Unprecedented Twenty-First Century Glacier Loss on Mt. Hood, Oregon, U.S.A.

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Abstract. As part of the southern Cascades, Mt. Hood is the tallest and most glacierized peak in Oregon, U.S.A. Despite alpine glaciers being one the clearest indicators of human-caused climate change, the 21st century behavior of glaciers on Mt. Hood has not been directly documented at the ground level. Here we directly measure changes in the extents of Mt. Hood's actively flowing glaciers from 2003 to 2023 and find dramatic retreat of all glaciers, with one glacier disappearing and another four retreating towards this status. By 2023, Mt. Hood glaciers lost ~18% of their 2015/2016 area and ~44% of their 1981 area. The seven largest glaciers on the volcano lost ~40% of their area between 2000 and 2023. Comparison to historic records of glacier area back to 1907 shows that this 21st-century retreat is unprecedented relative to the previous century and has outpaced modeled glacier changes of 21st century retreat. The rate of area loss over the last 23 years (1.7-1.8 % year^{-1}) is about triple the fastest rate documented in the last century from 1907 to 1946 (0.54-0.58 % year^{-1}) and about six times faster than the 20th century average (0.29-0.33 % year^{-1}). It has also equaled or exceeded by up to 67% the highest simulated rates of glacier recession under a high greenhouse gas emissions scenario. We demonstrate that this century-scale retreat strongly correlates with regional 30-year-mean climate warming of 1.1-1.2ºC and 15-year-mean climate warming of 1.3-1.5ºC since the early 1900s, but not with regional changes in precipitation. We conclude that Mt. Hood's glaciers are retreating in response to a warming climate and that this recession has accelerated in the 21st century.

1 Introduction

The global loss of mass and retreat of glaciers in the 21st century is accelerating (Zemp et al., 2015; Hugonnet et al., 2021) with century-scale glacier recession attributed to regional climate change in response to anthropogenic greenhouse gas emissions (Marzeion et al., 2014; Roe et al., 2017, 2021). The 2021-2022 hydrological year was the 35th consecutive year of negative annual mass balance for 50 reference glaciers on six continents (Pelto, 2023; World Glacier Monitoring Service, 2022). If global average temperature increases by 1.5°C relative to the pre-industrial period, the limit set forth in the Paris Agreement, roughly half of the world's individual glaciers are projected to disappear with ~26% loss in global glacier mass (Rounce et al., 2023). Indeed, in the western United States, this deglaciation is already coming to fruition (Fig. 1A). The Trinity Alps in the State of California (Fig. 1A) have lost ~97% of their late 1800s glacierized area, with only ~0.017 km^2 of one glacier still showing evidence of ice flow as of 2015 (Garwood et al., 2020). The Olympic Mountains of Washington

State (Fig. 1A) lost about half of their late 1800s glacier area by 2015 with 35 glaciers disappearing since 1980 (Fountain et al., 2022). Eleven of the 37 named glaciers in Glacier National Park in the State of Montana (Fig. 1A) ceased to be classified as glaciers as of 2015 with glacierized area in the park declining by ~68% from the 1800s to 2015 (Fagre et al., 2017). Washington State's Mt. Rainier (Fig. 1A), the most glacierized peak in the contiguous United States, has seen its glacierized area decline by ~42% between 1896 and 2021 and had one glacier recently disappear with two more nearing stagnation (Beason et al., 2023). Nearby in the Washington North Cascades (Fig. 1A), 33 glaciers were listed as extinct in the Global Land Ice Measurements from Space (GLIMS) Glacier Database at the National Snow and Ice Date Center (NSIDC) as of 2023 (GLIMS and NSIDC, 2023).

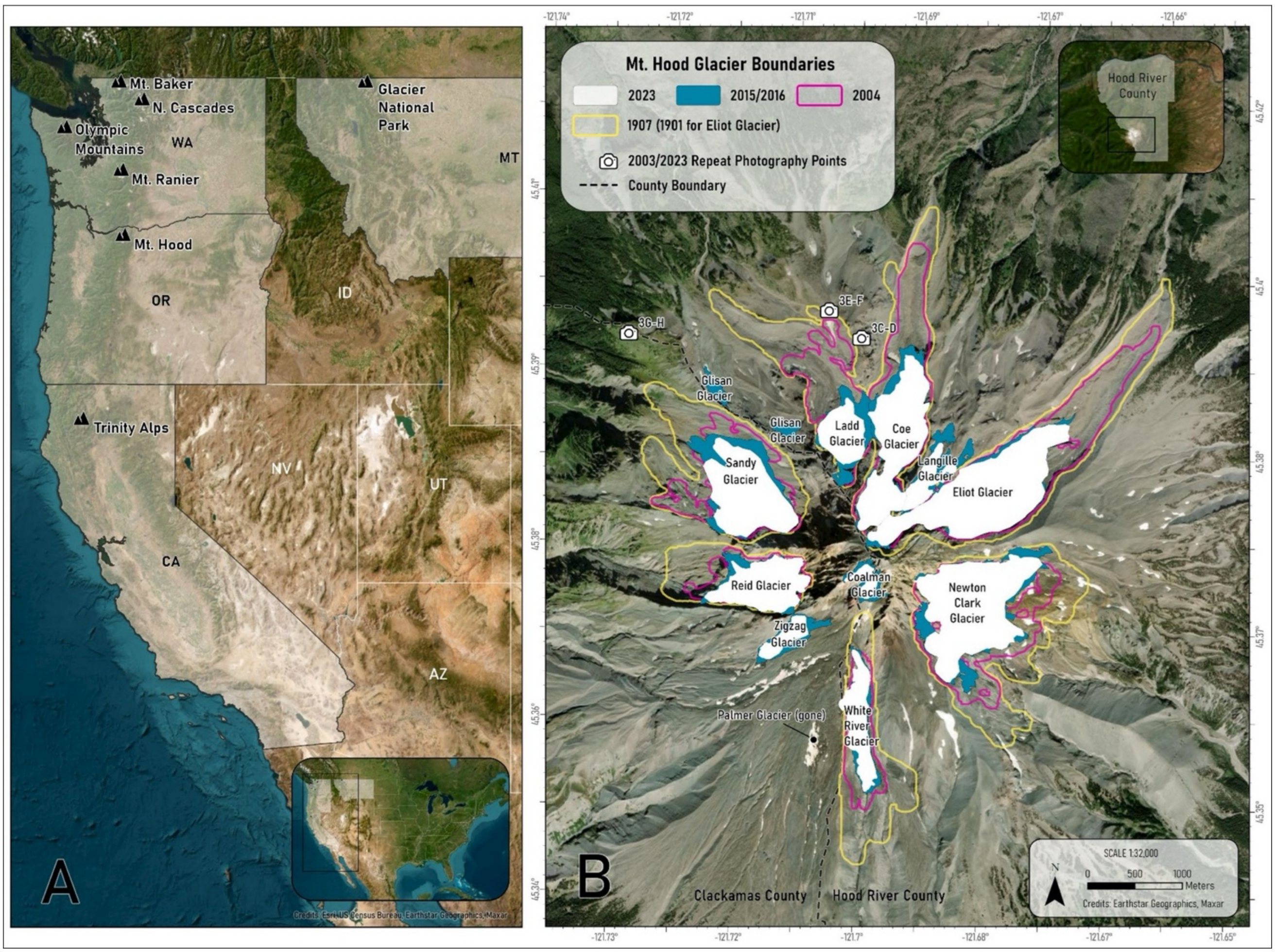


Figure 1: Location map of Oregon (A) and Mt. Hood (B). A. Western United States with mountain ranges mentioned denoted (WA = Washington, MT = Montana, OR = Oregon, CA = California, ID = Idaho, NV = Nevada, UT = Utah, AZ = Arizona); inset shows location with black outline. B. Glacier extents on Mt. Hood with photo locations in Fig. 3 noted. 1907/1901 and 2004 ice extents from Jackson & Fountain (2007); 2015/2016 ice extents from Fountain et al. (2023). 2023 extents from this study. Inset shows figure location (black outline) within Hood River County (area for reanalysis data in Fig. 6). Credits: Esri, U.S. Census Bureau, Earthstar Geographics, Maxar.

Despite these ominous predictions and dire observations for glaciers, data on the 21st century behavior of glaciers in the Cascade Range of Oregon are limited. Glaciers in Oregon were first noted in 1870 on Mt. Hood, the tallest and most glacierized peak in Oregon (Fig. 1A, B), only days after the first glaciers in the contiguous United States were recorded on Mt. Shasta in California (O'Connor, 2013). Mt. Hood is an active volcano that reached a height close to its current elevation of 3,425 meters above sea level by 30,000 years ago (U.S.G.S., 2023, https://www.usgs.gov/volcanoes/mount-hood/science/eruption-history-mount-hood-oregon). The last major eruption was ~1,500 years ago that created pyroclastic flows and lahars on the southwest side of the volcano upon which Zigzag and Palmer (now gone) glaciers rested (Fig. 1B). Its last eruption occurred in the late 1700s, producing a lava dome south of the summit around which Coalman Glacier flows (Fig. 1B). In the late 1800s, fumaroles formed near this lava dome (Lillquist and Walker, 2006). Mt. Hood has high amounts of rock fall and variations in geothermal heat that could affect ablation, ice flow, and ice extent (e.g., Lundstrom et al., 1993; Lillquist and Walker, 2006; Jackson and Fountain, 2007; Howcutt et al., 2023).

Changes in Mt. Hood's glaciers were monitored by the Research Committee of the Mazama Mountaineering Club from the 1930s to mid-1980s (e.g., Phillips, 1935, 1938; Mason, 1954; Handewith Jr., 1959; Dodge, 1971, 1987). In 1981, the U.S. Geological Survey measured the thickness and area of Mt. Hood's glaciers, estimating their volume (Driedger and Kennard, 1986a, 1986b). However, the extent of Oregon Cascade glaciers on current U.S. Geological Survey and U.S. Forest Service maps are still based on air photos from the 1950s (Fountain et al., 2017). The glacierized area of Mt. Hood was last measured with field observations in 2004 (Jackson and Fountain, 2007) whereas glacier lengths with field observations were last recorded in 2000 (Lillquist and Walker, 2006). Fountain et al. (2023) documented snow and ice areas in the western United States using 2015 and 2016 imagery for Mt. Hood's glaciers but did not test mapped accuracy with field observations. The timing of this imagery also missed what multi-year and longer impacts the 2015 record-low snowpack (Mote et al., 2016) and the June 2021 Pacific Northwest heatwave (Philip et al., 2022; Thompson et al., 2022) would have on Mt. Hood's glaciers (e.g., Pelto, 2018; Pelto et al., 2022).

Regarding climate change impacting Oregon's glaciers, Menounos et al. (2019) documented minimal elevation change for Mt. Hood's glaciers from 2000 to 2018, interpreting from this an approximately neutral mass balance for the first 19 years of the 21st century. Near zero mass balance for 2000-2018 is at odds with the mass changes for global reference glaciers that include four glaciers to the north of Mt. Hood in the state of Washington; these four all had cumulative negative mass balances for the same time period (Pelto, 2023). For the 20th century, Lillquist and Walker (2006) did not find a relationship between glacier-length change on Mt. Hood and temperature or precipitation change over the 20th century. Conversely, climate-glacier modeling simulates the emergence of glacier retreat from natural variability in western North America since the 1960s (Marzeion et al., 2014). As such, recent impacts of human-caused climate change on Mt. Hood's glaciers have been unclear and largely unexplored from direct field observations.

Glacier change on Mt. Hood is of importance to downstream ecosystems and economies (see Robel et al., 2024), such as orchards and farms in the Hood River Valley (Nolin et al., 2010; U.S. Bureau of Reclamation, 2015; Frans et al., 2016, 2018), unique glacier-fed spring water microbiomes (Miller et al., 2021), and salmon and steelhead (Pitman et al., 2020; Thieman et al., 2021). The Hood River Valley has 12,000 acres producing seven varieties of pears, 1500 acres producing five varieties of apples, 1500 acres devoted to cherries, and 100 acres of grapes for an expanding wine industry (Columbia Gorge Fruit Growers, 2024, http://www.cgfg.org/information/crops-information), along with two hydropower plants with 4.4 megawatt capacity (Farmers Irrigation District, 2024, https://www.fidhr.org/index.php/en/about-us/hydroelectric). Glaciers contribute ~40-70% of the stream flow in the late summer to the upper Hood River where flow is diverted for irrigation and local hydropower (Nolin et al., 2010). As such, future water resource management plans for the Hood River basin included projections of future glacier change on Mt. Hood (U.S. Bureau of Reclamation, 2015; Thieman et al., 2021). White River and Newton-Clark glaciers also contribute late-summer meltwater to a robust orchard industry in another county (Columbia Gorge Fruit Growers, 2024, http://www.cgfg.org/information/crops-information). Furthermore, Mt. Hood is also one of the most climbed mountaineering objectives in the world (~10,000 attempts per year), which is becoming more dangerous during a diminishing climbing season with greater rockfall as the volcano has changed in recent years (O'Neil, 2023).

Here we document glacier change on Mt. Hood over the last 20 years. We conducted new repeat photography and field observations of glacier extent in 2003 and 2023 to provide detailed ground-based evidence for glacier change during a period where satellite-based altimetry previously found no significant change in these glaciers. We also utilized a series of field campaigns with satellite imagery to determine the magnitude of glacier area and length change up to mid-September 2023. We place these 21st-century glacier changes in the context of 20th-century glacier changes and test the relationship between ~120 years of glacier-length variability and regional climate change.

2 Data and Methods

2.1 2003 Frontal GPS Positions and Repeat Photography

In 2003 (28 August to 4 October), the lowest observed actively flowing glacier-terminus positions and stagnant-ice positions were measured (latitude-longitude-altitude) by global positioning system (GPS) for every glacier on Mt. Hood (Fig. S1). These were discrete observations, which served as points to assess future minimum changes in terminus elevation. Repeat measurements and comparison to known elevation markers determined an elevation uncertainty of ±6 m. Termini were photographed with locations noted (Fig. S1) for future repeat photography (i.e., 2023). All glaciers were described in detail in the field (Supplement). The goal of this initial 2003 field effort was to provide baseline observations and archival photographic evidence from the early 21st century against which future glacier change could be assessed; we subsequently conducted further observations for this assessment 20 years later in 2023.

From 15 to 22 September 2023, repeat photographs were taken at the same locations as the 2003 photographs (Fig. S1) and new field observations were made for all of the glaciers (Supplement). From this repeat mapping (see below), we were able to determine the minimum amount the terminus rose in elevation over the last 20 years. We selected photographs to repeat from an archive of photographs taken in 2003. Using the image and field notes regarding the location of the images from 2003, we located the precise site of each selected 2003 photograph. The same frame was maintained using relatively unchanged features such as buttresses, cliffs, and moraines as points of reference.

2.2 2023 Glacier Inventory, Mapping and Uncertainty

In contrast to the point measurements in 2003, full glacier extents were mapped in 2023, using an iterative approach over the years 2020 to 2023. Note that we mapped only the extent of actively flowing glacier ice, both debris-free and debris-covered, and excluded stagnated non-flowing debris-free and debris-covered ice (see below for criteria for differentiation and delineation of flowing from stagnant glacier ice). We focused on actively flowing glacier ice, rather than include stagnant ice, to be consistent with prior glacier-extent mapping on Mt. Hood (e.g., Lillquist and Walker, 2006; Jackson and Fountain, 2007; Fountain et al., 2023) and in other mountain ranges of the western United States (e.g., Fagre et al., 2017; Garwood et al., 2020; Fountain et al., 2022; Beason et al., 2023).

In measuring glacier dimensions, it is important to be clear on what is considered a glacier and thus included in the glacier extents. Clarke (1987) noted in his review of glacier research since the 1820s that “the most interesting property of glaciers is that they flow”, using the present tense. The U.S. Geological Survey defines a glacier as “a large, perennial accumulation of crystalline ice, snow, rock, sediment, and often water that originates on land and moves down slope under the influence of its own weight and gravity” (U.S. Geological Survey, 2024, https://www.usgs.gov/faqs/what-glacier). The NSIDC, which hosts data for GLIMS, defines a glacier as “an accumulation of ice and snow that slowly flows over land” (NSIDC, 2024b, https://nsidc.org/learn/parts-cryosphere/glaciers/glacier-quick-facts). However, the NSIDC has another definition of a glacier as: “a mass of ice that originates on land, usually having an area larger than one tenth of a square kilometer; many believe that a glacier must show some type of movement; others believe that a glacier can show evidence of past or present movement” (NSIDC, 2024a, https://nsidc.org/learn/cryosphere-glossary/glacier). Therefore, our mapping of only actively flowing glacier ice follows many traditional definitions of what constitutes a glacier, but we recognize that another definition of a glacier exists that includes ice that used to move and is now stagnant. We return to our decision to map only actively flowing glacier ice, rather than include stagnant ice, in the Discussion section.

Because manual mapping is suggested for glaciers with debris cover (e.g., Paul et al., 2013), we initially manually mapped actively flowing glacier extents using composite Google Earth imagery in the application CalTopo (caltopo.com). As these images spanned multiple years and were not necessarily recent, we then manually refined ice margins using weekly Sentinel-2 satellite images that were taken shortly before the first snowfall from the summers of 2020, 2021, 2022, and 2023. These images were processed and made available in CalTopo one day after acquisition (see Supplement for a complete list of satellite imagery). The combination of satellite-imagery delineation of margins with ground-truth mapping relative to the images is a robust, effective technique. In October 2020, September 2021, and September 2023, we iteratively took these ice margins (updated year by year) into the field for direct mapping using CalTopo on a portable GPS enabled tablet. These three years were excellent for field mapping as the length of the 2020 summer and the warmth of the 2021 and 2023 summers resulted in extremely low snow cover that facilitated ice-margin identification in regions that would typically have snow cover throughout the summer.

In sequence, glacier margins were first manually mapped from Google Earth imagery, then modified by late summer 2020 Sentinel-2 imagery and finalized by in-the-field ice-margin mapping. Then, the 2020 ice-margin maps were updated with late summer 2021 Sentinel-2 imagery that were subsequently further adjusted and mapped in the field. The 2021 maps were updated with late summer 2022 Sentinel-2 imagery and again with late summer 2023 Sentinel-2 imagery, which were then adjusted and finalized in September of 2023 by in-the-field measurement. All termini in the end-of-summer ablation area were walked, resulting in ~60%, on average, of each ice margin being physically mapped in the field. Notably, this means all debris-covered ice margins were mapped in the field and their delineation was not based solely on satellite imagery. Two glaciers, Zigzag, Glisan, were field mapped entirely.

Debris-covered termini are common on Mt. Hood glaciers, and such field mapping of the termini is critical to accurately delineate glacier margins (e.g., Lundstrom et al., 1993; Lillquist and Walker, 2006; Jackson and Fountain, 2007; Ellinger, 2010). We followed prior methods for differentiating actively flowing debris-covered ice from stagnant debris-covered ice on Mt. Hood (e.g., Lillquist and Walker, 2006): an identifiable glacier front, a lobate form of the terminus, and a visible connection of the lobate terminus to debris-free flowing ice. This methodology is consistent with the observation of a convex shape of actively flowing glacier margins by Leonard and Fountain (2003) and Leigh et al. (2019). To these criteria, we added the presence of crevasses observed in the field as another indicator of ice flow whether under debris or in bare ice (Leigh et al., 2019).

Manual remote-sensed ice-limit comparisons with direct field observations yielded extent differences that were small enough (i.e., less than a meter or two) to make uncertainty difficult to quantify. Using only remote sensing, Fountain et al. (2023) had their lowest ice-extent uncertainty for a Mt. Hood glacier at ±1%, while Jackson and Fountain (2007) reported an uncertainty for their 2000 Mt. Hood glacier areas of ±0%. Our uncertainty is most likely lower than ±1%, but to be conservative we assumed a ±7% uncertainty in the glacier area for 2023. We based this ±7% uncertainty on the average area uncertainty for the 2004 extents of Mt. Hood glaciers determined by Jackson and Fountain (2007), which was ±7%. Our conservative ±7% is slightly greater than the uncertainties determined from testing the accuracy of remote sensed glacier area from the European Alps and Alaska of 2.6-5.7% (Paul et al., 2013). This means any conclusions we made from our mapped glacier area were likely not dependent on our assumed glacier area uncertainty.

2.3 Glacier Area Change and Uncertainty

To update glacier change on Mt. Hood for the 21st century, we compared our 2023 glacier extents to the most recent inventories conducted for Mt. Hood. Fountain et al. (2023) produced Mt. Hood glacier areas from remote sensing imagery from either 2015 or 2016; this allowed an assessment of glacier-area change over the last seven to eight years. Note that Fountain et al. (2023) also mapped snowfields (e.g., stagnant ice bodies) and debris-covered stagnant ice bodies in addition to actively flowing glaciers. When determining glacier change, we looked at changes in flowing glacier area for the ice bodies contiguous with those remaining actively flowing in 2023 (blue and white areas in Fig. 1B) as this area change is what relates to the mass balance of the glacier (e.g., Paterson, 1994). The Supplement contains further information on the additional ice bodies not classified by Fountain et al. (2023) as glaciers or small glacier bodies that were stagnating after separating from the main glacier; we discuss their potential impact on determination of glacier change in the Discussion section. We also compared our 2023 glacier areas to the 1981 glacier areas for Mt. Hood determined by Driedger & Kennard (1986b) that were based on field mapping and aerial photographs of actively flowing glacier ice; this afforded a 42-year perspective on glacier change.

We assessed rates of glacier change by comparing our 2023-measured area with the glacier area records of Jackson and Fountain (2007) for the time period 1907 (or 1901 in the case of Eliot Glacier) to 2004 for seven glaciers on Mt. Hood: White River, Newton-Clark, Eliot, Coe, Ladd, Sandy, and Reid. Because of the different temporal resolutions of each glacier-area record, we calculated area change between observational years common to all seven glaciers: 1907, 1946, 1972, 2000, and 2023. We focused on the change from 2000 to 2023, rather than 2000 to 2004 and then 2004 to 2023, to make the duration over which the most recent intervals of change were measured closer to the earlier temporal spacing. Newton-Clark Glacier lacked an aerial extent for 1946; we extrapolated between the measured extent in 1935 and 1956 when the glacier lost ~0.04 km^2 over these 21 years. To aid comparison between glaciers of different sizes on Mt. Hood and to other glaciers in the Pacific Northwest, we calculated relative changes in glacier area determined as a percent of its prior area. In calculating the rate of change, we propagated through the uncertainty in the area from Jackson and Fountain (2007) and our 2023 areas. For the 2000 area, we conservatively applied a ±7% uncertainty of the 2004 Jackson and Fountain (2007) glacier margins. The propagation of uncertainty was through quadrature where the squares of the individual percent uncertainties were summed, and their square root taken.

2.4 Change in Glacier Length and Climate

Glacier length changes are commonly used to assess glacier relationships to a changing climate (e.g., Harper, 1993; Haeberli and Hoelzle, 1995; Pelto and Hedlund, 2001; Oerlemans, 2005; Lillquist and Walker, 2006; Leclercq and Oerlemans, 2012; Leclercq et al., 2014; Pelto, 2016; Roe et al., 2016, 2021; Huston et al., 2021; Hoelzle et al., 2023). Here we compared the cumulative change in glacier length for five glaciers on Mt. Hood from 1901 through 2023 to records of regional climate change. Lillquist and Walker (2006) measured glacier-length change for White River, Newton-Clark, Eliot, Coe, and Ladd glaciers from 1901 to 2000. To this record we added the change in length up to 2023. Specifically, we calculated the distance between the lowest observed actively flowing ice in 2023 (Fig. 1B) and the lowest actively flowing ice in 2000 of Lillquist and Walker (2006) along the same flow line they used back to 1901, which was down the center of the glacier. In the case of Newton-Clark Glacier, the length was measured in the northern, due-east-facing Newton drainage (Fig. 1B). Changes in glacier length were normalized to the 1901 length of the glacier to account for different glacier sizes. Lillquist and Walker (2006) did not provide uncertainties in their glacier lengths and reported change at 1 m accuracy. Here, we report our length changes at 10 m accuracy.

For records of regional climate change, we used U.S. National Oceanic and Atmospheric Administration (NOAA) temperature and precipitation reanalysis data for the region of Hood River County (Fig. 1) from 1895 to 2023 (U.S. NOAA, 2024, https://www.ncei.noaa.gov/access/monitoring/climate-at-a-glance/). We chose Hood River County as this is the smallest geographic region for the reanalysis data that include these five glaciers and would still have direct weather station measurements within the geographic domain over the period of comparison. Snow telemetry stations on and around Mt. Hood were only installed in the late 1970s, with temperature sensors beginning to work consistently in the late 1980s (U.S. National Resources Conservation Service, 2024, https://www.nrcs.usda.gov/conservation-basics/conservation-by-state/oregon/oregon-snow-survey/about-us).

For temperature, we focused on changes in annual, May-October and June-September means. May through October is generally the period of time in the Oregon Cascades from peak winter snowpack to the first snowfall of the next winter, or the maximum length of the ablation season. Since this can vary, we also examined June-September temperature as a shorter ablation season. Pelto (2018) determined the best fit between mass balance and ablation temperature to be May-September or June-September for glaciers in Washington. For precipitation, we analyzed annual, November-April and October-May means. November through April in Oregon generally spans the time period from the first winter snow until peak winter snowpack, or the accumulation season. To account for seasonal variability, we also used October through May precipitation.

First, we calculated the changes in temperature and precipitation relative to their 1895-1924 means. Second, we produced a 30-year backward-running mean for the yearly changes in temperature and precipitation. We employed a 30-year backward-running mean because the response time of Pacific Northwest glaciers similar to those on Mt. Hood is 20-30 years (Pelto and Hedlund, 2001). The prior 30-year mean reflects this lagged relationship between climate change and glacier change. We explored the lower limit of the glacier-response times by using a 15-year backward-running mean. While Pelto and Hedlund (2001) found a lower limit to glacier-response time of 20 years, glaciers on Mt. Baker in Washington (Fig. 1A) may respond faster at 11-20 years (Pelto, 2016), which we encompass with our 15-year backward-running mean. Third, the relationship between the normalized change in glacier length at a given year of measurement was compared to the prior 30-year or 15-year mean change in temperature or precipitation. Correlations were determined through regression, with $p < 0.05$ indicating significant correlation.

3 Results

Since 2003, every glacier on Mt. Hood underwent a rise in terminus elevation (Table 1, Fig. 2), with an average rise of ~150 m (observed changes and repeat photographs provided in Supplement). Note that these are inherently minimum estimates of the rises given the point-nature of the 2003 observations. There does not appear to be any pattern in the degree of terminus rise relative to glacier aspect on Mt. Hood (Fig. 2). The greatest terminus rise occurred in the southeast-facing Clark drainage of Newton-Clark Glacier (>300 m) followed by the southwest-facing Zigzag Glacier (>250 m; Fig. 3A, B), the west-facing Sandy Glacier (>240 m; Fig. 3G, H) and the northwest-facing Ladd Glacier (>230 m; Fig. 3E, F). Of the three glaciers with substantial debris cover of their termini, Ladd (>230 m) and Coe (>170 m) (Fig. 3C, D) had terminus rises greater than the average while Eliot's terminus rose >70 m (Table 1, Fig. 2).

In the last seven to eight years, every glacier on Mt. Hood lost area (Fig. 1B), resulting in 18±1% loss in total glacier area (Table 1) relative to 2015/2016 at a rate of 2.40±0.02 % yr^{-1} (yr = year). Glisan Glacier ceased to show evidence of flow between 2015 (Fountain et al., 2023) and our first field observation in 2020, with a stagnant ice area of 0.009±0.0006 km^2 as of 2023. Zigzag, Coalman and Langille glaciers lost >40% of their area since 2015/2016. Ladd Glacier separated from its uppermost accumulation area (Fig. 3E, F) while Coe Glacier separated from its debris-covered terminus (Fig. 3C, D), both due to thinning over ice falls after 2016 (Fountain et al., 2023). A similar separation from its debris-covered terminus also occurred for Eliot Glacier (Fountain et al., 2023). When compared to the 1981 glacier inventory (Driedger and Kennard, 1986b), the glacierized area loss by 2023 for Mt. Hood glaciers was ~44% (Table 1) at a rate of ~1.0 % yr^{-1}. The largest percent area lost since 1981 was the disappearance of south-facing Palmer Glacier (100%), followed by southwest-facing Zigzag Glacier (~87%), and north-facing Ladd Glacier (~74%).

Glacier (Multiple Termini)	2003 Terminus Elevation (m asl)	2023 Terminus Elevation (m asl)	20-Year Terminus Δ Elevation (m)	1981 Area km^2	2015/16 Area km^2 (uncert)	2023 Area km^2 (uncert)	1981-2023 % Δ Area	2015/16-2023 % Δ Area (uncert)
Zigzag	2350	2600	250	0.77	0.168 (0.005)	0.101 (0.007)	87	40 (3)
Palmer	gone			0.13			100	
Coalman (E)	3130	3130	0	0.08	0.099 (0.001)	0.057 (0.004)	29	42 (3)
Coalman (W)	3190	3230	40					
White River	2130	2240	110	0.54	0.287 (0.046)	0.271 (0.019)	50	6 (1)
Newton-Clark (N)	2420	2480	60	1.99	1.134 (0.181)	0.975 (0.068)	51	14 (2)
Newton-Clark (S)	2320	2620	300					
Eliot	2050	2120	70	1.68	1.086 (0.174)	0.912 (0.064)	46	16 (3)
Langille (remain)		2520		0.40	0.233 (0.037)	0.138 (0.010)	66	41 (7)
Langille (upper)	2070	gone						
Langille (lower)	1960	gone						
Coe	1920	2090	170	1.24	0.779 (0.125)	0.696 (0.049)	44	11 (2)
Ladd	2100	2330	230	0.90	0.347 (0.055)	0.235 (0.016)	74	32 (6)
Glisan (upper)	2040	gone						
Glisan (lower)	1930	gone	>220		0.041 (0.006)			100
Sandy	1890	2130	240	1.19	0.751 (0.120)	0.631 (0.044)	47	16 (3)
Reid	2240	2350	110	0.75	0.469 (0.005)	0.417 (0.029)	44	11 (1)
Total				9.67	5.39 (0.32)	4.43 (0.12)	44	18 (1)

Table 1: Mt. Hood glacier observations from 2003 and 2023. Change (Δ) in terminus elevation, glacier area in 1981 (Driedger and Kennard, 1986b) and 2015/2016 (Fountain et al., 2023), and area change (Δ) as a percent (%) up to 2023 provided.

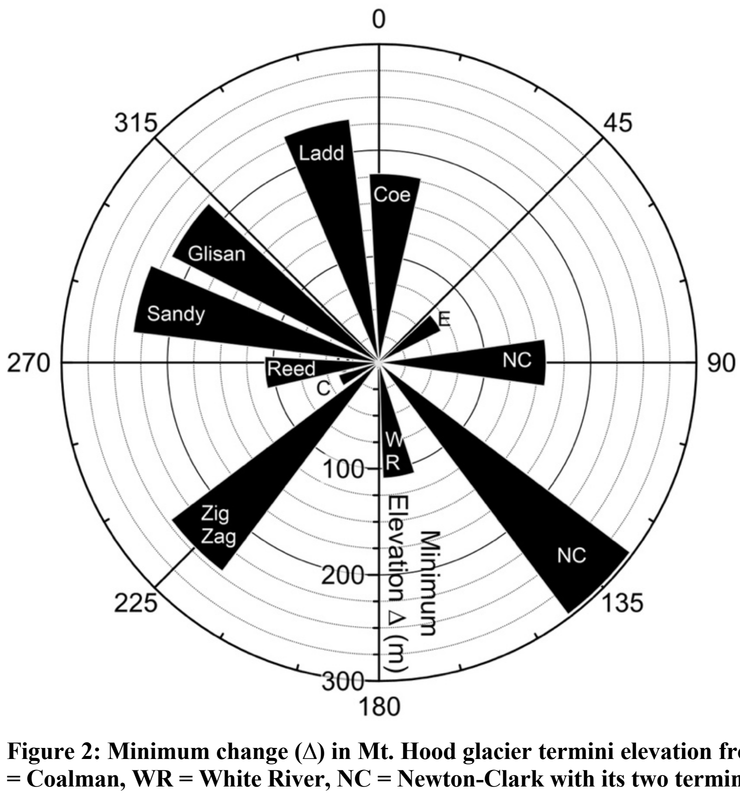
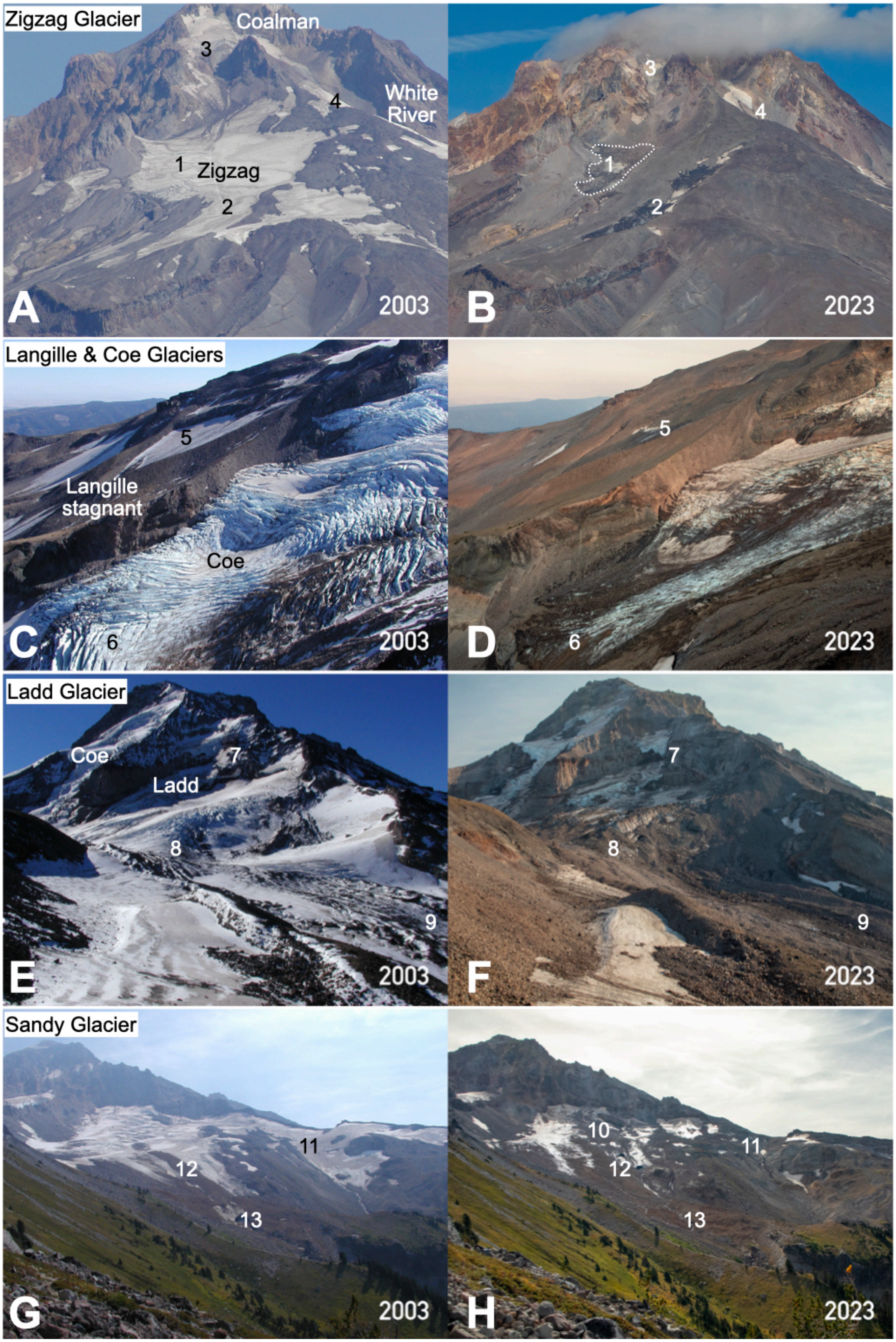


Figure 2: Minimum change (Δ) in Mt. Hood glacier termini elevation from 2003 to 2023 relative to glacier position on Mt. Hood; C = Coalman, WR = White River, NC = Newton-Clark with its two termini labeled, and E = Eliot.


Zigzag Glacier
Coalman
3
4
White River
1
Zigzag
2
A
2003
3
4
1
2
B
2023
Langille & Coe Glaciers
5
Langille stagnant
Coe
C
6
2003
5
D
6
2023
Ladd Glacier
Coe
7
Ladd
8
9
E
2003
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Sandy Glacier
11
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H
2023

Figure 3: Select repeat photographs from Mt. Hood; see Fig. 1B for photo locations. A and B: Zigzag Glacier across the valley (shot location 45.29275º, -121.80044º) repeat photograph from 2003 (A) and 2023 (B). 1. Denotes the reduction in area of Zigzag Glacier to its 2023 limit (dashed white line). 2. Remnant stagnant ice that used to be part of the actively flowing glacier. 3. Western terminus of Coalman Glacier that has retreated but is still visible in 2023 at edge of cloud. 4. Top of White River Glacier that has retracted since 2003. C and D: Langille and Coe Glaciers (shot location 45.39459º, -121.69982º) in 2003 (C) and 2023 (D). 5. Disappearance of remnant ice of Langille Glacier. 6. Loss of an ice fall on Coe Glacier due to terminus retreat to just below the 6 in D. E and F: Ladd Glacier (shot location 45.39718º, -121.70424º) in 2003 (E) and 2023 (F). 7. Separation of Ladd from its uppermost accumulation area. 8. Ice fall that is now the current terminus of Ladd. 9. Retreat of the ice margin where actively flowing ice is now detached stagnant ice. G and H: Sandy Glacier (shot location 45.39477º, -121.73124º) in 2003 (G) and 2023 (H). 10. Accumulation of rock fall on the glacier in the last 20 years. 11. Retreat of glacier ice that is now exposed bedrock. 12. 2023 terminus location and ice caves (H) that were in the centre of the glacier in 2003 (G). 13. 2003 terminus with ice cave (G) that is now stagnant, debris-covered ice (H).

The seven largest glaciers on Mt. Hood (White River, Newton-Clark, Eliot, Coe, Ladd, Sandy, and Reid) that have area records extending back to 1907 (Jackson and Fountain, 2007) lost as a whole 57±3 % of their area since 1907 and 39.8±1.7% of their area since 2000 (Table 2, Fig. 4). From 2000 to 2023, the rate of area loss was 1.73±0.17 % yr^{-1}, about six times faster than the 1907-2000 rate of 0.31±0.02 % yr^{-1} (Table 2). Ladd Glacier underwent the greatest rate of retreat in the 21st century, which was associated with the partial loss of its accumulation zone (Table 2; Fig. 3E, F). Conversely, White River Glacier had the greatest 20th century rate of retreat (Table 2), which has been previously attributed to the development of fumaroles by 1907 that reduced its accumulation area (Lillquist and Walker, 2006). Coe Glacier underwent the greatest increase in retreat rate in the 21st century about 12 times faster than its 20th century rate of area loss (Table 2).

Glacier	1907 Area km^2 (uncert)	2000 Area km^2 (uncert)	2023 Area km^2 (uncert)	1907-2023 % Δ Area (uncert)	2000-2023 % Δ Area (uncert)	1907-2000 % yr^{-1} (uncert)	2000-2023 % yr^{-1} (uncert)
White River	1.04 (0.11)	0.44 (0.03)	0.271 (0.019)	74 (13)	38.4 (3.8)	0.62 (0.08)	1.67 (0.17)
Newton-Clark	2.06 (0.15)	1.54 (0.11)	0.975 (0.068)	53 (10)	36.7 (3.7)	0.27 (0.03)	1.60 (0.16)
Eliot	2.03 (0.16)	1.66 (0.12)	0.912 (0.064)	55 (10)	45.1 (4.5)	0.18 (0.02)	1.55 (0.15)
Coe	1.41 (0.13)	1.21 (0.08)	0.696 (0.049)	51 (12)	42.5 (4.1)	0.15 (0.02)	1.85 (0.18)
Ladd	1.07 (0.11)	0.71 (0.05)	0.235 (0.016)	78 (12)	66.9 (6.6)	0.36 (0.04)	2.94 (0.29)
Sandy	1.61 (0.17)	1.02 (0.07)	0.631 (0.044)	61 (13)	38.1 (3.7)	0.39 (0.05)	1.71 (0.17)
Reid	0.79 (0.13)	0.53 (0.04)	0.417 (0.029)	47 (18)	21.3 (2.2)	0.35 (0.06)	0.90 (0.09)
Seven combined	9.98 (0.37)	7.11 (0.21)	4.282 (0.127)	57 (3)	39.8 (1.7)	0.31 (0.02)	1.73 (0.17)

Table 2: Area for seven largest glaciers on Mt. Hood and their change (Δ) in area and rate of change expressed as percent. 1907 and 2000 areas are from Jackson and Fountain (2007).

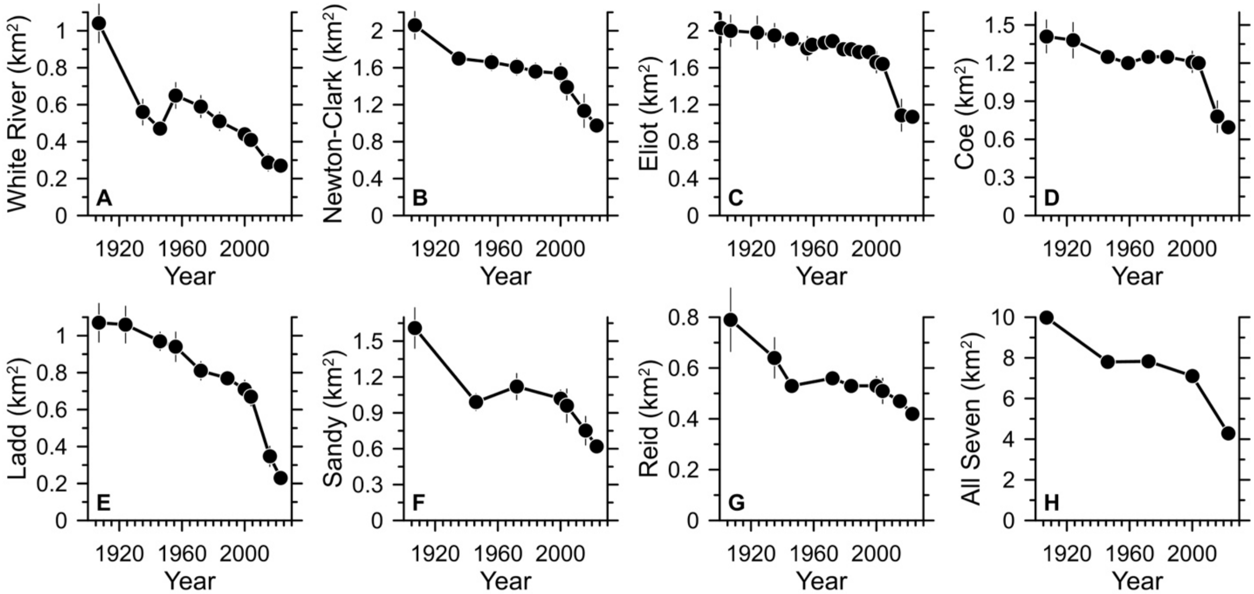

Figure 4: Glacier area from 1907 (or 1901 for Eliot Glacier) to 2004 from Jackson and Fountain (2007), 2015 or 2016 from Fountain et al. (2023), and 2023 (new data), with combined area noted in the lower right. Uncertainty noted by vertical bars; note that the uncertainty on the combined record is smaller than the symbol size. A. White River Glacier. B. Newton-Clark Glacier. C. Eliot Glacier. D. Coe Glacier. E. Ladd Glacier. F. Sandy Glacier. G. Reid Glacier. H. Combined record of seven glaciers.

The 21st century rate of total area loss for these seven glaciers (1.73±0.17 % yr^{-1}) exceeded the prior maximum rate of area loss from 1907-1946 (0.56±0.02 % yr^{-1}) by a factor of about three (Fig. 5H). Five of the seven glaciers had individual 2000-2023 recession rates faster than their 1907-1946 rates (Fig. 5B-F). Reid Glacier's 2000-2023 rate of recession was 0.90±0.09 % yr^{-1} while its 1907-1946 rate was 0.84±0.14 % yr^{-1} (Fig. 5G). White River Glacier retreated at 1.67±0.17 % yr^{-1} 2000-2023 whereas its 1907-1946 rate was 1.41±0.19 % yr^{-1} (Fig. 5A).

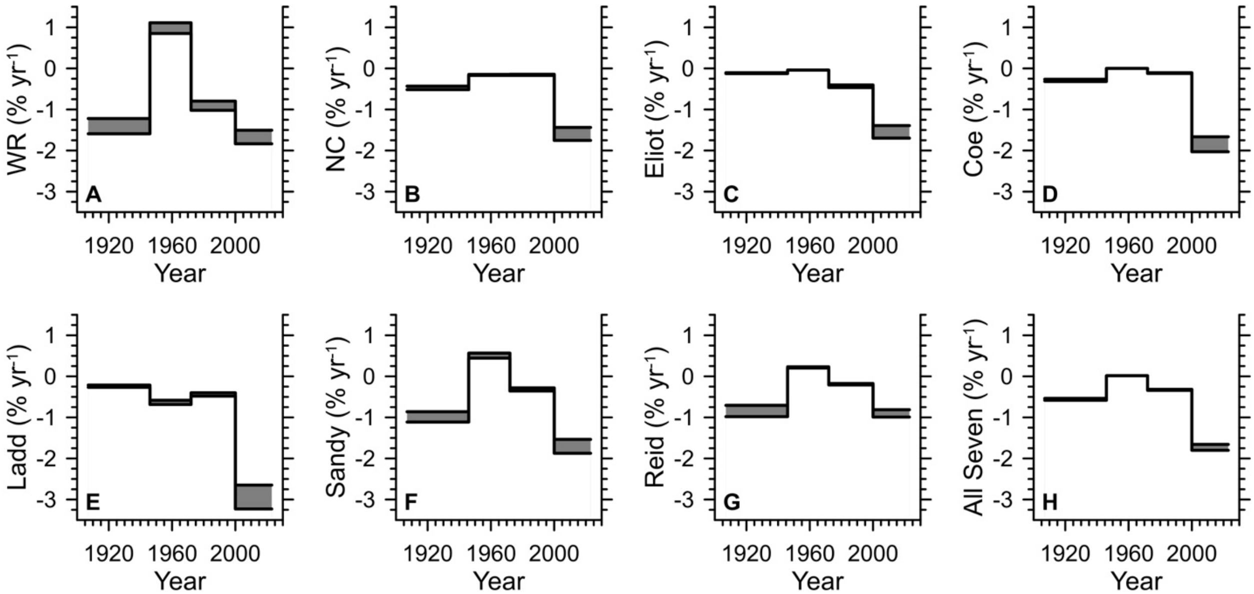

Figure 5: Area change with respect to preceding ice area expressed as % yr^{-1} (yr = year) for seven glaciers calculated from Jackson and Fountain (2007) (1907-2000) and 2023 observations, with combined rate in the lower right. Gray shading shows the uncertainty. A. White River (WR) Glacier. B. Newton-Clark (NC) Glacier. C. Eliot Glacier. D. Coe Glacier. E. Ladd Glacier. F. Sandy Glacier. G. Reid Glacier. H. Combined record of seven glaciers.

Updating the length records for White River, Newton-Clark, Eliot, Coe and Ladd glaciers of Lillquist and Walker (2006) to 2023 (Table S1) found that four of these glaciers had now lost ~35% (White River) to ~42% (Eliot) of their 1901 length while Ladd Glacier had lost ~65% of its 1901 length (Fig. 6C). Regression of relative-length change identified significant ($p < 0.05$) relationships (Table 3) with both 30-year and 15-year backward-running mean-annual, May-October and June-September temperature change relative to the 1895-1924 mean (Fig. 6B). Conversely, no significant relationships (Table 3) were found with either 30-year or 15-year backward-running mean-annual, November-April or October-May precipitation change relative to the 1895-1924 mean (Fig. 6A). Note that Newton-Clark and White River glaciers are missing an observation for 1928 while Ladd is missing the year 1959; this impacted the number of observations for determining regression significance.

Lillquist and Walker (2006) found that the ~560 m retreat of White River Glacier from 1901 to 1938 was facilitated by the development of fumaroles whereas the ~920 m retreat of Ladd Glacier from 1984 to 1989 was due to recession over a cliff (Table S1). To test the significance of these non-climate related recessions on the correlation of these two glaciers' lengths with the records of three different temperature seasons over two backward-running means, we removed these intervals of retreat from the length records and recalculated correlations. White River Glacier's retreat was still significantly correlated ($p < 0.05$) with 30-year and 15-year backward-running mean-annual, May-October and June-September temperature changes and their r^2s changed only at the third decimal place. Ladd Glacier's retreat was still significantly correlated ($p < 0.05$) with the six temperature-change records, albeit r^2s (0.56-0.83) were generally lower than for the full-length records (0.65-0.82).

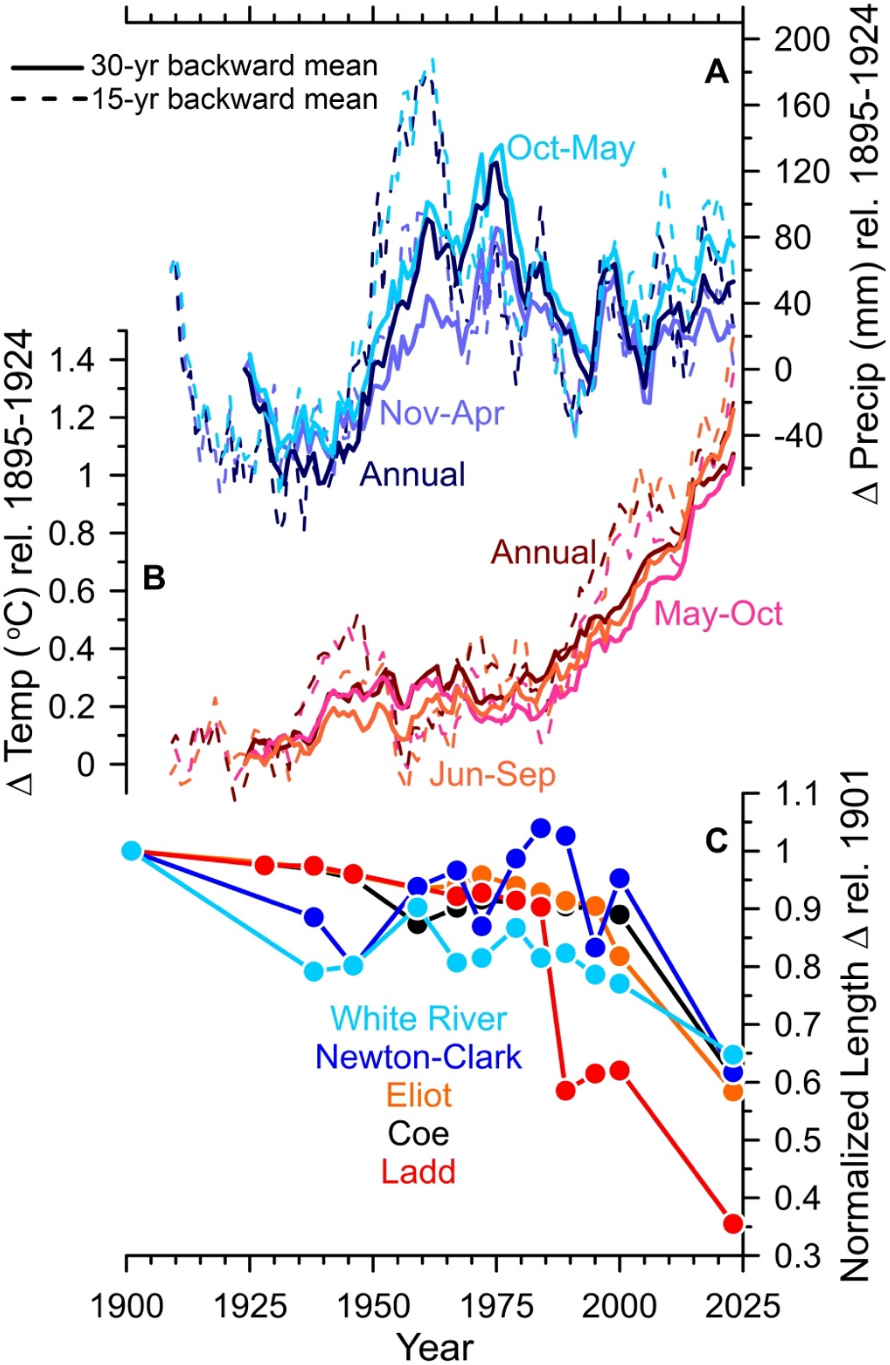

Figure 6: Hood River County climate change (NOAA) and Mt. Hood glacier length change (Lillquist and Walker, 2006). A. 30-year (solid) and 15-year (dashed) backward-running mean for total annual (dark blue) and November-April (light blue) precipitation relative to 1895-1924 average. B. 30-year (solid) and 15-year (dashed) backward-running mean for mean-annual (dark red) and May-October (pink) temperature relative to 1895-1924 average. C. Change in glacier length normalized to 1901 length (Lillquist and Walker, 2006) from 1901 to 2023 for White River (light blue), Newton-Clark (blue), Eliot (orange), Coe (black), and Ladd (red) Glaciers.

Glacier (30 yr)	Ann T	M-O T	J-S T	Ann P	N-A P	O-M P
White River	**0.63**	**0.67**	**0.69**	0.02	0.02	0.01
Newton-Clark	**0.42**	**0.58**	**0.46**	0.04	0.08	0.02
Eliot	**0.93**	**0.94**	**0.95**	0.07	0.05	0.07
Coe	**0.87**	**0.90**	**0.90**	0.16	0.09	0.16
Ladd	**0.82**	**0.73**	**0.77**	0.06	0.05	0.04
Glacier (15 yr)	**Ann T**	**M-O T**	**J-S T**	**Ann P**	**N-A P**	**O-M P**
White River	**0.78**	**0.76**	**0.70**	0.13	0.24	0.08
Newton-Clark	**0.50**	**0.62**	**0.50**	0.02	0.14	<0.01
Eliot	**0.79**	**0.85**	**0.86**	<0.01	<0.01	0.02
Coe	**0.60**	**0.66**	**0.72**	0.05	0.01	0.10
Ladd	**0.73**	**0.67**	**0.65**	<0.01	0.02	0.01

Table 3: Regression results (r^2) for 30-year (top) and 15-year (bottom) backward-running means of temperature (T) and precipitation (P) relative to normalized glacier length. Bold indicates significant results where p is <0.05. Ann = Annual, M-O = May-October, J-S = June-September, N-A = November-April, O-M = October-May.

4 Discussion

In the 21st century, every glacier on Mt. Hood has lost area, resulting in about 40% glacierized area loss since 2000, with a minimum rise in terminus elevation of ~150 m on average over the last 20 years. This rapid area loss combined with a rise in terminus elevation are indicative of large mass balance losses (e.g., Haeberli and Hoelzle, 1995; Pelto and Brown, 2012; Pelto, 2016; Hoelzle et al., 2023). Such clear glacier retraction and negative mass balance stand at odds with the Menounos et al. (2019) finding of near-neutral mass change for glaciers on Mt. Hood from 2000 to 2018. We note that their study lacked ground truthing of their geodetic measurements in Oregon, which combined with the high and growing debris cover on many of Mt. Hood's glaciers (e.g., Fig. 3H), could explain this disagreement. Furthermore, Florentine et al. (2024) found that not accounting for glacier area change when measuring geodetic mass balance reduces the mass-balance-change signal in western North American glaciers, with greater area loss leading to greater mass-balance bias. Here, our field observations clearly show large-scale glacier loss, consistent with the 21st-century retreat of glaciers around the globe (Zemp et al., 2015) and in agreement with the cumulative mass loss of benchmark glaciers to the north of Mt. Hood in Washington State (O'Neel et al., 2019; Pelto, 2023; World Glacier Monitoring Service, 2022).

The combined retreat for Mt. Hood's seven largest glaciers over the first 23 years of the 21st century stands out as unparalleled since at least the beginning of the 1900s (Fig. 4, 5), similar to the findings of Beason et al. (2023) for glaciers on Mt. Rainier in Washington and agreeing with a shift to more negative annual mass balance for western United States benchmark glaciers since 1990 (O'Neel et al., 2019). We compare Mt. Hood's rate of glacier recession of 1.73±0.17 % yr^{-1} from 2000 to 2023 (seven largest glaciers; Table 2) and 2.40±0.02 % yr^{-1} from 2015/2016 to 2023 (all glaciers; Table 1) to other western United States glacierized ranges with comparable records of actively flowing glacier area. To the north in Washington State (Fig. 1A), Mt. Rainier glaciers retreated at 0.59±0.05 % yr^{-1} from 1994 to 2021 and 0.69±0.05 % yr^{-1} from 2015 to 2021 (Beason et al., 2023) while glaciers in the Olympic Mountains retreated at 1.44±0.02 % yr^{-1} from 1990 to 2015 and 2.75±0.04 % yr^{-1} from 2009 to 2015 (Fountain et al., 2022). To the northeast in Montana (Fig. 1A), Glacier National Park glaciers receded at ~0.77 % yr^{-1} from 1998 to 2015 and ~0.83 % yr^{-1} from 2005 to 2015 (Fagre et al., 2017). Lastly, to the south in California (Fig. 1A), glaciers in the Trinity Alps retreated at 3.89±0.02 % yr^{-1}, between 1994 and 2015, leading to near complete deglaciation of the mountain range by 2015 (Garwood et al., 2020). Thus, the rates of glacier retreat on Mt. Hood in the 21st century are some of the highest rates in the western United States, but have yet to exceed the 2009-2015 rate in the Olympic Mountains, where the rate-change record ended in 2015, or the rate in the Trinity Alps, where the record ended in 2015 with near complete deglaciation.

We now return to our finding of unprecedented 21st century retreat of glaciers on Mt. Hood based on mapping only actively flowing glacier ice and comparing 2023 areas to equivalent actively flowing glacier areas in 2015/2016, 2000 and earlier years. If we had followed the other interpretation of what constitutes a glacier and included all stagnant ice in the 2023 glacier extents, would retreat in the 21st century still be unprecedented? As a test, we added to the 2015/2016 and 2023 areas of glaciers (Table 1) the area of additional snow/ice bodies noted in the Supplement mapped by Fountain et al. (2023). We conservatively assumed that these snow and ice bodies did not change in area from 2015/2016 to 2023, which was not the case as some of these ice bodies disappeared (see Supplement). With this additional fixed area, the change in glacierized/perennial snow area on Mt. Hood from 2015/2016 to 2023 was >14±1% versus the change in area for actively flowing glaciers of 18±1%. We thus conclude that defining a glacier as a flowing ice body does not greatly change the percentage of glacier area loss in the last seven to eight years.

As another test, we looked at the seven glaciers with records back to 1907 (Fig. 4, 5) (Jackson and Fountain, 2007). We added their peripheral 2015/2016 stagnant buried ice/stagnating ice/perennial snowfield area that Fountain et al. (2023) mapped as separate from the contiguous flowing glacier area to our 2023 glacier areas (Table S2). This additional area was 1.085±0.041 km^2. About 0.718 km^2 (~66%) of this area was in the two buried ice bodies that were explicitly mapped as separate from and not parts of Coe and Eliot glaciers as of 2016 (Fountain et al., 2023). Another 12% of this area was in stagnating ice/perennial snowfields that had separated from Ladd Glacier as of 2016. We then compared these new larger glacier/ice/snow areas to the 2000 areas for these seven glaciers, noting that this is not an equal comparison. First, we again assumed that the areas of these peripheral snow/ice bodies did not change in the last seven to eight years, which is not the case. Second, the 2000 areas of these glaciers only included contiguous actively flowing glacier ice and explicitly did not include such peripheral snow ice/bodies or contiguous stagnant ice (Jackson and Fountain, 2007). With these assumptions, we found that these seven glaciers lost area at >1.07±0.1 % yr^{-1} 2000-2023, which is still unprecedented with respect to 20th century average rate (0.31±0.03 % yr^{-1}) and the fastest 20th century rate (0.56±0.02 % yr^{-1}) (Table S2). Similarly, the retreat of Eliot, Coe, and Ladd glaciers remained unparalleled relative to both the average and fastest 20th century rates despite containing 78% of the non-flowing ice area added to 2023 extents (Table S2). White River's rate of area loss was also unequaled with respect to the 20th century average and remained within uncertainty of its fastest 20th century rate (Table

S2). Newton-Clark and Sandy glaciers likewise still had unmatched rates of retreat in the 21st century whereas Reid's rate did not change (no additional ice added) (Table S2). Therefore, our finding of unprecedented 21st century retreat of glaciers on Mt. Hood does not depend on how one defines a glacier.

In the last 20 years, Glisan Glacier on Mt. Hood has retreated to a 2023 area of ~0.009 km^2 and ceased to be an actively flowing glacier, joining Palmer Glacier in this former-glacier status (Table 1; Supplement). We find that two other glaciers are nearing this reclassification as former glaciers: Zigzag and Coalman (Supplement). At ~0.1 km^2, Zigzag Glacier was only distinguishable from stagnant ice due to the presence of a few crevasses that have yet to start melting in on themselves (i.e., movement is keeping them open). Coalman Glacier at ~0.06 km^2 (Table 1) is now below the area threshold of 0.1 km^2 used by the U.S. Geological Survey to distinguish active glaciers (Fagre et al., 2017), but is above the 0.01 km^2 threshold used in global inventories (Pfeffer et al., 2014). More importantly, Coalman still showed evidence of flow with one active crevasse. With these two glaciers losing 40-42% of their area in the last seven to eight years (Table 1), we predict that in the near future they will stagnate and become former glaciers. Langille Glacier also lost >40% of its area while Ladd Glacier lost about a third of its area, both in the last seven years (Table 1). If this rapid retreat continues, we predict that Langille and Ladd glaciers will be the next Mt Hood glaciers, after Zigzag and Coalman, to stagnate.

Because of the significant relationship between the change in glacier length for five of Mt. Hood's glaciers and the change in regional temperature up to 2023 (Fig. 6B, C; Table 3), we argue that the retreat of glaciers over the last ~120 years reflects regional climate warming (Roe et al., 2016, 2021). We do not find a similar relationship with precipitation (Fig. 6A, C; Table 3), which does not necessarily mean that precipitation changes are not important but rather that no long-term trend exists for precipitation. A Mt. Hood glacier-length-temperature relationship agrees with mass-balance-temperature relationships for glaciers to the north in Washington State and for western United States benchmark glaciers. Pelto (2018) found significant relationships between annual mass balance with June-September temperature for 11 glaciers in Washington. O'Neel et al. (2019) noted the lack of a winter-mass-balance trend for the four benchmark glaciers in Washington and Alaska and a positive winter-mass-balance trend for the one glacier in Montana, meaning these glaciers' negative annual-mass-balance trends were being driven by summer temperatures.

We suspect that the lack of a Mt. Hood glacier length-temperature relationship for the 20th century in the Lillquist and Walker (2006) study may partly reflect their methodology. Lillquist and Walker (2006) used a 5-year running average for both temperature and precipitation, shorter than the 11- to 30-year response time for glaciers like those on Mt. Hood (Pelto and and Hedlund, 2001; Pelto, 2016), which we approximate with our 30-year and 15-year backward-running means.

Frans et al. (2016) modeled the evolution of Newton-Clark, Eliot, Coe, and Ladd glaciers from 2000 to the end of the century under intermediate (RCP4.5) and high (RCP8.5) emission scenarios, with 10 simulations per emission scenario. From 2000 to 2025, they simulated a 10-30% loss in glacier area regardless of emission scenario. In contrast, we find that the these four glaciers lost 30-50% of their combined area between 2000 and 2023. This means that glacier recession on Mt. Hood in the 21st century has proceeded at a faster rate than simulated for even the highest emission scenario. This also raises concerns over the persistence of Mt. Hood glaciers at all in the 21st century. Frans et al. (2016) modeled continued glacier presence on Mt. Hood in 2100 even under RCP8.5 forcing. However, the observed glacier retreat in the last 20 years has equaled to exceeded by 67% the maximum loss simulated under RCP8.5 emissions for the last 20 years.

We hypothesize that the observed faster retreat of glaciers on Mt. Hood relative to their simulated retreat may, in part, be due to climate-related weather phenomena that had yet to occur at the time of the model forcing of Frans et al. (2016). In 2015, Oregon experienced the lowest spring snowpack ever recorded (Mote et al., 2016), which was followed by the warmest summer ever recorded (U.S. NOAA, 2024, https://www.ncei.noaa.gov/access/monitoring/climate-at-a-glance/). Such extreme events are absent from the Frans et al. (2016) forcing and may have significantly impacted glacier mass balance (Pelto, 2018). Likewise, the June 2021 Pacific Northwest heatwave was one of the six most extreme events ever recorded on the planet (Thompson et al., 2022), which would have negatively impacted glacier mass balance (Pelto et al., 2022). In 2020, more forest area burned in the Oregon Cascades than all 36 prior years of record combined (Abatzoglou et al., 2021) while the 2021 heatwave further exacerbating forest fires (Jain et al., 2024). Since 2015, fire-smoke particulates have been rising in Oregon (Burke et al., 2023). The particulates from these fires accumulate on Oregon glaciers, where they reduce albedo and increase ablation (Kaspari et al., 2015; Allgaier et al., 2022). Given the under projection of glacier change on Mt. Hood and given the analogous-regional snow-drought and heatwave impacts (Mote et al., 2016; Philip et al., 2022; Thompson et al., 2022) and rise in fire-smoke particulates (Neff et al., 2012; Kaspari et al., 2020) in both Washington and British Columbia, new assessments of recent (e.g., post 2015) glacier retreat in Washington's Olympic, Central Cascade, and North Cascade ranges and in the ranges of British Columbia where similar glacier model simulations have been conducted (Clarke et al., 2015; Frans et al., 2018) could be used to test the accuracy of these model results for the first quarter of the 21st century.

Our finding that the Frans et al. (2016, 2018) model under simulates recent glacier recession on Mt. Hood is of vital import to downstream communities. The U.S. Bureau of Reclamation conducted a Hood River Basin Study that utilized the same model as Frans et al. (2016, 2018). This federal study projected only a 1-4% decline in Mt. Hood glacier area through 2060 (U.S. Bureau of Reclamation, 2015). We argue that this study, which underlies water management plans for the Hood River Basin and reliant agriculture (Thieman et al., 2021), contains overly optimistic simulations of future glacier retreat, and that water resource managers who rely on this federal study are ill-prepared for future late-summer declining stream flow and rising instream temperatures. Thieman et al. (2021) noted that glacier disappearance in the Hood River Basin would be catastrophic for certain salmon and steelhead populations (fall Chinook, summer steelhead, and Coho). Our findings imply this this could happen sooner than is projected in the current Hood River Basin plans that have 2100 as the earliest possible year for deglaciation. The cold instream temperatures of Hood River are due to glacier meltwater and afford the river its diversity in salmon, steelhead, and bull trout (Thieman et al., 2021), which deglaciation of the river basin in this century would upset. Rapid glacier recession also imperils unique, and recently discovered, microbiomes on Mt Hood that only exist at glacier-fed springs on the volcano (Miller et al., 2021). As such, glacier-dependent ecosystems on Mt. Hood may be more at risk than previously surmised. However, the most visible impact, and the one affecting the greatest number of people in the near future, will likely be on the orchards of Hood River and Wasco counties whose orchards are the most important component of their economies (Columbia Gorge Fruit Growers, 2024, http://www.cgfg.org/information/crops-information).

5 Conclusions

We documented from field observations that the glaciers of Mt. Hood retreated and most likely lost mass, in the 21st century, losing ~40% of their area (seven largest glaciers) in the last 23 years and ~18% of their area (all glaciers) in the last seven to eight years at unprecedented rates with respect to the last 120 years (1.73±0.17 % yr^{-1} and 2.40±0.02 % yr^{-1}, respectively). This is contrary to geodetic mass balance change suggested by remote-sensing data alone (Menounos et al., 2019). The rate of area loss in the 21st century has proceeded about three times faster than the fastest rate of the 20th century and about six times faster than the average 20th century rate. Two glaciers have ceased to be glaciers (Glisan, Palmer) with another four glaciers rapidly losing area towards this reclassification (Zigzag, Coalman, Langille, Ladd). The century-scale retreat of Mt. Hood glaciers can be attributed to a warming climate, with regional 30-year mean temperature 1.1-1.3ºC warmer and 15-year mean temperature 1.3-1.5ºC warmer than the 1895-1924 mean. As such, the warming climate of the last 120 years, especially the last 20 years, has significantly impacted the glacier coverage of Mt. Hood, with this recession continuing unless and until the sign of multi-decadal temperature change is reversed.

Data availability

The data referred to in this paper have all been provided within the tables and figures in the main text and supplement or as an asset available on a FAIR-aligned data repository (available at https://doi.org/XX.XXXX/XXXXXXXXX-XXXX-XXX).

Author contributions

The author contributions, following the CRediT authorship guidelines, are as follows: NB-F, SJB, and AEC: conceptualization; NB-F, SJB, WCS, and AEC: methodology; NB-F, SJB, WCS, and AEC: validation; NB-F, SJB, WCS, MT, and AEC: analysis; NB-F, SJB, WCS, MT, DHR, and AEC: investigation; NB-F, SJB, WCS, DHR, and AEC: resources; NB-F, SJB, WCS, MT, and AEC: data curation; AEC: original draft; NB-F, SJB, WCS, MT, DHR, and AEC: review and editing; NB-F, SJB, WCS, MT, DHR, and AEC: visualization; NB-F, SJB, WCS, MT, DHR, and AEC: administration; NB-F, SJB, WCS, MT, DHR, and AEC: funding acquisition.

Competing interests

The authors declare that they have no conflict of interest.

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