs can be summarised by parts-per-million (ppm) CO<sub>2</sub>-equivalent; in RCP2.6 CO<sub>2</sub>-equivalent peaks at 490 ppm before 2100 and then declines, whereas RCP4.5 sees CO<sub>2</sub>-equivalent stabilize after 2100 at 650 ppm and RCP8.5 sees CO<sub>2</sub>-equivalent exceeding 1370 ppm in 2100 (Moss et al. 2010). Recent CO<sub>2</sub>-equivalent were calculated at 504 ppm in 2020, rendering the atmospheric conditions of RCP2.6 unlikely to occur (NOAA Global Monitoring Laboratory 2021). Much of the scientific literature refers to RCP8.5 as “business as usual” under which unmitigated consumption of fossil fuels occurs into 2100. Though current emission levels do track those of RCP8.5 (Schwalm et al. 2020) there is debate as to how useful this scenario is to consider, given existing and proposed climate mitigation efforts (Hausfather and Peters 2020, Pielke and Ritchie 2021). This report does not purport to predict which scenarios are going to occur, however it does present the projected outcomes for the glaciers in Kwoiek watershed under the three RCPs presented.

The projection data are available through the data portal for Statistically Downscaled Climate Scenarios at 10 km grid cell and daily timestep resolutions (PCIC 2018). Daily minimum and maximum data for air temperature and total precipitation were acquired from a grid cell centred in the Kwoiek watershed for this project. Annual mean air temperature and total precipitation were calculated for each Global Circulation Model (GCM) for the period of 2005–2100, and subsequently summarised into ensemble datasets of mean temperature and precipitation values across all models.

**Table 1. Climate and reanalysis datasets acquired for this study.**

Data Type	Model	Spatial Resolution
CMIP5 Climate Projection	CSIRO-Mk3-6-0-r1, CanESM2-r1, GFDL-CM3-r1, HadGEM2-ES-r1, MIROC-EMS-r1, MPI-ESM-LR-r1	300 arc seconds (~10 km)
Validation - Reanalysis	ERA5-Land	360 arc seconds
Validation - Interpolated	PRISM	30 arc second (~1 km)

To evaluate the projection data for biases, validation of the projection ensembles for the period of 2005–2021 was undertaken by acquiring comparison datasets from the ERA5-LAND atmospheric reanalysis dataset (Muñoz 2019), and the Parameter-elevation Regressions on Independent Slopes Model (PRISM)(PCIC and PRISM 2014).



The ERA5-Land reanalysis dataset is modelled via a combination of historical observational and forecast datasets over a 9 km resolution land surface model at an hourly timestep, resulting in a spatially accurate representation of past climate conditions where observational data are not available (Muñoz 2019). Monthly reanalysis data of mean air temperature and total precipitation were acquired from a grid cell in the same location as that of the PCIC data to compare with the projection datasets (PCIC, and PRISM 2014).

Thirty-year climatology data from PRISM via the PCIC PRISM Climatology and Monthly Timeseries Portal were acquired to provide an additional validation dataset (PCIC and PRISM 2014). Mean precipitation and air temperature data for the period of 1981–2010 were collected for 178 grid cells overlapping with the CMIP5 and ERA5 grid cells to interpret the impact of grid cell elevations on the modelled precipitation and air temperature values (Figure 1).

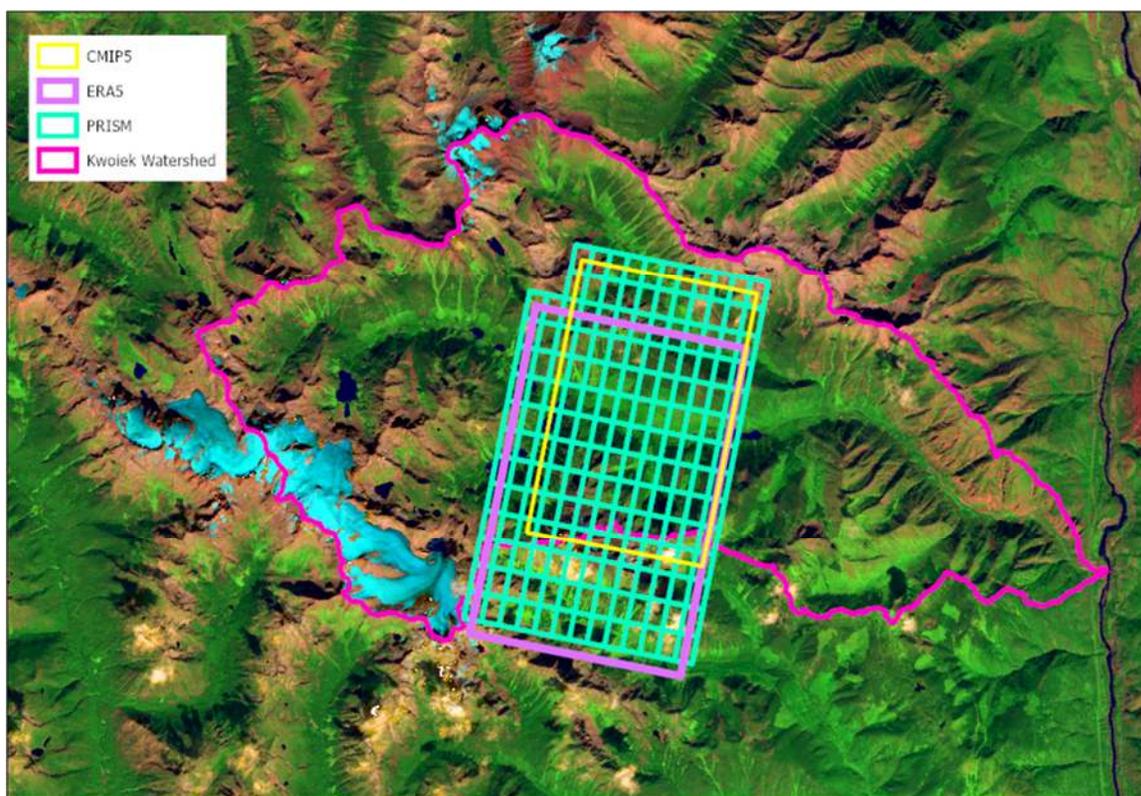


Figure 1. CMIP5, ERA5, and PRISM grid cells used in the climate analysis.

## 2.2 PAST AND PRESENT GLACIER CHANGE

Glacier extents from 1951, 1985, 2005, and 2021 (Table 2) were used to calculate past and present glacier retreat and area change for the four glaciers of interest: Chochiwa, Kwoiek, Rutledge, and Unnamed glacier.



**Table 2. Data sources for glacier extents from 1951, 1985, 2005, and 2021.**

Year	Imagery Source	Glacial Extent Source
1951	Air Photos	Digitized by EDI from air photos ordered from the National Air Photo Library, Government of Canada.
1985	Air Photos	Bolch et al. (2010), potentially modified from the original Terrain Resource Inventory Management program data from the Government of British Columbia.
2005	Landsat 5	Randolph Glacier Inventory (RGI Consortium 2017), originally from Bolch et al. (2010).
2021	Landsat 8	Digitized by EDI from September 2, 2021, Landsat 8 satellite image.

Four air photos from 1951 were georeferenced using a spline transformation and 42 to 123 ground control points (GCPs) with tie points (Table 3). The GCPs were taken from the 2021 Landsat 8 image and the Kwoiek Watershed boundary from the BC Freshwater Atlas (Ministry of Forests, Lands, Natural Resource Operations and Rural Development 2021). Tie points were used to combine air photos together where overlap occurred between them. Georeferencing was limited to only the area around the glaciers. The georeferencing uncertainty was estimated at two times the Landsat pixel resolution, equivalent to 60 m. Glacier extents were manually digitized from the air photos.

**Table 3. Air photos used to digitize the 1951 glacier extents and the number of ground control points (GCPs) and tie points used to georeference the photos.**

Roll/Frame	Date	Scale	Scan Resolution (dpi*)	Number of GCPs/Tie Points
A13249/018	Aug 17, 1951	1:70,000	600	42
A13249/046	Aug 17, 1951	1:70,000	600	66
A13249/115	Aug 17, 1951	1:70,000	600	81
A13249/116	Aug 17, 1951	1:70,000	600	123

\*dpi: dots per inch

Glacier extents were also manually digitized from a georeferenced September 2, 2021, Landsat 8 image (path/row: 47/25) downloaded from the USGS Earth Explorer website on September 23, 2021 (USGS 2021). A 7-5-3 band combination image was used to highlight the glaciers for delineation of the extents. The 1985 and 2005 glacier extents were extracted from existing inventories for the glaciers of interest. The 1985 extents were from Bolch et al. (2010) and the 2005 extents were downloaded from the Randolph Glacier Inventory (RGI) on August 31, 2021 (RGI Consortium 2017). The 2005 extents were originally from the Bolch et al. (2010) study and were uploaded to the RGI. All data were projected into the Lambert Conformal Conic projection used for the modeled glacier data in Clarke et al. (2015) to confirm comparable measurements.

The 1985 and 2005 extents were divided based on glacier flow divides and given an RGI index number (Map 1). The 1951 and 2021 extents were divided and given RGI index numbers corresponding with the 1985 and 2005 data. The glacier analysis was conducted on the individual RGI index ice masses and the results were grouped into the four glaciers of interest.



Glacier retreat was calculated as the mean value of three to five length measurements at each terminus between extents from the start and end year of each period: 1951–1985, 1985–2005, and 2005–2021 and an example of this approach for Chochiwa Glacier is shown in Figure 2. The length measurement was calculated as the 3D length derived from the Shuttle Radar Topographic Mission (SRTM) digital elevation model (Farr et al. 2007) to account for the elevation component. The rate of retreat was calculated using the glacier retreat for each period divided by the number of years in the period.

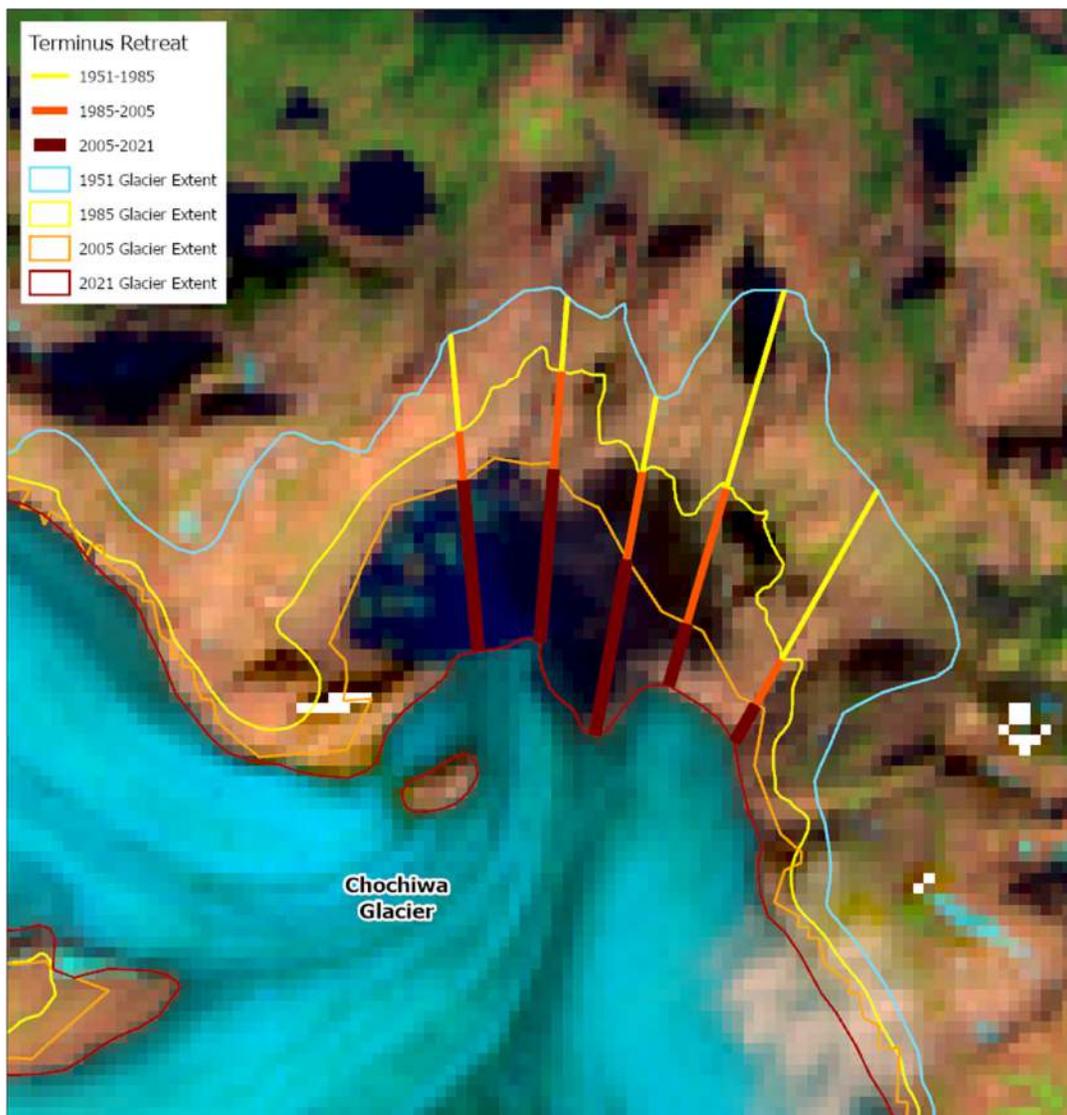


Figure 2. Glacier terminus retreat measurements on Chochiwa Glacier.

Change in glacier area was calculated as the difference in area between extents from the start and end year for the periods 1951–1985, 1985–2005, and 2005–2021. The rate of area change was calculated as the area change divided by the number of years for each period.



## 2.2.1 UNCERTAINTY CALCULATIONS

For the 1951 data, the quality of the air photos was poor as the glaciers and surrounding rock/snow were washed out due to oversaturation, making delineation of the glacier extent difficult. Based on the data review and visual inspection, a mapping uncertainty of 30 m was included to account for this.

The uncertainty in glacier terminus retreat was calculated as the root sum of squares of the uncertainty in the start and end year for each period. For 1951, the uncertainty consisted of the 60 m georeferencing uncertainty and the 30 m mapping uncertainty. For the other years, the uncertainty was the pixel resolution, 30 m. The uncertainty in retreat rate was the uncertainty in glacier retreat divided by the number of years in each period.

To calculate the uncertainty in glacier extents, buffers equal to half the estimated positional shift between the different datasets were created (Bolch et al. 2010). A value of 7.5 m was used in the Bolch et al. (2010) study and has been applied to the 1985, 2005, and 2021 extents. A value of 30 m, half the georeferencing uncertainty, was used for the 1951 extents. The glacier extent uncertainty was calculated by differencing the glacier buffer area from the glacier extent area. The uncertainty in area change was calculated as the root sum of squares of the uncertainty in the start and end year for each period. The uncertainty in the rate of area change was calculated as the area change uncertainty divided by the number of years in each period.

## 2.3 PROJECTED GLACIER CHANGE

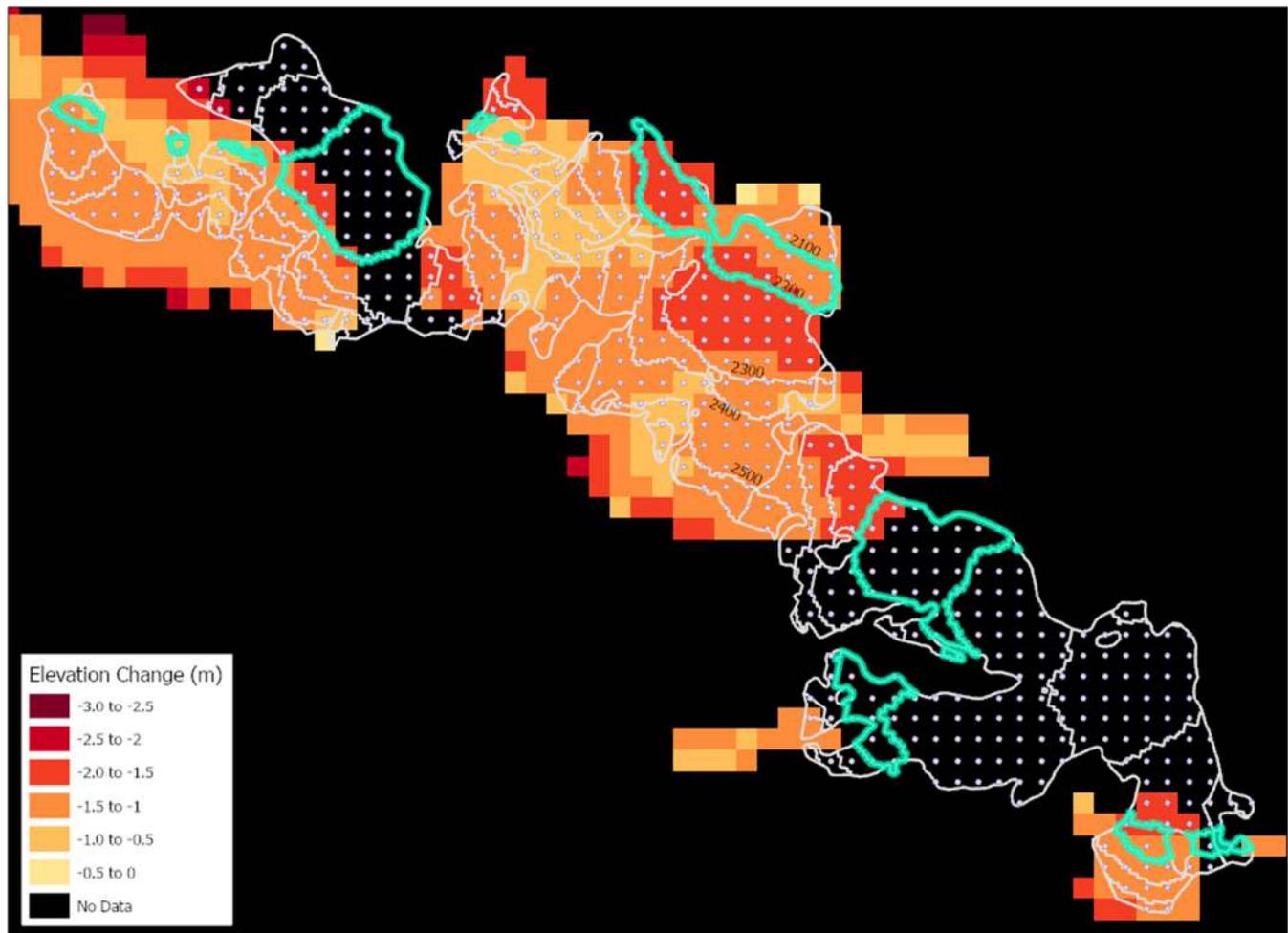
Projected glacier area and ice volume changes from 2010 to 2100 were derived from modeled glacier data from Clarke et al. (2015). This dataset consists of glacier base elevations derived from ice thickness calculations and modeled glacier surface elevations from a Regional Glaciation Model (RGM). The RGM models glacier movement, growth, and melting rates based on climate inputs. The glacier surface elevations were modeled at a 200 m pixel resolution from 2010 to 2100 under different RCP scenarios using climate projection datasets from six different GCMs with the CMIP5 group of experiments. This glacier analysis focuses on RCP2.6, 4.5, and 8.5.

For each GCM and RCP scenario, the glacier base and surface elevations were extracted for the glaciers of interest. The surface and base elevations were differenced to produce a glacier thickness surface. Differencing the thickness surfaces from two years resulted in elevation change values which were converted to points. The points were grouped by glacier and clipped to the 2005 glacier extents for years prior to 2021 and to the 2021 glacier extents for the remaining years.

Within the boundaries of the glaciers of interest, glacier thickness and elevation change surfaces had no data for some areas. The no data areas are assumed to be a product of errors in the modeled glacier base elevations and the glacier growth during the RGM model spin up and calibration period (0 to 1901). Kwoiek Glacier had 95% coverage, Rutledge Glacier had 63% coverage, and Chochiwa and Unnamed glaciers had 20% and 33% coverage, respectively (Figure 3).



Assuming glaciers in the same watershed undergo similar ice surface elevation change, the missing values were estimated by calculating and assigning the mean elevation change for each 100 m elevation band to points with missing values within the same band (Figure 3). Only points with elevations greater than lowest valid point were estimated. It was assumed that points with elevations below the lowest valid point had zero thickness and were not missing values. The 100 m elevation bands were extracted from the Shuttle Radar Topography Mission digital elevation model. If there were no valid pixels within the modeled glacier extent for a given model year, the glacier was considered to have disappeared from the landscape and no values were filled.



**Figure 3.** Example of missing ice elevation change values and 100 m elevation bands used for filling in the missing data. In the highlighted elevation band (2100–2200 m), the mean elevation change was calculated from the valid points and used to fill the missing point values (black pixels) in the same elevation band.

For each glacier, the projected area was calculated as the number of pixels with elevation change values (including filled values) multiplied by the pixel area (40,000 m<sup>2</sup>). The projected volume change for each glacier was calculated as the sum of each pixel elevation change multiplied by the pixel area. The mean and standard deviation of the six GCMs for each RCP scenario was calculated for area and volume change. The standard deviation represents the uncertainty in the modeled results.



The year a glacier disappeared was assumed to be the start year of the period with the first zero area. This year was determined for each GCM and RCP scenario. The minimum, maximum, mean, and standard deviation of the year of glacier disappearance from the six GCMs for each RCP scenario were calculated. The standard deviation represents the uncertainty in the modeled results.

## 3 RESULTS AND DISCUSSION

### 3.1 CLIMATE

The ensemble annual mean air temperature and total precipitation projections from the six CMIP5 models for the mid point of the Kwoiek watershed, considered representative of the area of glacial analysis, are presented in Figure 4. By the end of the century, mean annual air temperature is projected to rise approximately 2 °C, 3.5 °C and 5 °C under RCPs 2.6, 4.5, and 8.5 respectively. Temperatures are projected to stabilize after 2050 for both RCPs 2.6 and 4.5 while RCP8.5 models project increasing trends throughout the simulation period. Precipitation projections have greater variance across models for the simulation period due to inherent spatial variability. However, precipitation projections do show an increase in mean annual precipitation by as much as 100 mm by 2100. As projected air temperatures increase over time freezing levels will also climb in elevation over time, and as a result, precipitation phases will continue to shift from snow to rain.

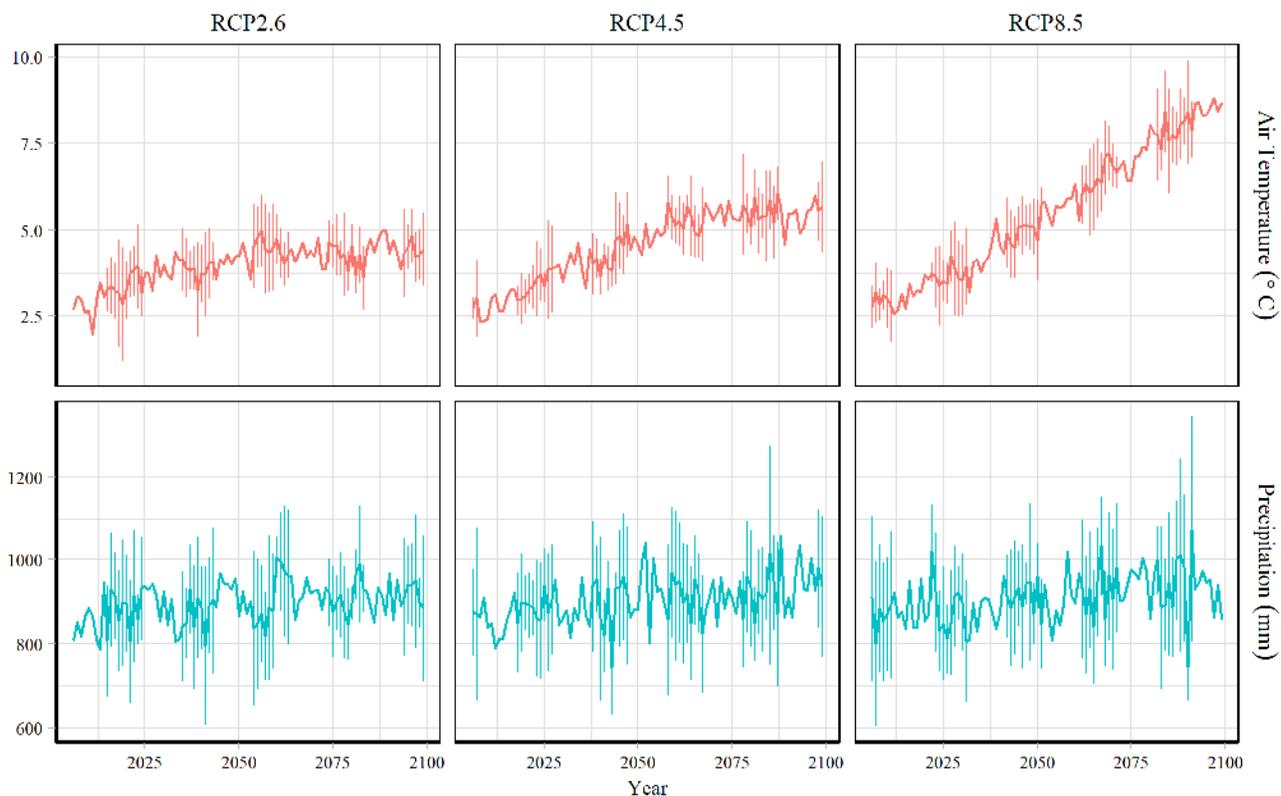


Figure 4. Mean and standard deviation of the six CMIP5 projection models for mean annual air temperature and total annual precipitation for the period of 2005–2100 at the mid point of the Kwoiek Watershed.

### 3.2 GLACIER RETREAT

This glacial analysis for the period of 1951–2021 found that Rutledge Glacier has the greatest terminus retreat, retreating  $1,575 \pm 73$  m, followed by Chochiwa Glacier retreating  $987 \pm 73$  m. Kwoiek and Unnamed glaciers both have approximately 550 m of retreat (Table 4 and Map 2).

Table 4. Glacier terminus retreat (m) from 1951 to 2021.

Period	Chochiwa	Kwoiek	Rutledge	Unnamed
1951–1985	$382 \pm 73$	$416 \pm 73$	$1,109 \pm 73$	$246 \pm 73$
1985–2005	$244 \pm 42$	$42 \pm 42$	$325 \pm 42$	$100 \pm 42$
2005–2021	$361 \pm 42$	$130 \pm 42$	$141 \pm 42$	$192 \pm 42$
1951–2021	$987 \pm 73$	$588 \pm 73$	$1,575 \pm 73$	$538 \pm 73$

The 1985–2005 period, compared to the 1951–1985 period, showed a decrease in the rates of terminus retreat for all glaciers except for Chochiwa Glacier (Figure 5). This was followed by an increase in rates of retreat between 2005 and 2021 for Kwoiek, Chochiwa, and Unnamed glaciers. Rutledge Glacier experienced another decrease in the rate of retreat.

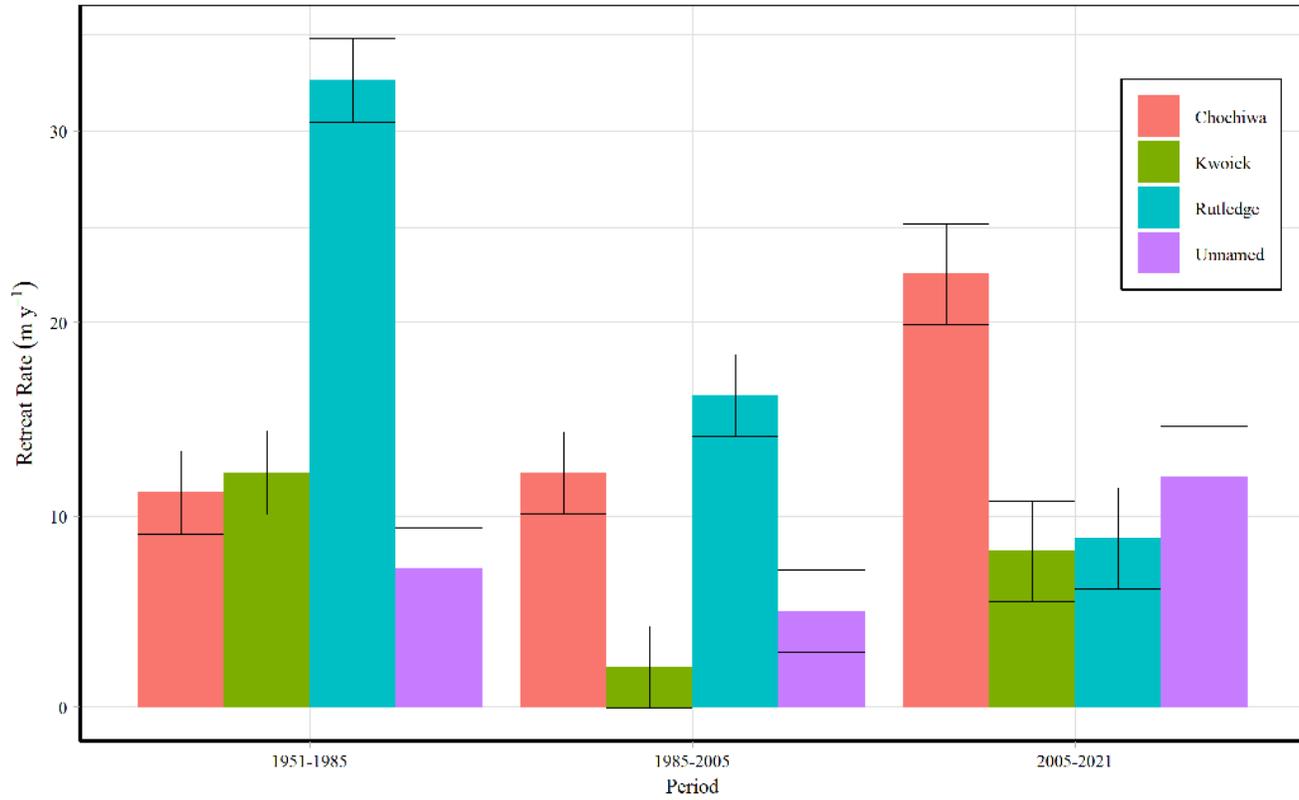
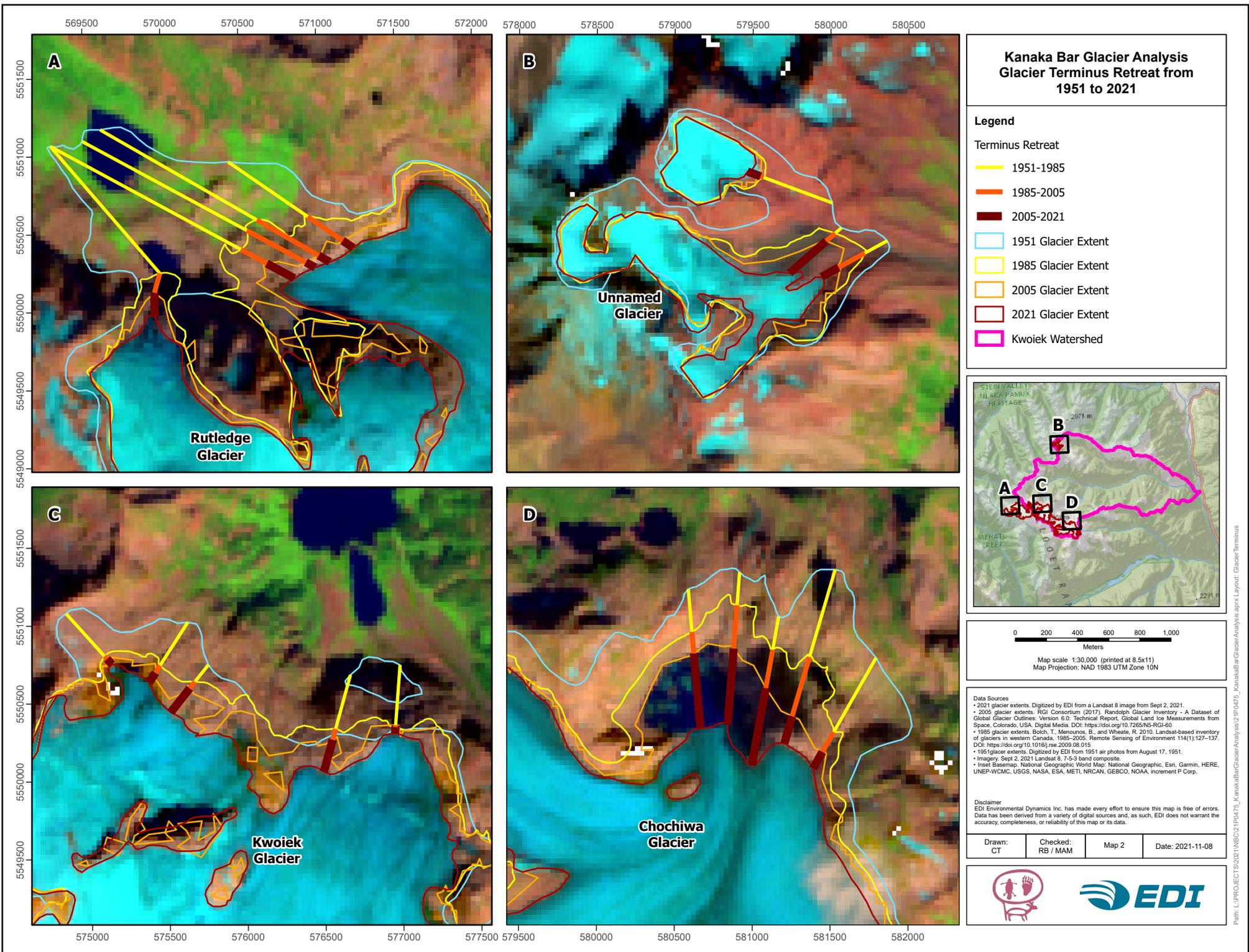


Figure 5. Observed rates of glacier terminus retreat from 1951 to 2021.





### 3.3 GLACIER EXTENT

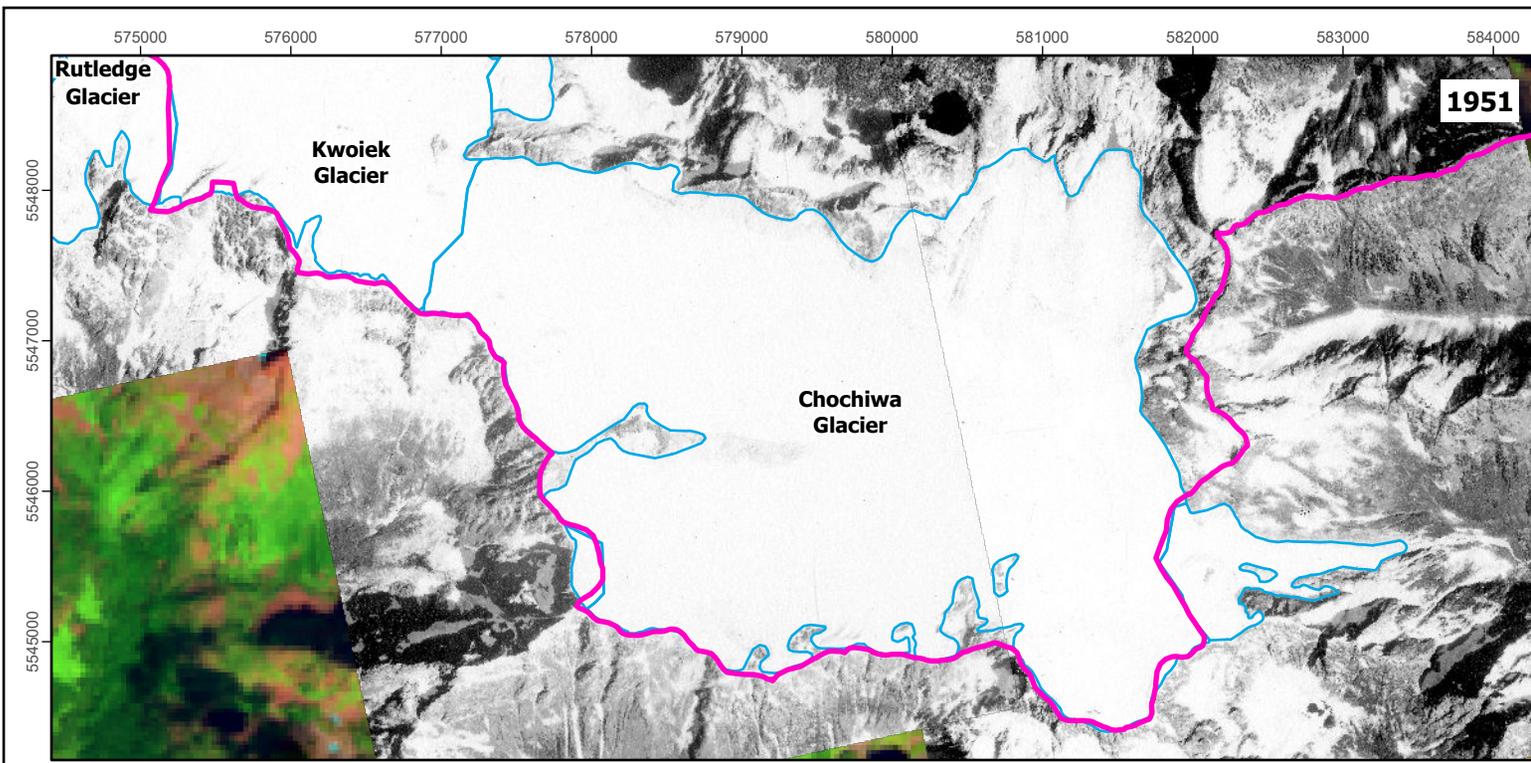
There was a decrease in area for the four glaciers of interest from 1951 to 2021 (Table 5, Map 3 to Map 5). Chochiwa lost the largest amount of area (5.20 km<sup>2</sup>) and Unnamed glacier the least (0.94 km<sup>2</sup>) (Table 6, Map 3 and Map 5). However, converting the area loss to a percentage, results in a 31%, 32%, and 37 % loss of area for Rutledge, Kwoiek, and Chochiwa glaciers, respectively, and a 52% loss of area for Unnamed glacier between 1951 and 2021.

**Table 5. Glacier area (km<sup>2</sup>) in 1951, 1985, 2005, and 2021.**

Year	Chochiwa	Kwoiek	Rutledge	Unnamed
1951	13.92 ±0.94	9.81 ±0.86	9.13 ±0.67	1.80 ±0.28
1985	11.96 ±0.26	8.22 ±0.20	7.51 ±0.17	1.20 ±0.07
2005	10.86 ±0.27	7.70 ±0.26	7.06 ±0.19	1.05 ±0.07
2021	8.71 ±0.27	6.68 ±0.24	6.32 ±0.19	0.86 ±0.07

**Table 6. Glacier area loss (km<sup>2</sup>) from 1951 to 2021. Percentages are calculated using the area at the start of the period.**

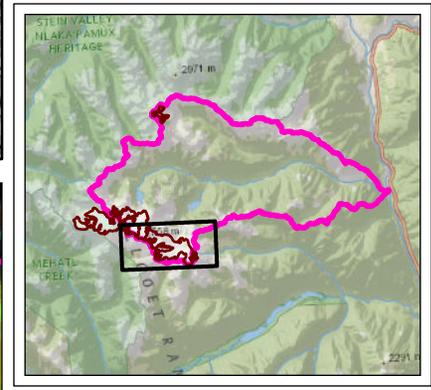
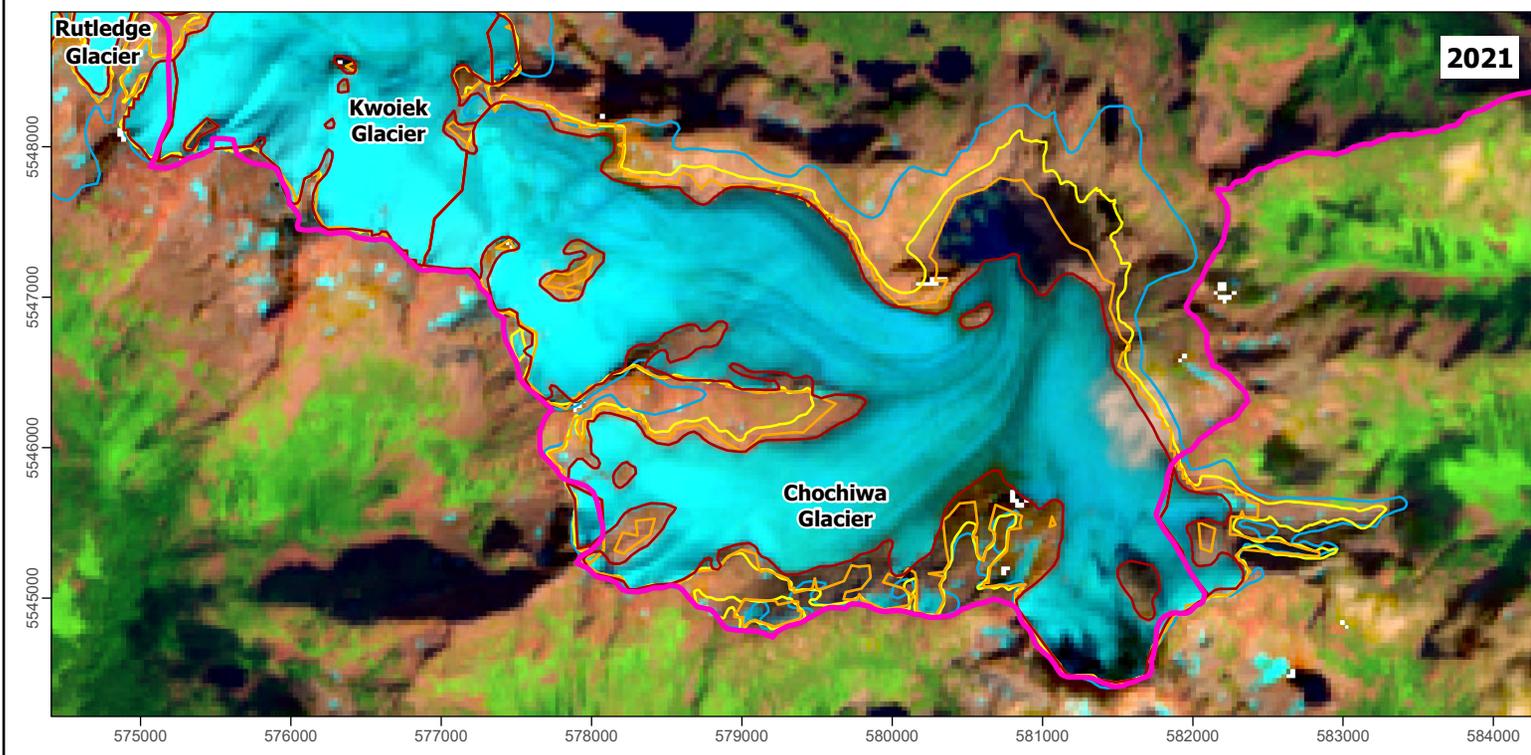
Period	Chochiwa	Kwoiek	Rutledge	Unnamed
1951–1986	1.95 ±1.02 (14%)	1.59 ±0.88 (16%)	1.62 ±0.69 (18%)	0.6 ±0.29 (33%)
1986–2005	1.10 ±0.56 (9%)	0.52 ±0.33 (6%)	0.45 ±0.26 (6%)	0.14 ±0.10 (12%)
2005–2021	2.15 ±0.47 (20%)	1.02 ±0.36 (13%)	0.73 ±0.27 (10%)	0.19 ±0.10 (18%)
1951–2021	5.20 ±0.97 (37%)	3.13 ±0.89 (32%)	2.80 ±0.69 (31%)	0.94 ±0.29 (52%)



### Kanaka Bar Glacier Analysis Chochiwa Glacier Extents 1951 to 2021

**Legend**

- 2021 Glacier Extent
- 2005 Glacier Extent
- 1985 Glacier Extent
- 1951 Glacier Extent
- Kwoiek Watershed



0 200 400 600 800 1,000  
Meters

Map scale: 1:50,000 (printed at 8.5x11)  
Map Projection: NAD 1983 UTM Zone 10N

**Data Sources**

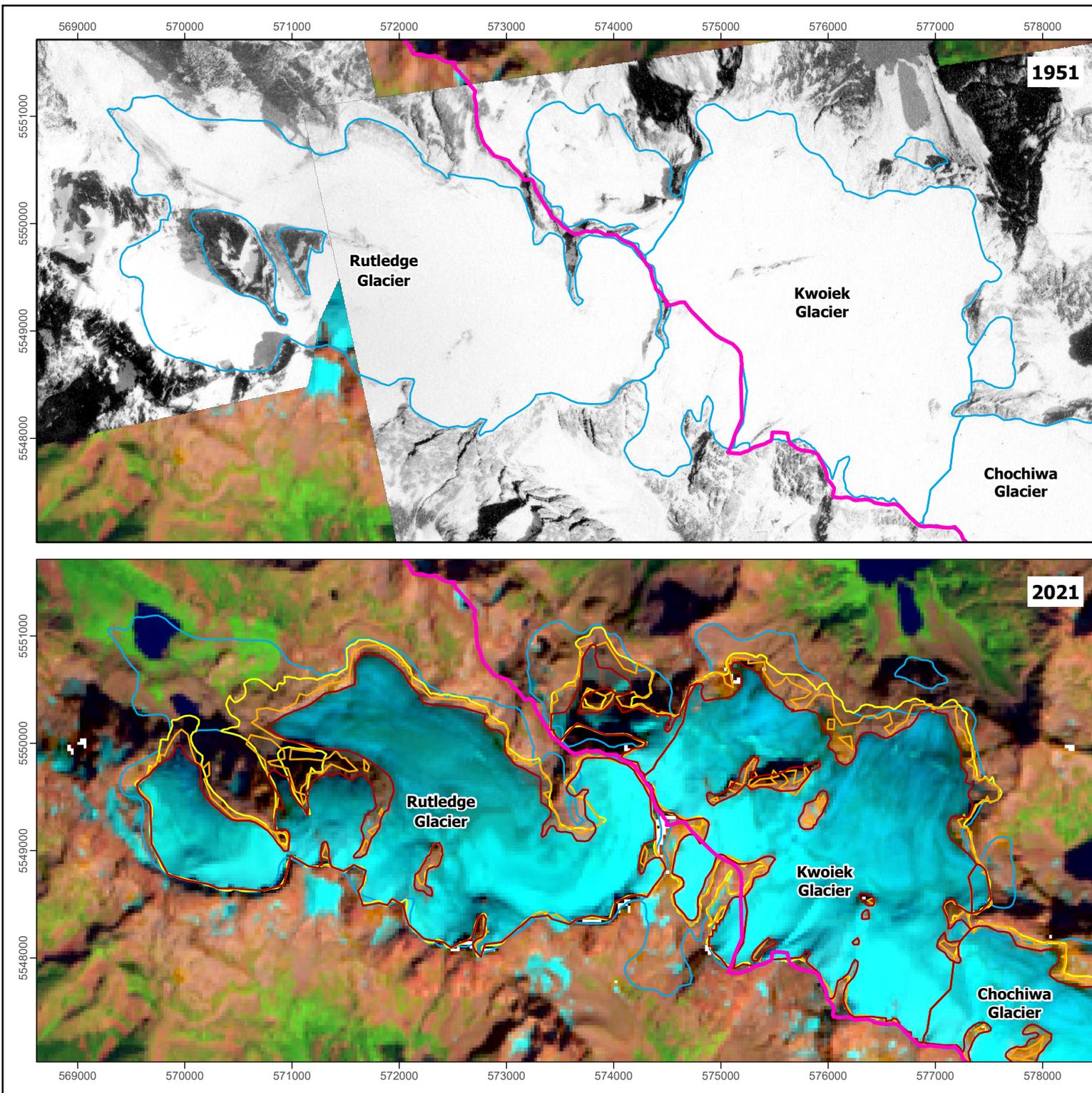
- 2021 glacier extents. Digitized by EDI from a Landsat 8 image from Sept 2, 2021.
- 1951 glacier extents. Digitized by EDI from 1951 air photos from August 17, 1951.
- 2021 Imagery, Sept 2, 2021 Landsat 8, 7-5-3 band composite.
- 1951 Imagery, August 17, 1951 air photos, National Air Photo Library.
- Inset Basemap, National Geographic World Map; National Geographic, Esri, Garmin, HERE, UNEP-WCMC, USGS, NASA, ESA, METI, NRCAN, GEBCO, NOAA, increment P Corp.

**Disclaimer**  
EDI Environmental Dynamics Inc. has made every effort to ensure this map is free of errors. Data has been derived from a variety of digital sources and, as such, EDI does not warrant the accuracy, completeness, or reliability of this map or its data.

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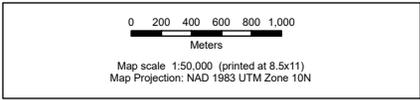
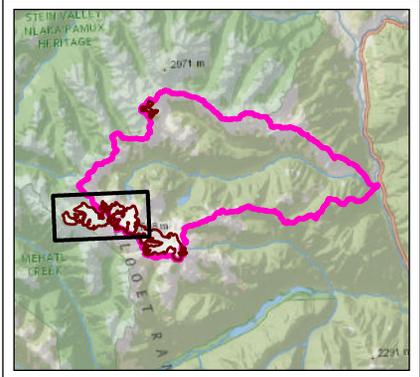
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## Kanakab Bar Glacier Analysis Kwoiek and Rutledge Glacier Extents 1951 to 2021

### Legend

- 2021 Glacier Extent
- 2005 Glacier Extent
- 1985 Glacier Extent
- 1951 Glacier Extent
- Kwoiek Watershed



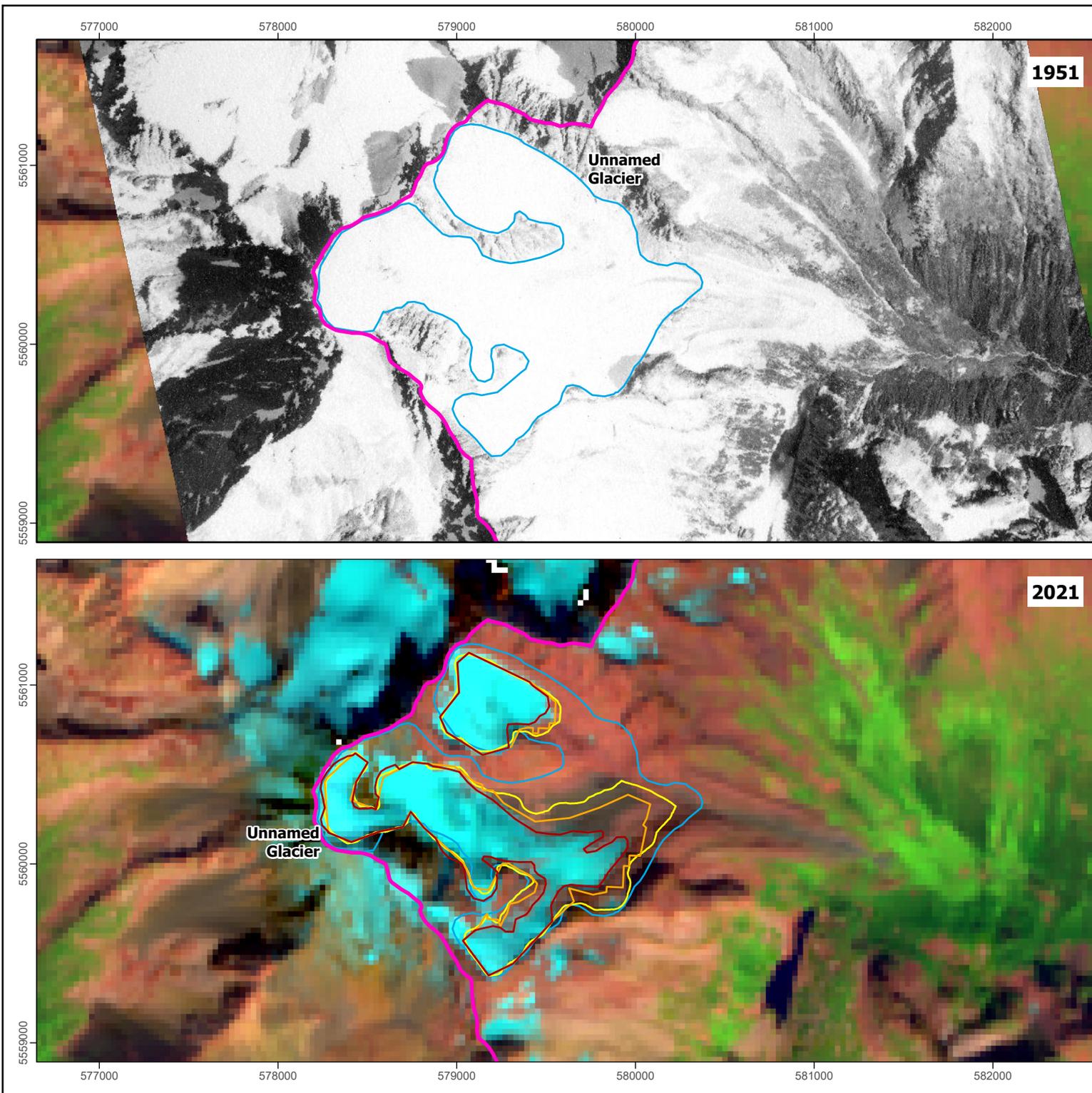
**Data Sources**

- 2021 glacier extents. Digitized by EDI from a Landsat 8 image from Sept 2, 2021.
- 1951 glacier extents. Digitized by EDI from 1951 air photos from August 17, 1951.
- 2021 Imagery. Sept 2, 2021 Landsat 8, 7-5-3 band composite.
- 1951 Imagery. August 17, 1951 air photos. National Air Photo Library.
- Inset Basemap. National Geographic World Map. National Geographic, Esri, Garmin, HERE, UNEP-WCMC, USGS, NASA, ESA, METI, NRCAN, GEBCO, NOAA, increment P Corp.

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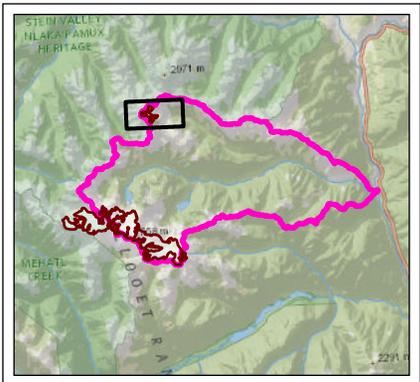




### Kanaka Bar Glacier Analysis Unnamed Glacier Extents 1951 to 2021

#### Legend

-  2021 Glacier Extent
-  2005 Glacier Extent
-  1951 Glacier Extent
-  Kwoiek Watershed



Map scale: 1:30,000 (printed at 8.5x11)  
Map Projection: NAD 1983 UTM Zone 10N

**Data Sources**

- 2021 glacier extents. Digitized by EDI from a Landsat 8 image from Sept 2, 2021.
- 1951 glacier extents. Digitized by EDI from 1951 air photos from August 17, 1951.
- 2021 Imagery. Sept 2, 2021 Landsat 8, 7-5-3 band composite.
- 1951 Imagery. August 17, 1951 air photos. National Air Photo Library.
- Inset Basemap. National Geographic World Map: National Geographic, Esri, Garmin, HERE, UNEP-WCMC, USGS, NASA, ESA, METI, NRCAN, GEBCO, NOAA, increment P Corp.

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The four glaciers showed an increase in the rate of area loss from the 1985–2005 period when compared to the 2005–2021 period, with Chochiwa showing the greatest increase in all periods (Figure 6). Although an increase in the rate of area loss was observed in the 2005-2021 period for Rutledge and Unnamed glacier, the rates were similar to those observed in the 1951–1985 period.

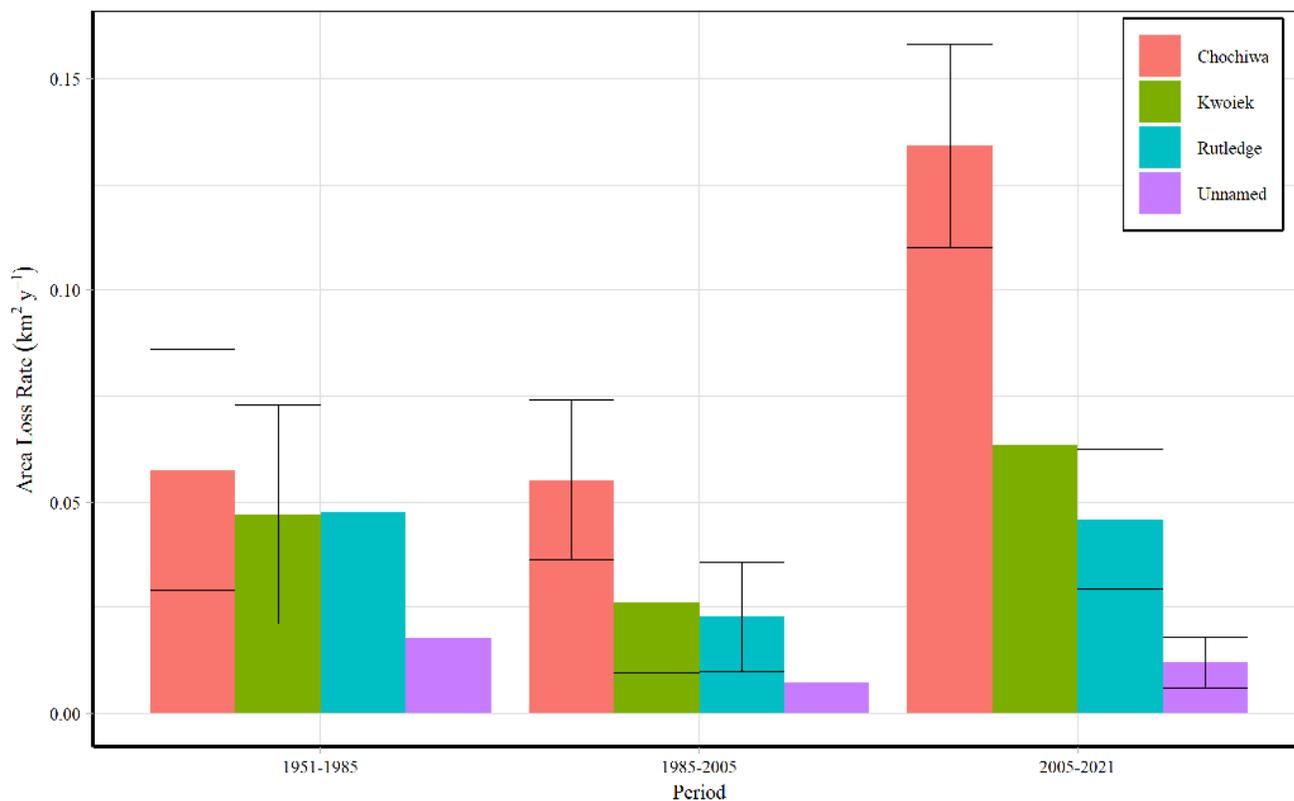


Figure 6. Observed rates of area loss from 1951 to 2021.



The projected glacier areas (2010–2100) did not show much change in the first 30 years of the models. There was a step in the glacial areas at year 2021 when the observed 2021 glacier extents were used to constrain the modeled data (Figure 7). The projected glacier area over time for Kwoiek Glacier (Figure 7) had a less stepped curve than the projected area decreases for the other glaciers. The smoothed line was likely a result of higher coverage (95%) of valid modeled points for Kwoiek Glacier. All the glaciers had an estimated general downward trend in area with some variability.

The four glaciers are predicted to have higher rates of area loss and disappear sooner with the higher RCP scenarios (Table 7). The rates of area loss estimated for RCP2.6 for 2010–2100 were similar to those observed between 1951 and 2021 whereas the area loss rates are markedly higher for RCPs 4.5 and 8.5 due to the greater projected increases in air temperature for these scenarios. RCP8.5 has the most rapid decline in glacier area due to the consistent rapid climb in air temperature into 2100. Although in RCP4.5 the air temperature trend stabilizes after 2060, (Figure 4) its rate of area loss does not correspondingly reduce (Figure 7) because the initial temperature increase of 2.5 °C likely causes freezing levels to climb high enough in elevation that the glaciers effectively no longer accumulate.

**Table 7. Observed rates of glacier area loss (km<sup>2</sup>/y) between 1951 and 2021 and projected rates of glacier area change between 2010 and 2100 for the three RCP scenarios.**

Glacier	Observed (1951–2021)	Projected (2010 to 2100)		
		RCP2.6	RCP4.5	RCP8.5
Chochiwa	0.074 ±0.014	0.070 ±0.038	0.117 ±0.002	0.151 ±0.008
Kwoiek	0.045 ±0.013	0.055 ±0.018	0.078 ±0.001	0.091 ±0.0003
Rutledge	0.040 ±0.010	0.035 ±0.024	0.079 ±0.003	0.105 ±0.0002
Unnamed	0.013 ±0.004	0.013 ±0.004	0.017 ±0.005	0.023 ±0.005

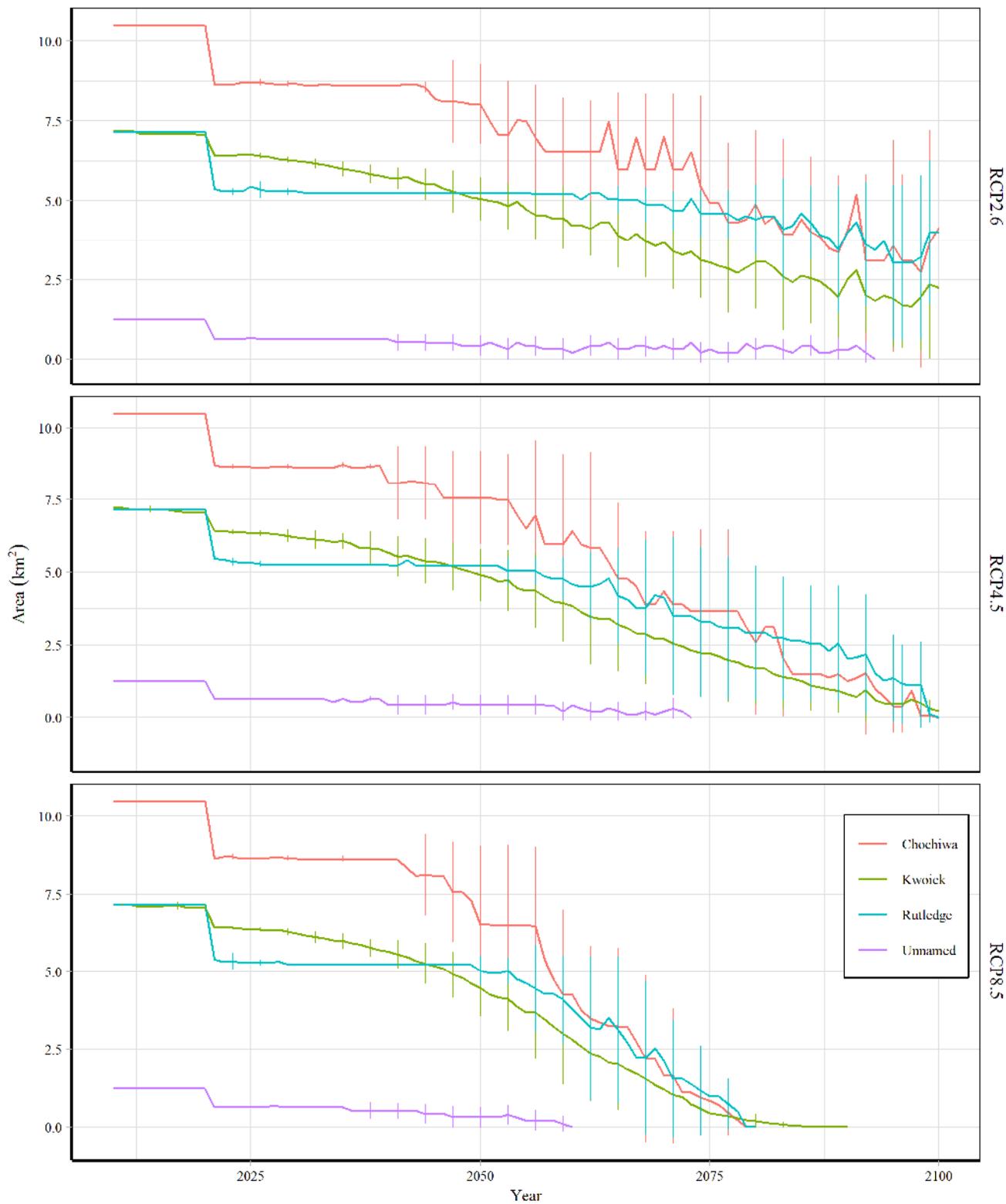


Figure 7. Mean and standard deviation of the six CMIP5 projection models for glacier area for the three RCP scenarios from 2010 to 2100.



### 3.4 GLACIER VOLUME

The four glaciers were projected across all scenarios to have consistent decreasing trends in ice volume over time and an overall decrease in ice volume (Figure 8). The estimated total ice volume lost at the end of the modelling period for each glacier was 832,000,000 m<sup>3</sup> for Chochiwa Glacier, 477,000,000 m<sup>3</sup> for Kwoiek Glacier, 400,000,000 m<sup>3</sup> for Rutledge Glacier, and 34,000,000 m<sup>3</sup> for Unnamed glacier. Unnamed glacier was projected to be the first to disappear in all scenarios, followed by Chochiwa and Rutledge glaciers. Kwoiek Glacier was calculated to be the last to disappear.

The estimated volume loss remained consistent among the three emission scenarios until approximately year 2040, after which ice volume losses were projected to proceed at a greater rate in the higher RCP scenarios. These trends mirror the projected mean annual air temperatures, which show increasing trends across all emissions scenarios (Figure 8).

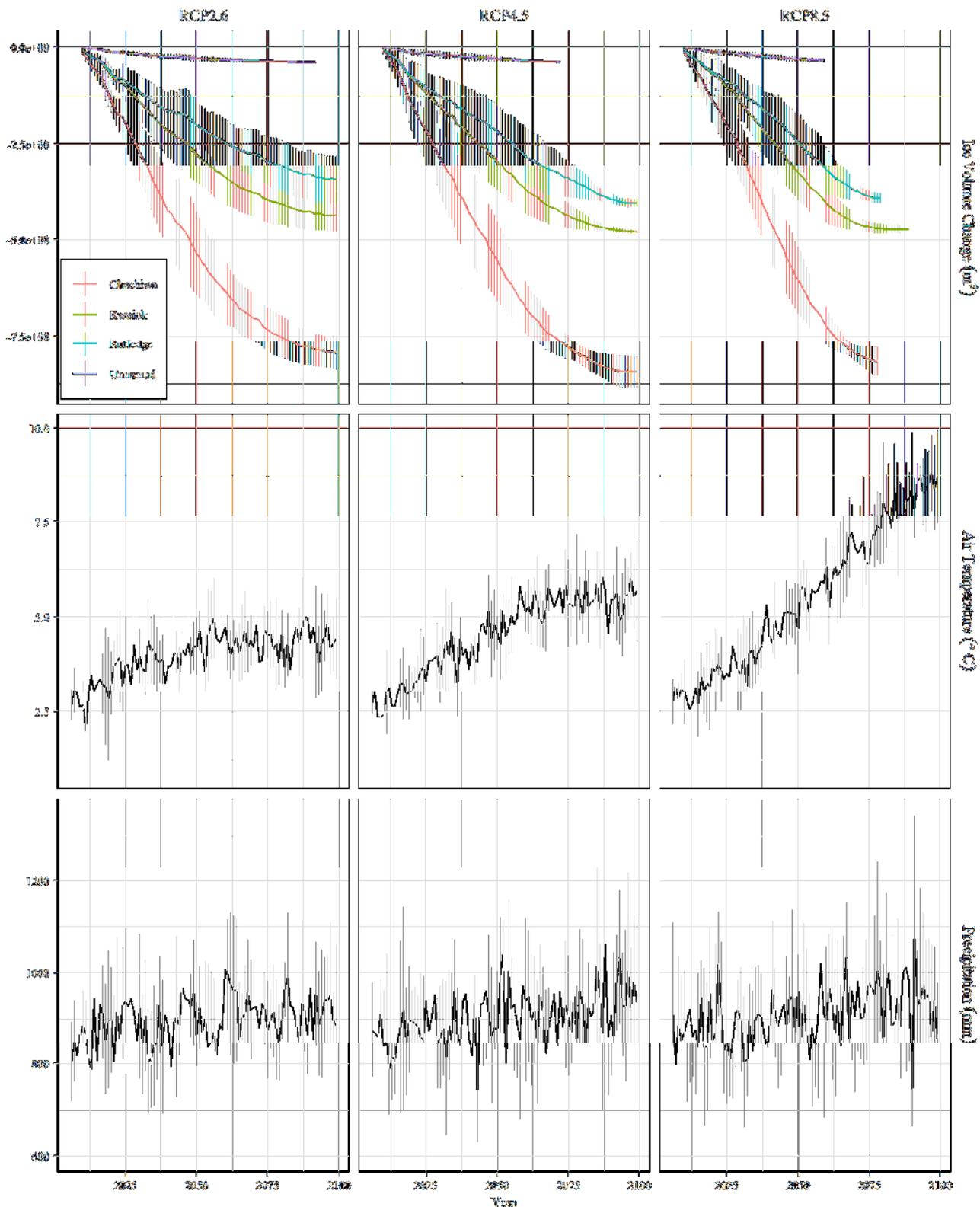


Figure 8. Cumulative mean ice volume change for projection models, mean annual air temperature, and total annual precipitation for the three RCP scenarios from 2010 to 2100. Vertical bars represent the standard deviation.



### 3.5 GLACIER DISAPPEARANCE

The year of glacier disappearance was calculated as the start year of the period with the first zero for each GCM and emission scenario. The minimum, maximum and mean years of disappearance projected for each emission scenario are listed in Table 8. For the RCP2.6 scenario, Unnamed glacier disappeared in all GCMs, with a mean year of disappearance of 2062. Kwoiek Glacier was not projected to entirely disappear in any of the GCMs. Chochiwa was estimated to disappear in three of the six GCMs, with a minimum year of disappearance of 2082, and Rutledge Glacier was estimated to disappear in two of the six GCMs with a minimum year of disappearance of 2089.

**Table 8. Projected minimum, maximum, and mean year of glacier disappearance for the three climate scenarios.**

Glacier	RCP2.6			RCP4.5			RCP8.5		
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Chochiwa	2082	NA	NA	2067	2100	2087 ±14	2061	2079	2072 ±7
Kwoiek	NA	NA	NA	2082	NA	NA	2072	2090	2083 ±7
Rutledge	2089	NA	NA	2068	2100	2088 ±15	2062	2080	2072 ±8
Unnamed	2041	2087	2062 ±20	2034	2070	2054 ±14	2036	2060	2050 ±10

An “NA” value indicates the glacier did not disappear in all GCMs.

In the RCP4.5 scenario, all four glaciers, except for Kwoiek Glacier, are expected to disappear for all GCMs. Kwoiek Glacier was predicted to disappear in two of the six GCMs, with a minimum year of disappearance of 2082. Unnamed glacier had a predicted mean year of disappearance of 2054. Chochiwa and Rutledge glaciers had mean years of disappearance in the 2080s.

All four glaciers disappeared in all GCMs for the RCP8.5 scenario. The mean years of disappearance were estimated to be 2050 for Unnamed glacier, 2072 for Chochiwa and Rutledge glaciers, and 2083 for Kwoiek Glacier.

Unnamed glacier has an earlier minimum disappearance year for RCP4.5 (2034) than RCP8.5 (2036). Both of these minimum disappearances occur in the GFDL model data roughly when outputs between different pathways start to diverge from each other (Figure 7). This counterintuitive result is therefore attributed to model variability.

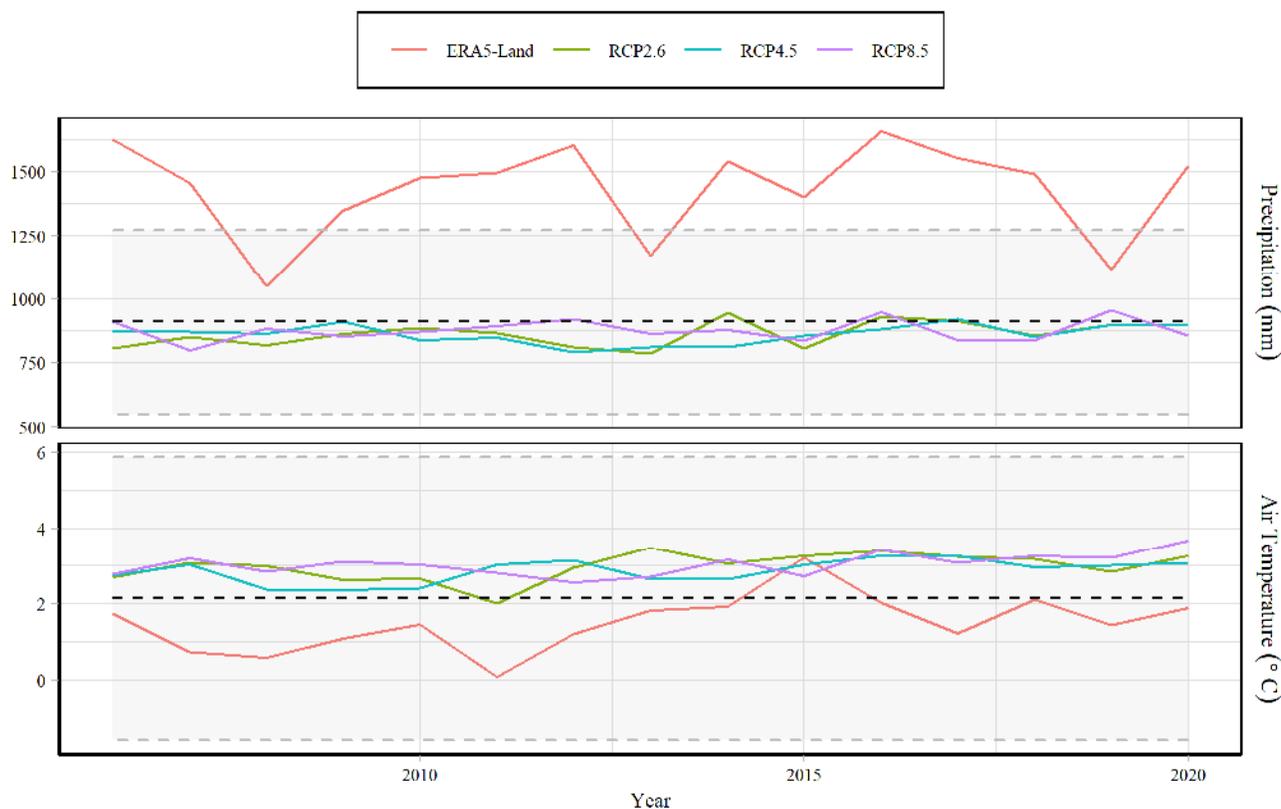
## 4 UNCERTAINTY

### 4.1 CLIMATE

Comparison of the ensemble of the six CMIP5 projections of total precipitation and air temperature with the ERA5-Land dataset revealed biases in the projection data. ERA5-Land total annual precipitation exceeds that of the CMIP5 projections by a mean and standard deviation of 567 ±183.43 mm at the same grid location. Additionally, ERA5-LAND has lower mean annual air temperatures for the comparison period



than projection datasets by  $-1.46 \pm 0.67$  °C. These disparities reflect weakness of the CMIP5 projection data with respect to modelling in areas of higher topography. As the ERA5-Land dataset incorporates land surface modelling, it can more accurately captures variability in temperature and precipitation resulting from topography. Comparing these results with the 30-year climatology data from PRISM, the CMIP5 projections do correspond well within with historical means; however, they are more accurate when modelling low elevation areas.



**Figure 9.** Validation of CMIP5 RCP Scenarios for the period of 2010–2020 with ERA5-Land reanalysis data (red) and the mean (dashed black) and range (dashed grey) of values of the PRISM climatology for 1981–2021.

The uncertainty stemming from the CMIP5 projection’s inability to capture elevational trends may result in the model underestimation of precipitation amounts, and overestimation of air temperatures during the simulation period. As these datasets were used as climate forcings for the glacier modelling in Clark et al. (2015), this could result in the projection datasets providing lower amounts of snow accumulation to the modelled glaciers in winter, and greater melting of glacial ice during summer months, overall resulting in a more pessimistic outlook for the glaciers melting rates

## 4.2 GLACIER EXTENT

The 2021 Landsat 8 glacier extents were used as a validation dataset and compared with the mean projected area at the year 2021. The mean projected areas underestimate the observed 2021 glacier extents by 1% to



25% (Table 9). The underestimation is mainly due to the 200 m resolution of the modeled glacier data. Along the boundary of the finer resolution 2005 and 2021 observed glacier extents used to constrain the modeled glacier data, some of the 40,000 m<sup>2</sup> pixel area may be added or missing. This effect was strongest for the small Unnamed glacier because a larger relative portion of the points are along the glacier extent boundary. The underestimation of glacier extents may result in an underestimation of volume loss. However, for this project the glacier extents are corrected to the 2021 extents at the start of the modelling timespan, and as a result the edge effect will be less dominant as the glaciers retreat from the corrected 2021 extents.

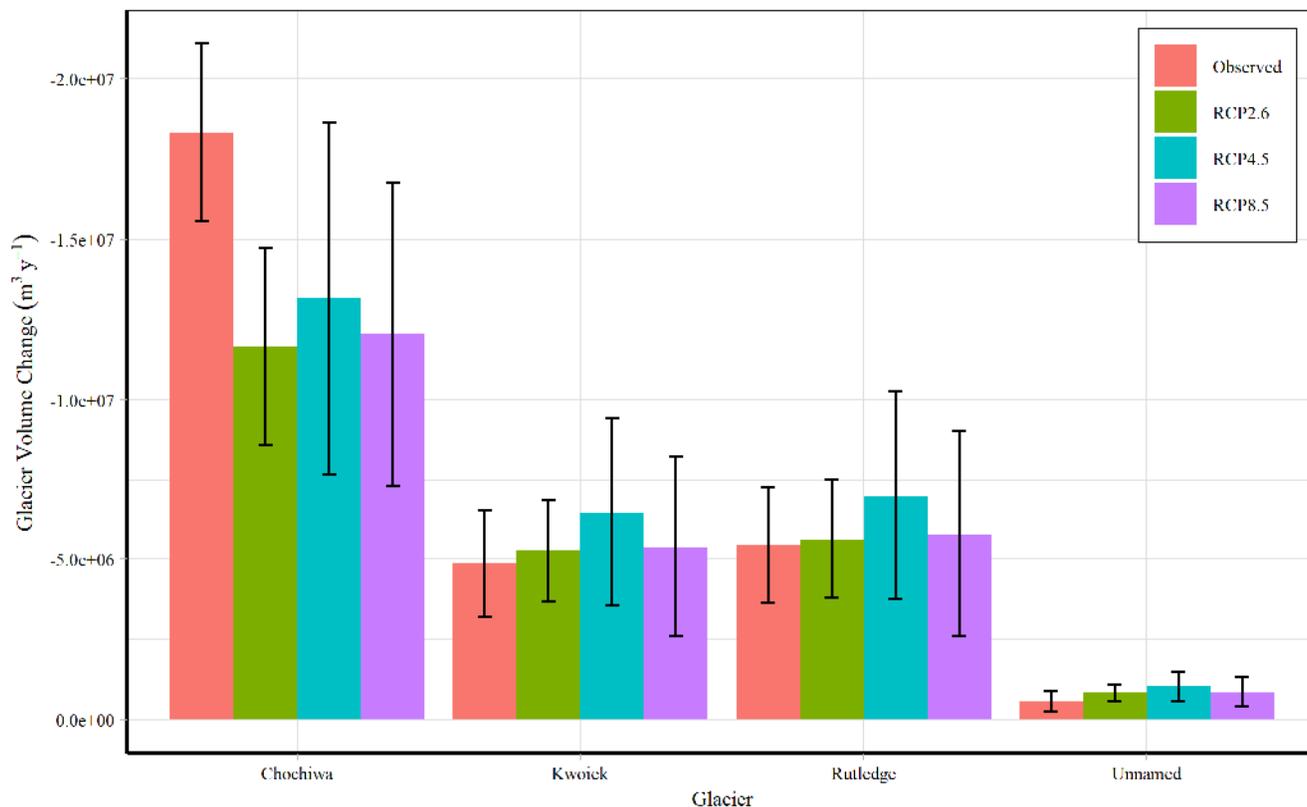
**Table 9. Percent difference of 2021 glacier area between the observed glacier area and the three RCP scenarios.**

Glacier	Observed (km <sup>2</sup> )	RCP2.6 (%)	RCP4.5 (%)	RCP8.5 (%)
Chochiwa	8.71	-0.8	-0.2	-0.8
Kwoiek	6.68	-4.0	-3.7	-4.0
Rutledge	6.32	-15.3	-13.6	-14.8
Unnamed	0.86	-25.9	-25.9	-25.9

Uncertainty resulting in potential overestimation of glacial extent may be introduced by estimating the missing data across 100 m elevation bands, and may affect the extents for Chochiwa, Unnamed, and to a lesser extent, Rutledge glacier. To help reduce this effect, the minimum elevation of the valid points within a band was used as a limiting parameter. Points with missing values with elevations below the minimum elevation of the valid points were not estimated and were not included in the projected glacier extents. An overestimation of projected glacier extents could potentially result in calculations of greater volume loss. The timing of glacier disappearance is not affected by filling in the missing data as it is based on the valid points within a glacier.

### 4.3 GLACIER VOLUME

The projected glacier volume change rates from 2010 to 2020 were compared with the rates observed from satellite imagery derived volume change in the study by Hugonnet et al. (2021). Kwoiek, Rutledge, and Unnamed glaciers have similar, but slightly greater, projected rates of ice volume loss compared to the observed rates (Figure 10). The observed rate of ice loss for Chochiwa Glacier is greater than the projected rates, but still within the error of the RCP4.5 and RCP8.5 scenarios. The lower rates of projected ice loss for Chochiwa Glacier may result in an underestimation of projected ice volume loss.



**Figure 10. Observed rates of glacier volume change compared to the projected rates from the three emission scenarios for the period 2010 to 2020.**

The uncertainty in the glacier projection outputs suggest some overestimation in extents and potentially in volume loss, and the uncertainty in the climate datasets may overestimate melting rates and underestimate accumulation rates. The projected glacier extents and volume loss represent Kwoiek Glacier well, most likely due to the 95% coverage of model data, however, climate uncertainties may result in pessimistic estimates in rates of glacial decline. The other glaciers have more uncertainty in glacier extents with Chochiwa Glacier additionally holding uncertainty in volume loss. The relatively stable projected extents of Chochiwa, Rutledge and Unnamed glaciers for the first 30 years of the glacier model projection suggest that the glacier areas may be overestimated in the early years of the model, and this may carry forward into the volume loss calculations as the starting areas are oversized. The projected glacier model uncertainty coupled with the climate uncertainty for these glaciers potentially leads to an overestimation of ice volume loss, especially in the early years of the model projections. The results presented here provide an estimate of the earlier ranges of disappearance years due to the climate uncertainty tending toward high melt rates and low accumulation amounts.



## 5 CONCLUSIONS AND RECOMMENDATIONS

The last 70 years has seen the observed terminus of the glaciers retreat by 550 m for Kwoiek and Unnamed glaciers,  $987 \pm 73$  m for Chochiwa Glacier, and  $1,575 \pm 73$  m for Rutledge Glacier, with some variation in retreat rates over this period. During this time, Chochiwa, Kwoiek, and Rutledge glaciers lost 37 %, 32%, and 37 % of their total areas, respectively, and up to 52 % of area loss occurred on Unnamed glacier. Glaciers within the Kwoiek watershed are projected to decline in all emissions scenarios into 2100. Given that current atmospheric CO<sub>2</sub>-equivalent already exceeds the projected peak value for RCP2.6, RCPs 4.5 or 8.5 are more likely to occur which suggest the disappearance of a majority of glacier ice within the watershed by the mid 2080s.

Glacier decline is projected to continue through the latter part of the century with glacier volumes declining as much as 832,000,000 m<sup>3</sup> for Chochiwa Glacier; 477,000,000 m<sup>3</sup> for Kwoiek Glacier; 400,000,000 m<sup>3</sup> for Rutledge Glacier; and 34,000,000 m<sup>3</sup> for the Unnamed glacier by the end of the modelling period (i.e., year 2100). Glacier disappearances are projected to predominantly occur in the latter part of the century for the larger glaciers. Under RCP4.5, Chochiwa and Rutledge glaciers are projected to disappear at  $2087 \pm 14$  years and  $2088 \pm 15$  years, respectively. Under RCP8.5, disappearances occur at  $2072 \pm 7$  years,  $2083 \pm 7$  years and  $2072 \pm 8$  years for Chochiwa, Kwoiek, and Rutledge glaciers. The Unnamed glacier disappears in all modelling scenarios at 2087 under RCP2.6 and at approximately 2035 for RCPs 4.5 and 8.5.

Climate data validation indicates that the CMIP5 projections for the start of the modelling period follow the 30-year air temperature and precipitation normals as presented by the PRISM dataset. Comparison with the ERA5-Land reanalysis data, however, show that the projection datasets underestimate the effects of topography resulting in overestimates of air temperatures and underestimates of precipitation. These uncertainties, stemming from the climate forcing data used in the glacier modelling of Clark et al. (2015), may result in more pessimistic projections of glacier declines. However, the validation process for the glacier projections found that volume projections for the first 15 years of the model run were a good fit with observed volume losses.

## 6 PHASE 2 AND 3

The analysis of glacier recession rates within the Kwoiek watershed outlined in this Phase 1 report will be the foundation for developing the next two phases. For Phase 2, the hydrological impacts of reduced glacier melt will be analysed within the Kwoiek watershed. The projected ice volume loss calculated in Phase 1 will be converted to water equivalent volumes and used in the Phase 2 analysis. Phase 3 will then look at potential effects glacier loss may have on water temperature in Kwoiek's lake and creek systems, on the Fraser River, and on salmon lifecycles/habitat. Impacts on the ecosystem, such as forest composition and Biogeoclimatic Ecosystem Classification (BEC) Zones within the Kanaka Bar Band territory will also be explored.



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