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The Response of Taku and Lemon Creek Glaciers to Climate

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Abstract

Surface height and mass balance changes of Taku and Lemon Creek Glaciers within Juneau Icefield, Alaska, are examined to determine the relationship between these parameters and climatic forcing. Both Taku and Lemon Creek Glaciers are located in a maritime climate, but they behave very differently. Taku Glacier, a former tidewater glacier, is ~70 times larger than Lemon Creek Glacier, and its dynamics are largely a result of the post-tidewater glacier cycle which causes insensitivity to climate change during advance phases. Taku Glacier is advancing at present but its surface height, mass balance, and rate of advance have decreased since 1988. Lemon Creek Glacier, a small alpine glacier, is retreating and has maintained a negative mass balance since 1953. Mass balance records from both Taku and Lemon Creek Glaciers correlate well with temperature and show little correlation with precipitation. The mass balance of these glaciers also correlates with the Pacific Decadal Oscillation (PDO). However, the Lemon Creek Glacier mass balance record shows a stronger correlation with the PDO than that of Taku Glacier. Taku Glacier shows a longer delay in response to warming in Southeast Alaska likely due to post-tidewater glacier dynamics, its large accumulation area ratio (AAR), and its size.

Introduction

Juneau Icefield provides an ideal location for the study of glacier response to climatic change. Alaska contains the largest ice mass outside of Greenland and Antarctica (Meier and Dyurgerov, 2002). Alaska's temperate glaciers respond sensitively to climate change and are an important consideration for sea level rise projections (Meier, 1993; Hodge et al., 1998; Hooker and Fitzharris, 1999; Meier and Dyurgerov, 2002). Ablation of Alaskan glaciers contributes more to global sea level rise than any other glaciated region measured with the exception of the polar ice caps (Dyurgerov and Meier, 1997; Arendt et al., 2002). In turn, glaciers in the mountain ranges of southeast Alaska contribute most to global sea-level rise statewide (Larsen et al., 2007). The ablation season for southeast Alaska lengthened by 30 days between 1988 and 1998 (Arendt et al., 2002), and an increase in ablation season temperature has been determined to be a major factor driving glacier recession (Ramage and Isacks, 2003).

Juneau Icefield is the fifth largest icefield in the western hemisphere and spans a 240 km distance between Juneau, Alaska, and Atlin, British Columbia (Fig. 1). It extends from 58°20′ to 59°30′ north latitude and covers an area of approximately 4000 km^2 (Sprenke et al., 1999). During the period 1949–1998, one of the highest annual mean temperature increases in Alaska (2.0 °C) occurred directly over Juneau Icefield (Stafford et al., 2000).

This study focuses on two temperate, maritime glaciers in Juneau Icefield: Taku and Lemon Creek Glaciers. Here, we define maritime glaciers as those influenced by a coastal, maritime climate, but not necessarily terminating in water. In general, maritime glaciers are strongly influenced by high winter snowfall (Hooke, 2005). For example, mass balance changes of maritime glaciers often do not correlate well with temperature alone; however, such correlations are considerably improved by including winter precipitation (Hooke, 2005). In the case of Taku Glacier, glacier behavior is also the result of tidewater glacier cycle dynamics (explained in greater detail in "Study Area" section).

Advance and retreat of temperate glaciers are affected by temperature and precipitation, both of which are linked to large-scale atmospheric patterns. The Pacific Decadal Oscillation (PDO) is a large-scale circulation pattern that has a direct impact on glaciers in southeast Alaska (Mantua et al., 1997). The PDO is characterized by decadal oscillations of anomalous sea level pressures (SLP) in the Pacific Ocean between 20°N and 60°N (negative SLP anomalies during positive PDO phases). The PDO has a strong impact on sea surface temperature (SST), air temperature, and precipitation along the Gulf of Alaska (Mantua et al., 1997). The positive phase of the PDO is associated with an intensification of the Aleutian Low, warm SSTs and air temperatures (Fig. 2), below average winter precipitation (Fig. 3), and negative annual glacier mass balance trends in Southeast Alaska (Mantua et al., 1997; Bitz and Battisti, 1999). The negative phase of the PDO is associated with a weak Aleutian Low, cool SSTs and air temperatures, above average winter precipitation, and positive annual glacier mass balance trends in Southeast Alaska (Mantua et al., 1997; Bitz and Battisti, 1999). Especially important is the large regime shift in Pacific climate in 1977 (Mantua et al., 1997; Hodge et al., 1998; Stephens et al., 2001), which is evident in the meteorological and mass balance data presented in this paper. This shift consisted of a 1.5 °C warming of the eastern equatorial Pacific Ocean, and a 1.0 °C cooling of the North Pacific Ocean which occurred as a result of a deepening in sea level pressure in the North Pacific (Stephens et al., 2001). The 1977 regime shift has affected the mass balance of Wolverine Glacier in Alaska and South Cascade Glacier in Washington (Hodge et al., 1998).

In this study we investigate recent changes at Taku and Lemon Creek Glaciers, and the various climatic parameters which

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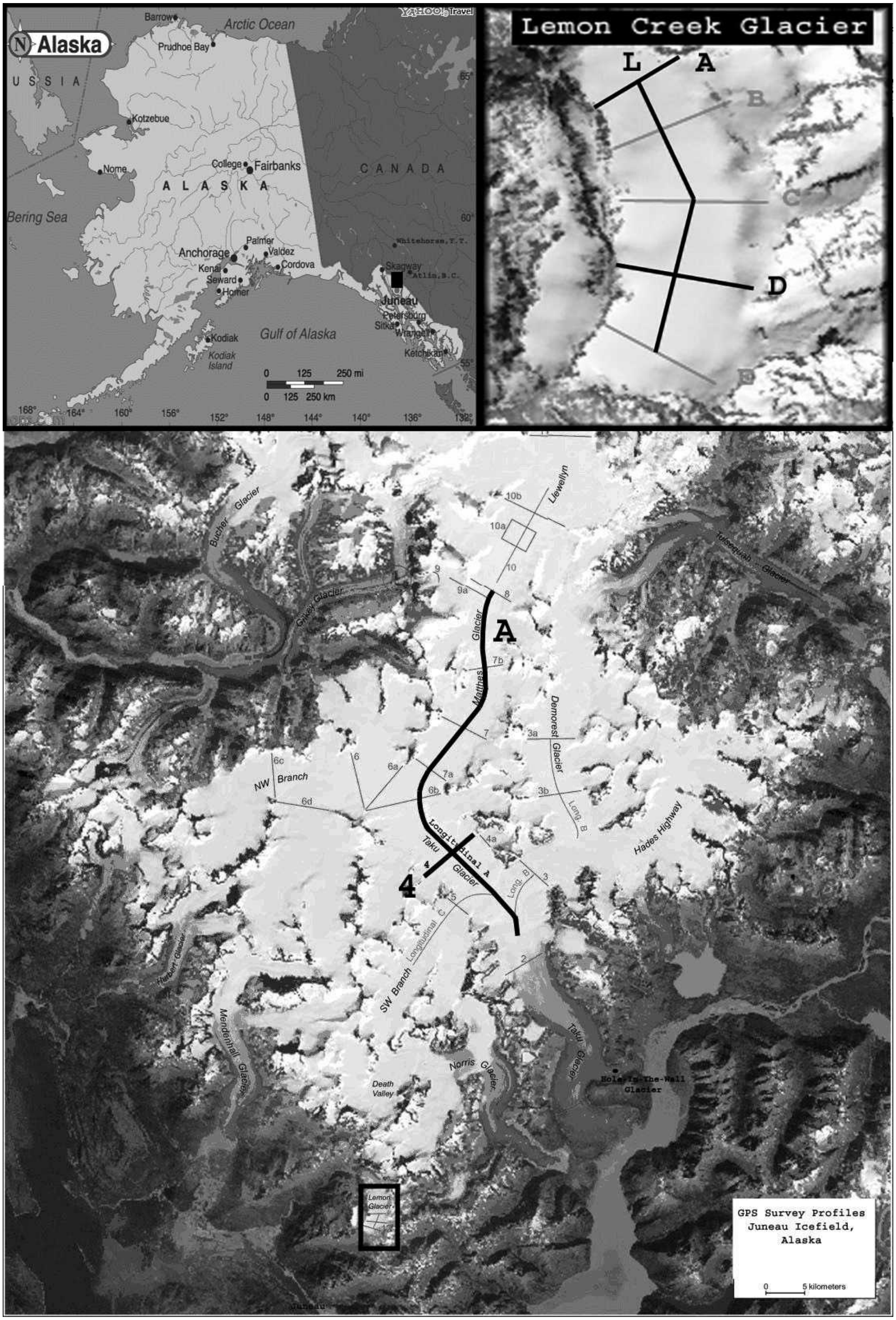

FIGURE 1. Top left panel: Map of Alaska with location of Juneau Icefield (black filled rectangle). Main panel: Locations of the major transverse and longitudinal survey profiles on Juneau Icefield, Alaska. Profiles discussed in the paper (Profiles 4 and A) are shown in bold lines. Top right panel: Enlarged image of Lemon Creek Glacier survey profile locations (location shown in black open rectangle on main panel).

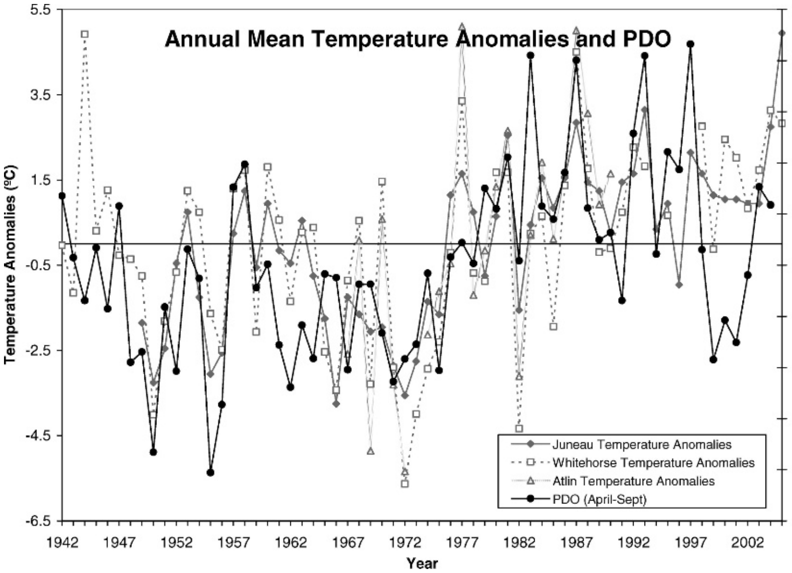

FIGURE 2. Juneau, Atlin, and Whitehorse annual mean temperature anomalies and the ablation season (April–September) Pacific Decadal Oscillation (PDO) record. PDO is a large-scale circulation pattern that impacts glaciers in southeast Alaska and is characterized by decadal oscillations of anomalous sea level pressures (SLP) in the Pacific Ocean between 20°N and 60°N.

may have influenced these changes. We determine surface height and mass balance data from Taku and Lemon Creek Glaciers and compare these with temperature and precipitation records from weather stations near Juneau Icefield. Glacier surface height and mass balance data are also are compared with the PDO record. We integrate analyses of meteorological data (temperature and precipitation), glaciological data (mass balance and survey), and a climatic index (PDO) to improve the understanding of past and projected future glacier behavior changes in Southeast Alaska.

Previous Work

Numerous glaciological studies have been conducted on Juneau Icefield, largely due to well-established logistics provided by the Juneau Icefield Research Program (JIRP). JIRP has been collecting annual mass balance and survey data since 1946. It should be noted that these measurements are made by different people annually, which may introduce significant errors. Other error sources are discussed later in the "Methods" section. Many studies provide glaciological information about the Juneau Icefield (e.g., Miller, 1951, 1954, 1957; Wu and Christensen, 1964; Miller and Anderson, 1974; Pelto, 1987; Pelto and Miller, 1990; Daellenbach and Welsch, 1993; Marcus et al., 1995; Nolan et al., 1995; Miller and Pelto, 1999; Caldwell, 2005). For example, a study of Lemon Creek Glacier reported an ice-margin retreat of 700 m, an area loss of 10.3%, and a glacier volume loss of 14.6% between 1957 and 1989 (Marcus et al., 1995). This study indicated that the ice-margin retreat and negative mass balance of Lemon Creek Glacier are, at least in part, a result of increasing temperature. Several studies have shown that changes in the position of the Arctic Front are apparent in Juneau Icefield glaciological records (Miller and Anderson, 1974; Pelto and Miller, 1990).

Prior research most relevant to the present study includes recent mass balance measurements and glacier modeling research (Beedle, 2005; Bhatt et al., 2007; Pelto et al., 2008). Beedle (2005) correlated mass balance records from Taku, Lemon Creek, Wolverine, and Gulkana Glaciers in Alaska with National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data and several climatic indices including the Arctic Oscillation (AO), North Pacific Index (NPI), Southern Oscillation Index (SOI), Pacific-North American Pattern (PNA), and others. Beedle (2005) concluded that increased ablation season temperature is the overall primary climatic driver

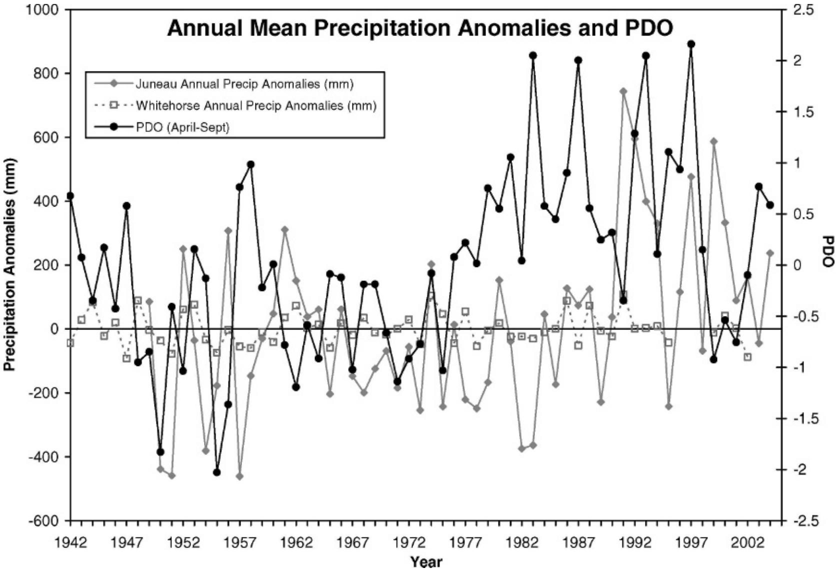

FIGURE 3. Annual precipitation anomalies from Juneau and Whitehorse and the ablation season Pacific Decadal Oscillation (PDO) record.

of glacier changes seen in southeast Alaska since 1989. Moving window correlations show that the PDO was more strongly correlated to Juneau ablation season temperature prior to 1989 than after 1989 (Beedle, 2005). Another recent study indicates that the flow of Taku Glacier near the equilibrium line was in a state of equilibrium during the period from 1950 to 2006 (Pelto et al., 2008). Prior to 1998, Taku Glacier was thickening near its equilibrium line but has since been thinning as a result of mass balance decrease (Pelto et al., 2008). Bhatt et al. (2007) developed a model that simulated past and estimated future mass balances of Hubbard and Bering Glaciers in Alaska. Over the period 2010 to 2030, both glaciers are projected to have increased accumulation on upper glacier areas and increased ablation on lower glacier areas (Bhatt et al., 2007). Such a model applied to Taku Glacier would further our understanding of how present changes may result in future negative mass balance in this part of Alaska, and will be included in future work.

Finally, several recent papers discuss detailed observations and measurements of Taku Glacier. These studies indicate the importance of tidewater glacier dynamics on Taku Glacier's present behavior (Motyka and Begét, 1996; Motyka et al., 2002; Motyka and Echelmeyer, 2003; Kuriger et al., 2006; Motkya et al., 2006; Pelto et al., 2008) and are discussed in detail below.

Study Area

TAKU GLACIER

Taku Glacier is the largest glacier draining Juneau Icefield (Fig. 1). It has an area of 700 km^2 and is approximately 60 km long. The terminus forms a piedmont lobe 9 km wide (Motyka and Echelmeyer, 2003). Airborne altimetry indicates that Taku Glacier is one of only a few glaciers in Alaska and Northwest Canada that has thickened over the last half century (Echelmeyer et al., 1996; Arendt et al., 2002; Motyka and Echelmeyer, 2003). Previous studies show Taku Glacier to be the one of the deepest temperate glaciers ever measured, with a maximum ice thickness of 1477 m (Nolan et al., 1995), and 40 km of Taku Glacier's 60-km-long centerline lying below sea level (Motyka and Echelmeyer, 2003). Taku Glacier has advanced over 7 km since the late 19th century (Motyka and Post, 1995; Motkya et al., 2006) and is the only glacier on Juneau Icefield that is in a state of advance (Nolan et al., 1995). This terminal advance generally increased from 8 m yr^{-1} in the mid-1990s to 73–110 m yr^{-1} measured in summer 2001 and 2002 (Motyka and Echelmeyer, 2003).

Present advance of Taku Glacier is partly attributed to its post-calving phase in the tidewater glacier cycle (Post, 1975; Meier and Post, 1987; Post and Motyka, 1995; Motyka and Begét, 1996; Kuriger et al., 2006). The tidewater glacier cycle generally includes the following phases: a stable phase with the terminus at the head of the fjord, a slow advance phase, a stable phase of extended position, and finally rapid retreat (Paterson, 1994). It is important to note that the tidewater glacier cycle is not directly related to climatic changes, and therefore nearby glaciers may behave very differently (Meier and Post, 1987; Paterson, 1994).

Taku Glacier had a calving ice front until 1948, when the fjord began to fill in with glaciomarine sediment (Post and Motyka, 1995; Motyka and Echelmeyer, 2003). The terminal moraine shoal was raised above sea level as glacier advance forced proglacial sediment in front of the terminus and resulted in the formation of push moraines greater than 20 m above sea level (a.s.l.) by 2004 (Motyka and Echelmeyer, 2003; Kuriger et al., 2006). Push moraine development and proglacial redeposition of subglacially eroded sediments since 1948 have enhanced glacier advance by protecting the terminus from coming into contact with ocean water, thereby preventing ice loss due to calving and melting below sea level (Post and Motyka, 1995; Hunter et al., 1996; Kuriger et al., 2006; Motyka et al., 2006). Radio echo sounding surveys show a deeply incised channel that coincides with the major outlet stream, which likely plays a significant role in subglacial erosion and sediment removal (Nolan et al., 1995; Motyka et al., 2006). The 19th century calving retreat led to a large AAR (the percentage of a glacier's area that remains snow-covered through the end of summer) of 0.90 during the past century (Post and Motyka, 1995; Motyka and Echelmeyer, 2003). Current advance is in part the result of the large AAR and reduced calving at the terminus as the fjord has filled in with glaciofluvial sediments. While we acknowledge that tidewater glacier dynamics complicate the behavior of Taku Glacier, we use records from Taku Glacier because few long-term records exist on Juneau Icefield (only for Lemon Creek and Taku Glaciers). Records such as near-terminus velocity, calving rates over time, and water depth at the terminus do not exist, and would be needed to quantitatively constrain the tidewater cycle effects on Taku Glacier (Paterson, 1994).

More than 20 survey profiles have been established on Taku Glacier. Two major survey profiles on Taku Glacier presented in this paper are Profile 4 and Profile A (Fig. 1). Profile 4 is aligned transverse to ice flow and is located approximately halfway between the accumulation zone and terminus of the glacier. Profile A is aligned parallel to ice flow and extends from the Taku/Llewellyn Glacier divide toward the glacier terminus.

LEMON CREEK GLACIER

Lemon Creek Glacier is relatively small and has an area of 11.7 km^2. It occupies a single basin located on the southwest border of Juneau Icefield (Fig. 1). Lemon Creek Glacier was selected for monitoring during the International Geophysical Year (1957–1958) as one of nine representative American glaciers in a global glacier network (Pelto and Miller, 1990). It was chosen because of its subarctic location and because mass balance measurements had been made on it since 1948. Lemon Creek Glacier has continuously retreated since its Little Ice Age maximum in 1750 (Miller and Pelto, 1999). Miller and Pelto (1999) show that Lemon Creek Glacier's negative mass balance led to a terminal retreat of over 700 m and a net surface height decrease of 24.7 m during the period 1953–1998. It has maintained a negative mass balance from 1998 to the present. The dynamics of Lemon Creek Glacier are simpler than those of Taku Glacier because Lemon Creek Glacier is a typical mountain glacier and is not affected by tidewater processes.

There are six survey profiles on Lemon Creek Glacier (Fig. 1). Three major profiles on Lemon Creek Glacier presented in this paper are Profiles A, D, and L. Profile A is aligned transverse to ice flow and is located at the accumulation zone of Lemon Creek Glacier. Profile D is aligned transverse to ice flow and is located near the terminus of Lemon Creek Glacier. Profile L is aligned parallel to ice flow and extends from the accumulation zone to the glacier terminus.

Methods

SURFACE HEIGHT DATA

Glacier surface elevation was measured at points within an established survey network consisting of 119 km of profiles, with points spaced regularly both along and across glacier flow direction. The first author collected survey and mass balance data in 2003 and 2005. Data collected since 1993 have been assembled by McGee (2000). Exact latitudes and longitudes of survey point coordinates loaded in the roving unit are located to within 0.5 m using a survey grade real-time Differential Global Positioning System (DGPS) (Pelto et al., 2008). Cumulative surface height data errors for the entire data set are <0.5 m. All surface height data in this paper reflect measurements made annually in July and August with survey-grade, dual-frequency, real-time kinematic GPS systems (Leica System 300, Leica System 530, or Trimble 5700) (Pelto et al., 2008). The roving unit receiver is mounted on an aluminum pole, and height above the snow surface of the antenna is recorded for every measurement. The reference receiver is always centered and leveled over a bedrock benchmark on a nunatak. The real-time kinematic method involves sending a correction signal from the reference station to a roving unit in real time. Standard GPS procedures were followed for all post-1993 surveys, including minimization of the distance between roving and reference units, recording data only when the Percent Dilution of Position (PDOP) was ≤6, and use of a 15° elevation mask (McGee, 2001). The average baseline length was 5 km, and the longest baseline used was 8.5 km (McGee, 2001). All data coordinates are translated from a geocentric coordinate system to one based on a Transverse Mercator projection (datum WGS84) centered on Juneau Icefield (McGee, 2001). Detailed descriptions of the survey techniques used are given in Lang (1993) and McGee (1994).

Survey data have been collected annually on Juneau Icefield since 1946. All data analyzed in this study were collected in the field during the period 1993 to present. Prior to 1993 survey records are not consistent because profiles were not yet standardized and surveying was conducted using theodolites. The errors introduced by these factors prevent the use of data collected prior to 1993. Long-term height change data are based on actual survey dates which may differ from year to year by a few days. No interpolation in time was attempted for surface height data, and surface elevation changes do not necessarily account for potential changes in subglacial erosion rates which are unknown.

MASS BALANCE DATA

Mass balance measurements were completed in the field annually between June and August since 1946 by JIRP participants. Annual net accumulation or ablation was determined using crevasse stratigraphy and hand-dug pits. Pits were dug in the same 17 locations each year in stable areas near the centers of the glaciers where external factors such as avalanching and wind erosion are minimal. The depth of pits extended to the previous year's glacier surface so that the retained snow water equivalent (SWE) could be determined by snow density measurements. Identification of the summer surface was determined by locating one or more of the following features: a characteristic undulating dirty layer, a persistent density change, or a depth hoar layer. Possible misidentification of summer surface layers is mitigated by annual supervision of field work by a minimum of one experienced researcher (Pelto et al., 2008). We note here that some mass balance data may be erroneous, as determination of the previous year's glacier surface is not always located correctly by JIRP participants. SWE is the amount of water contained within the snowpack, and is equivalent to the depth of liquid water that would result from melting the snowpack (here we use a snow depth to liquid water equivalent ratio of 10:1). This allows us to report snowfall data in SWE. Average daily ablation rates in both the accumulation and ablation zones were calculated at pit locations by drilling arrays of ablation stakes into the glacier surface and by analysis of the transient snow line migration (Pelto and Miller, 1990; Miller and Pelto, 1999; Pelto et al., 2008), allowing ablation to be extrapolated to the end of the melt season. Error is introduced here, as ablation stakes were drilled in only ~20% of the field seasons. The Equilibrium Line Altitude (ELA) is derived annually from Landsat imagery, and in the ablation zone the mass balance curve was adjusted based on both ELA and ablation measurements from 9 years between 1950 and 1997 (Pelto and Miller, 1990; Pelto et al., 2008). The extrapolated accumulation and ablation rates were translated into glacier mass gain or loss. Dividing glacier mass gain or loss by surface area provides an index of net mass balance (bn) that can be compared to other glaciers. Glacier extent and ELA location were determined by Pelto using a 1974 reference surface (Pelto, 1987). Mass balance data have been assembled and corrected using ablation rates by Beedle (2005). Field methods used to determine mass balance are discussed further in Pelto and Miller (1990, 2001) and Miller and Pelto (1999). Total annual mass balance errors for Taku and Lemon Creek Glaciers are 0.14 and 0.20 m SWE, respectively (Cogley and Adams, 1998; Pelto and Miller, 2001; Beedle, 2005). Long-term mass balance calculations require that Sorge's Law (Paterson, 1994) holds at all elevations, which may introduce small errors in mass balance calculations if old firn is removed by melting near the ELA (Motyka et al., 2002).

Extrapolation of mass balance measurements to the end of the melt season are necessary, as JIRP field logistics made it impossible to take measurements at the end of the ablation season at all locations on the glaciers monitored. While it is a source of error, extrapolation to the end of the melt season is a typical method employed in mass balance calculations of Alaskan glaciers (Miller and Pelto, 1999). There are 17 measurement sites on Taku Glacier which result in multiple measurements at each elevation. This provides a "more robust basis for annual extrapolation of mass balance change with elevation" (Pelto et al., 2008). The shift in ELA position has been used as a measure of ablation and has been useful in adjusting mass balance pit measurements (Pelto et al., 2008). To additionally address errors from extrapolation during certain years, 100–500 point probing transects were completed around pit sites, which indicate consistency of mass balance measurements (standard deviation of ±0.09 m SWE for sites within 3 km and with <100 m elevation change) around test pit sites (Pelto et al., 2008).

To summarize, large cumulative errors in annual mass balance result from the methods employed. As a result of Taku Glacier's large size, there is a sparse density of measurement points (~1 per 37 km^2) (Pelto et al., 2008). For both glaciers, other errors include extrapolation to the end of the melt season, infrequent measurements in the ablation zone, and identification of the previous year's surface by different researchers annually. These error sources are reduced by annual measurements at the 17 fixed pit locations using the 9-year ablation record to extrapolate ablation zone mass balance, and the annual balance gradient calculated from the 17 fixed locations and known ablation zone values derived from annual ELA location (Pelto and Miller, 1990; Pelto et al., 2008). The main source of error, however, is the lack of data from the ablation zone. On Taku Glacier, cumulative mass balance data have been verified by several methods (Motyka and Echelmeyer, 2003; Larsen et. al., 2007; Pelto et al., 2008). On Lemon Creek Glacier, cumulative mass balance data have been verified by laser altimetry (Sapiano et al., 1998; Miller and Pelto, 1999). Taku Glacier and Lemon Creek Glacier annual mass balance cumulative errors for all figures are ±0.15 m SWE and ±0.20 m SWE, respectively.

METEOROLOGICAL DATA

There are no reliable annual records of meteorological conditions from locations directly on Juneau Icefield. As a proxy for meteorological conditions on Juneau Icefield, we use data collected at nearby weather stations in Atlin, British Columbia; Whitehorse, Yukon Territory; and Juneau, Alaska (Fig. 1). Meteorological data from the weather station in Atlin, located at the northern edge of Juneau Icefield, include temperature records from 1967 to 1990. Records of precipitation and snowfall depth do not exist for Atlin. To supplement this record, precipitation and snowfall depth records from 1942 to 2002 were obtained from the weather station in Whitehorse, located ~180 km northwest of Atlin. Together, the meteorological records from stations in Atlin and Whitehorse are used as an estimate for conditions at the accumulation zone of Taku Glacier. Meteorological data from the weather station at the Juneau International Airport located ~1220 m below and ~15 km southwest of the southern edge of Juneau Icefield were also used as an estimate of conditions at the Lemon Creek Glacier accumulation zone and the ablation zones of both Taku and Lemon Creek Glaciers. Although temperatures on Juneau Icefield are likely to follow the same pattern as the Juneau Airport temperature record, strong variations in precipitation in the region exist as a result of orographic effects. For example, precipitation amounts and the ratio of snow to rain at high elevations on Juneau Icefield may be very different from the conditions in Juneau. The data from Juneau Airport include temperature, precipitation, and snowfall depth records from 1949 to 2006.

Results and Discussion

TEMPERATURE AND PRECIPITATION TRENDS

In this section, we examine temperature and precipitation records from Atlin, Whitehorse, and Juneau. When a significance level is stated, it is always referring to the 95% significance level. The Bootstrap Method (Efron and Tibshirani, 1994) was used to determine the significance of Spearman correlations. All correlations that are statistically significant are noted as such.

A significant correlation coefficient (0.92) between Atlin and Whitehorse annual mean temperature records confirms that these locations are in the same climate regime. The Atlin temperature record (1967–1990) shows a warming trend of 0.13 $^{\circ}\mathrm{C}\cdot\mathrm{yr}^{-1}$ (Fig. 2). The Whitehorse temperature record shows a similar warming trend (0.14 $^{\circ}\mathrm{C}\cdot\mathrm{yr}^{-1}$) over the same time period, although mean annual temperatures in Whitehorse were lower than those in Atlin by ~1 °C. The Whitehorse precipitation record (1942–2002) shows an increase in total annual precipitation of 0.091 $\mathrm{mm}\cdot\mathrm{yr}^{-1}$ SWE (Fig. 3). The Whitehorse total annual snowfall record shows a positive trend of 0.57 $\mathrm{mm}\cdot\mathrm{yr}^{-1}$ SWE over the same time period. These records, interpreted as the climate conditions near the Taku Glacier accumulation zone, suggest a decline in liquid precipitation, an increase in solid precipitation, and a longer ablation season. The combination of these factors suggests that snowfall amount increased but occurred during a shorter period of time.

The Juneau temperature record (1949–2005) shows a warming trend of 0.04 $^{\circ}\mathrm{C}\cdot\mathrm{yr}^{-1}$ (Fig. 2). Mean annual temperatures rose by 1.6 °C during this time period, with increases in winter temperature contributing most to this trend. The PDO correlates well with ablation season (April–September) temperature records from Juneau ($r = 0.65$), suggesting that the local climate of Juneau is strongly linked to the PDO (Fig. 2). The Juneau precipitation and snowfall depth records (1949–2005) show an increase in liquid precipitation of 5.72 $\mathrm{mm}\cdot\mathrm{yr}^{-1}$ SWE (Fig. 3) and a decrease in total annual snowfall of -2.69 $\mathrm{mm}\cdot\mathrm{yr}^{-1}$ SWE. Figures 2 and 3 show that temperature and precipitation decreased from 1942 to 1977, and that this trend reversed after 1977 (the year of the noted PDO shift). Together, these meteorological data suggest an increase in temperature, an overall increase in liquid precipitation, and a decrease in solid precipitation since 1948 near Lemon Creek Glacier and the terminus of Taku Glacier. These effects led to negative glacier mass balances and have been shown to be the dominant climatic factors influencing a negative mass balance of nearby Mendenhall Glacier since 1950 (Motyka et al., 2002). It is likely that with future warming in Juneau, a greater amount of total annual precipitation will fall as liquid precipitation. Warming temperatures, lengthened ablation season, increase in liquid precipitation, and decrease in solid precipitation are all factors that would cause a decrease in glacier surface height and mass balance, and are consistent with results produced by the Bhatt et al. (2007) model for other Alaskan glaciers.

TAKU GLACIER SURFACE HEIGHT AND MASS BALANCE DATA

In this section, Taku Glacier surface height data from Profile 4 and Profile A (Fig. 1) and mass balance data are presented. All transverse and longitudinal survey profiles on Taku Glacier show significant surface height decreases during the past 13 years, although a consistent year-to-year decrease in surface height is not seen each consecutive year. The surface height at the center of Profile 4 (surveyed 1993–2005) decreased by 3.4 m (Fig. 4). The average surface height along Profile A (surveyed 2001–2005) decreased by 3.4 m. There is no definitive correlation between Taku Glacier surface height and Atlin, Whitehorse, or Juneau records of temperature or precipitation or the PDO. This lack of correlation may partly be the result of the relatively short duration (13 years) of the survey data. However, it is likely that post-tidewater glacier dynamics currently have a stronger influence on Taku Glacier behavior than climate (Motyka and Echelmeyer, 2003).

Taku Glacier has experienced a positive mass balance between 1946 and 1988 (Fig. 5). Since 1988 the mass balance has been predominantly negative. In apparent contrast to its mass balance, Taku Glacier has continued to advance from 1988 to the present. However, the advance velocity has been decreasing since 1963 (Pelto et al., 2008). A substantial decrease in rate of advance occurred in the 1990s despite glacier thickening (Motyka and Echelmeyer, 2003). Factors contributing to a slower rate of advance may include broadening of the piedmont lobe (Motyka and Post, 1995), continued subglacial sediment excavation near the terminus (Nolan et al., 1995; Kuriger et al., 2006), capturing of the increased ice flux by the distributary Hole-In-The-Wall Glacier (Fig. 1; Motyka and Echelmeyer, 2003), and decrease in mass balance. Airborne altimetry has shown that between 1950 and 2000, Taku Glacier thickened ~20–30 m near the mean ELA (Echelmeyer et al., 1996; Arendt et al., 2002). Surface height data at the mean ELA from 1950 to 2000 do not exist, but such overall thickening during this time period would correspond to an increase in surface height. These results suggest that Taku Glacier will sustain its terminal advance in the future despite its current negative mass balance. For Taku Glacier, retreat may lag many years behind changes in atmospheric conditions and glacier mass balance due to its large size and present high AAR. It is important to note that once retreat is initiated, rapid ice loss will ensue. This is a result of the terminus being left in water, exposed to calving in the deeply incised, below-sea-level troughs that Taku Glacier has formed (Pelto and Warren, 1991).

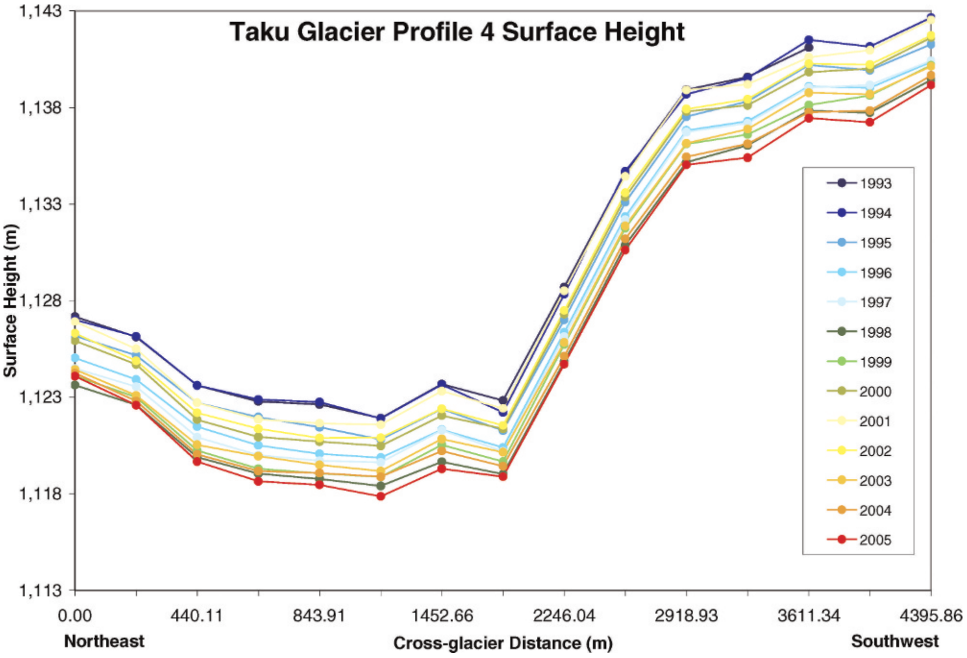

FIGURE 4. **Surface height elevations at survey points along Profile 4 on Taku Glacier. Each line represents the annual surface height of the glacier during the period 1993–2005. A negative trend is observed during this period. The location of Profile 4 is shown in Figure 1. Cumulative error for all data points is ±0.5 m.**

LEMON CREEK GLACIER SURFACE HEIGHT AND MASS BALANCE DATA

In this section, Lemon Creek Glacier surface height data from Profiles A, D, and L (Fig. 1) and mass balance data are presented. Surface height data from Lemon Creek Glacier show larger negative surface height trends than those from Taku Glacier. Surface height data points for all six profiles on Lemon Creek Glacier decreased from 1997 to 2005 (Fig. 6). At Profile A (surveyed 1997–2004), near the head of the glacier, average surface height decreased 5.06 m. At Profile D (surveyed 2001–2005), near the glacier terminus, average surface height decreased 7.24 m. The overall surface height decrease corresponds to an approximate volume loss of 0.07 km^3 since 1997, approximately 5% of the total volume. At the center of Profile L (surveyed 1997–2004), surface height decreased 5.8 m. There is no definitive correlation between Lemon Creek Glacier annual surface height and Juneau records of temperature and precipitation or the PDO (annual or seasonal). Again, this lack of correlation is likely due to the relatively short duration of the surface height data.

Lemon Creek Glacier has experienced a predominantly negative mass balance between 1953 and the present and has lost 25 m SWE during this time (Miller and Pelto, 1999) (Fig. 5). During the 1990s the glacier experienced dramatic negative mass balances, with 1996 and 1997 revealing no retained accumulation (Miller and Pelto, 1999) for the first time since measurements began in 1948. Presumably due to its small size and relatively simple alpine glacier dynamics, Lemon Creek Glacier exhibits a faster response time to climatic change than Taku Glacier.

GLACIER RESPONSE AND CLIMATIC FORCING

Mean height change at Lemon Creek Glacier Profile L correlates significantly with mean height change at Taku Glacier Profile 4 from the period 1997–2005 ($r = 0.55$). While it is expected

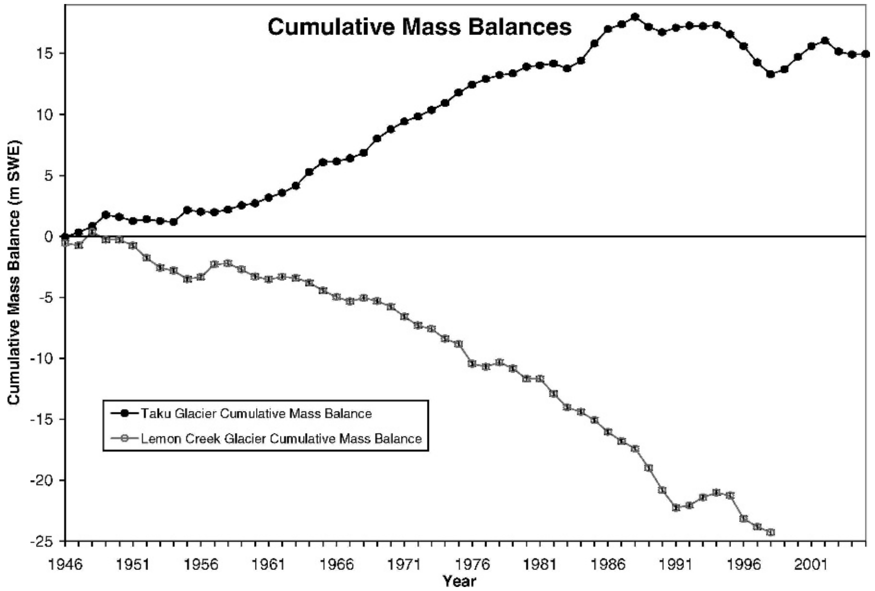

FIGURE 5. **Cumulative annual mass balance (bn) for Taku and Lemon Creek Glaciers. A significant decrease is observed in the positive mass balance trend on Taku Glacier beginning in 1988. Error bars show Taku Glacier and Lemon Creek Glacier annual mass balance errors of ±0.15 m SWE and ±0.20 m SWE, respectively.**

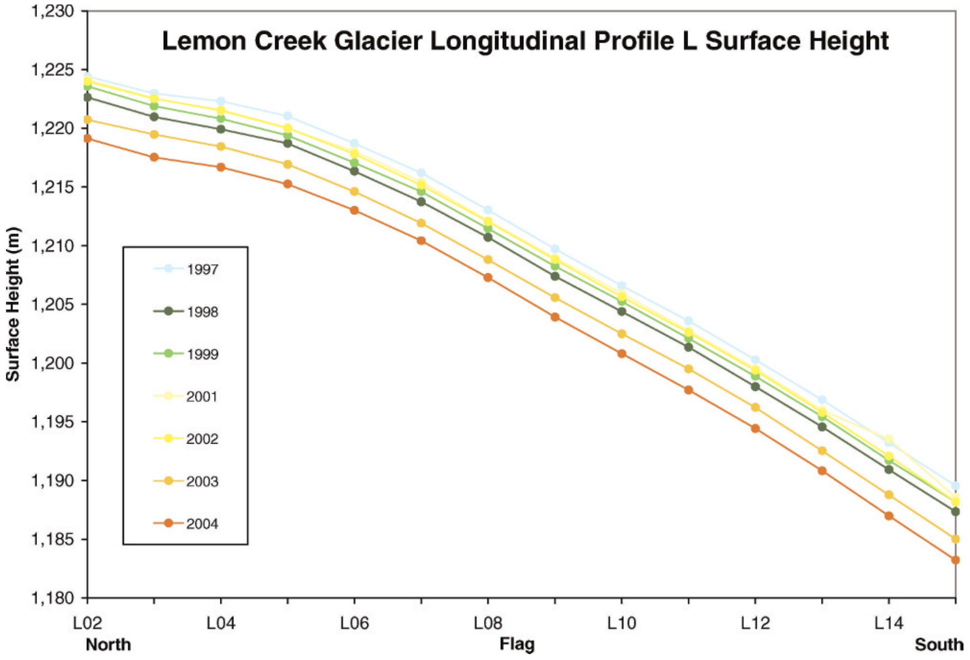

FIGURE 6. Surface height elevations at survey points along Profile L on Lemon Creek Glacier, 1997–1999 and 2001–2004. Cumulative error for all data points is ±0.5 m.

that these two time series would co-vary with one another, the extent to which they do was not anticipated because of their different sizes, post-tidewater glacier dynamics that affect only Taku Glacier, and the fact that one survey profile runs parallel to glacier flow and the other runs perpendicular to glacier flow. The common variable between Taku and Lemon Creek Glaciers is the maritime climate. For Taku Glacier, these results suggest that climatic conditions have a smaller effect on glacier surface height and mass balance than post-tidewater glacier dynamics and resultant hypsometry. For Lemon Creek Glacier, this indicates that climatic conditions have the largest effect on glacier surface height, and suggests that large-scale atmospheric patterns such as PDO are the dominant factors affecting this glacier's behavior.

Taku Glacier

Taku glacier mass balance was compared with meteorological records from Atlin, Whitehorse, and Juneau and the PDO index. Taku Glacier mass balance does not correlate with the mean annual temperature records from Atlin or Whitehorse ($r = -0.14$ and $r = -0.17$, respectively). Taku Glacier mass balance correlates significantly with the ablation season temperature record from Whitehorse ($r = -0.61$). However, Taku Glacier mass balance correlates significantly with both annual and ablation season temperature records from Juneau ($r = -0.29$ and $r = -0.63$, respectively). This result suggests that Juneau meteorological records are more representative of conditions in both the accumulation and ablation zones of Taku Glacier and that ablation zone conditions in combination with post-tidewater glacier dynamics and hypsometry influence Taku Glacier behavior.

Taku Glacier mass balance correlates significantly with the annual PDO record ($r = -0.29$). However, a stronger correlation is found between Taku Glacier mass balance and the ablation season PDO record ($r = -0.41$; Fig. 7A). The correlation between the winter PDO record and Taku Glacier mass balance is not statistically significant ($r = -0.11$). The correlations between Taku Glacier mass balance and temperature and PDO records show that Taku Glacier is more sensitive to climatic forcing during the ablation season.

Taku Glacier mass balance records also were compared with precipitation records from Whitehorse. Taku Glacier mass balance shows little to no correlation with the total annual precipitation and the solid precipitation records from Whitehorse ($r = 0.05$ and $r = 0.043$, respectively). However, this may be due to elevation effects changing the solid/liquid precipitation distribution previously discussed. While the Whitehorse weather station is located at 703 m above sea level (a.s.l.), the Taku Glacier accumulation zone is located around 1200 m a.s.l. Because of this discrepancy, liquid precipitation recorded at the Whitehorse weather station may fall as solid precipitation on the Taku Glacier accumulation zone, as precipitation varies locally and regionally.

Taku Glacier has a complex response to climatic changes as a result of post-tidewater glacier dynamics and its large size. By definition, a tidewater glacier is insensitive to climatic changes during advance phases. There is a strong correlation between Taku Glacier mass balance and the Juneau temperature record. Despite the glacier's negative annual mass balance since 1988, it has continued to advance. Advance has been slowing, however, and unknown subglacial bedrock topography and basal melt rates may factor into Taku Glacier's advance as well. The effects of increased temperature and liquid precipitation at the ablation zone have had a larger impact on glacier behavior than accumulation zone conditions.

Lemon Creek Glacier

Lemon Creek Glacier mass balance was compared with meteorological records from Juneau. The correlation between mass balance and the annual temperature record is not statistically significant ($r = 0.23$). However, the correlation between mass balance and the ablation season temperature record is significant ($r = -0.56$). Lemon Creek Glacier mass balance also correlates with the solid precipitation record ($r = 0.41$), but not with the total annual precipitation record ($r = -0.14$). A stronger correlation is observed between Lemon Creek Glacier mass balance and the solid precipitation record from Juneau than Taku Glacier mass balance and the solid precipitation record from Whitehorse. This may be partly due to the closer proximity of Lemon Creek Glacier to

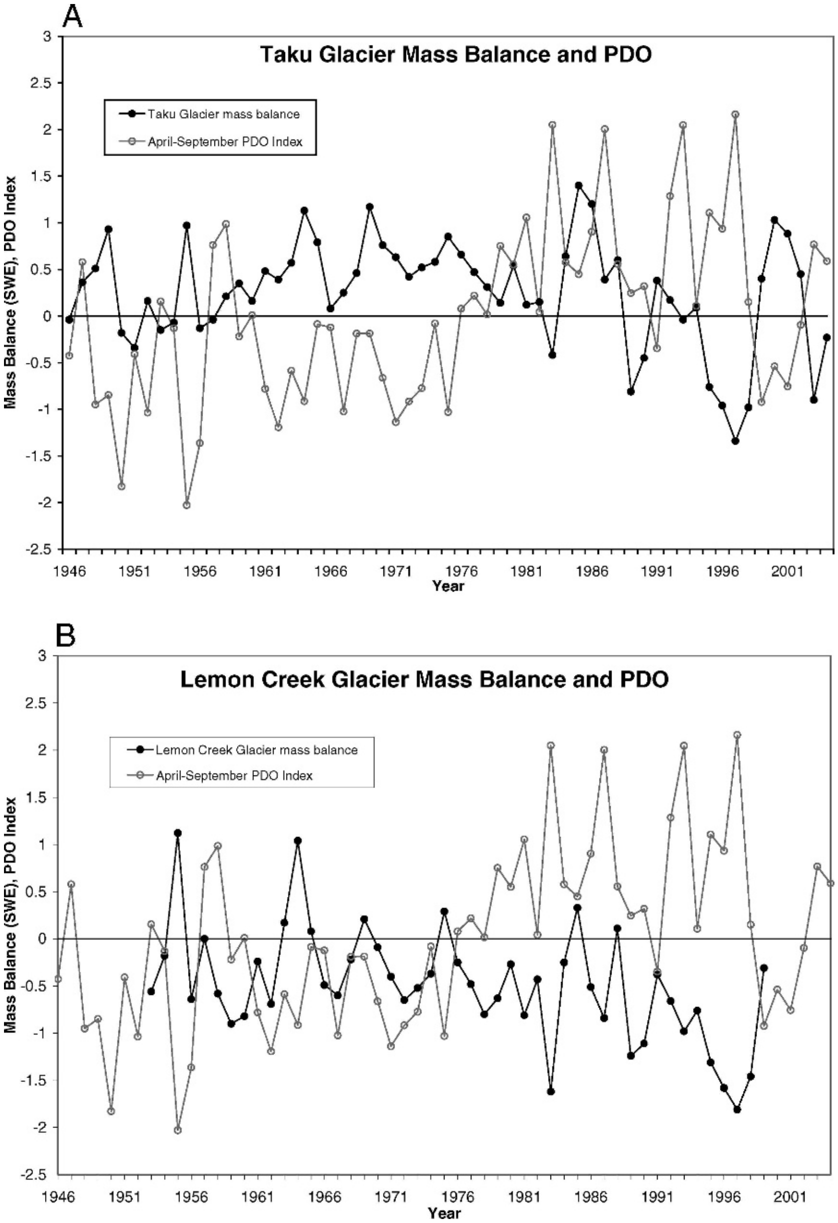

FIGURE 7. (A) Taku Glacier mass balance (m SWE) and the ablation season Pacific Decadal Oscillation (PDO) record (*r* = −0.41). (B) Lemon Creek Glacier mass balance (m SWE) and the ablation season Pacific Decadal Oscillation (PDO) record (*r* = −0.57). Taku Glacier and Lemon Creek Glacier annual mass balance errors are ±0.15 m SWE and ±0.20 m SWE, respectively.

Juneau than of Taku Glacier to Whitehorse. As mentioned above, precipitation is generally more variable than temperature over equal distances. These differences may account for weaker correlations between Taku Glacier mass balance and precipitation records.

The strongest correlation ($r = -0.57$) is observed between Lemon Creek Glacier mass balance and the ablation season PDO record (Fig. 7B). Lemon Creek Glacier mass balance and the winter season PDO record also correlate significantly ($r = -0.29$). Lemon Creek Glacier mass balance shows a significant correlation with the annual PDO record ($r = -0.50$), although again this correlation is not as strong as that with the ablation season PDO record. All periods between 1963 and 2001 when mass balance increased on Lemon Creek Glacier correspond to years when the annual PDO index was negative. This sensitivity of Lemon Creek Glacier to the ablation season PDO record is consistent with correlations of temperature and precipitation previously shown. Observations of other Alaskan glaciers (Field, 1975; Hodge et al., 1998; Sapiano et al., 1998; Motyka et al., 2002) show that trends observed on Lemon Creek Glacier are representative of regional glacier trends.

On a small glacier such as Lemon Creek Glacier, we would anticipate significant decreases in surface height to coincide with negative mass balance years. Surface height data from both glaciers do not correlate significantly with mass balance, meteorological or PDO records; however, Taku and Lemon Creek Glacier surface height records correlate well with one another. It is likely that the duration of the surface height records is not sufficient to detect evidence of climatic forcing. The mass balance record is significantly longer in duration and is a better indicator of the response of glaciers in Southeast Alaska to climatic forcing.

Conclusions

In this study we examined the surface height and mass balance changes of Taku and Lemon Creek Glaciers on the Juneau Icefield. Correlations of surface height and mass balance of these glaciers with local meteorological data and the PDO are used to examine the relative influence of parameters such as temperature and precipitation on glacier behavior. Four main conclusions are based on the results. (1) Local mean annual temperature and liquid precipitation records correlate more significantly with the ablation season PDO record than the annual or winter PDO records. (2) Taku Glacier mass balance correlates strongly with ablation season temperature and ablation season PDO records and less so with precipitation and annual mean temperature and annual PDO records. (3) Lemon Creek Glacier mass balance correlates strongly with ablation season temperature and ablation season PDO records, and less (but more strongly than Taku Glacier) with precipitation and annual mean temperature and annual mean PDO records. (4) Whereas Lemon Creek Glacier mass balance changes are likely driven by climatic changes, Taku Glacier mass balance changes are likely driven both by post-tidewater glacier dynamics and, more recently and to a lesser extent, by climatic changes. As a result of its location in a maritime climate and its smaller size, a more dramatic decrease in surface height and mass balance is observed in Lemon Creek Glacier than in Taku Glacier since 1946.

The results presented above show that Taku and Lemon Creek Glaciers are strongly influenced by ablation season temperature and suggest that both glaciers are influenced more by climatic parameters (temperature and precipitation) at the glacier terminus than in the accumulation zone. The warmer winter temperatures observed since 1977 result in an increase in the ratio of liquid to solid precipitation. Both summer and winter trends observed result in ice mass loss: warmer summer temperatures increase glacier ablation, and warmer winter temperatures result in an increased ratio of liquid to solid precipitation. Both effects lead to negative glacier mass balances and have been shown to be factors affecting Taku and Lemon Creek Glaciers for our period of study.

Taku Glacier's continued advance since 1988 appears anomalous considering these meteorological trends and the glacier's negative mass balance since 1988. However, a high AAR as well as a decrease in calving at the terminus both support Taku Glacier advance. Additionally, rate of advance has been decreasing since 1988, and other unknowns discussed such as basal melting rates and subglacial bedrock topography may also currently influence Taku Glacier advance. Our results show that the effects of increased temperature and liquid precipitation at the coastal ablation zone of Taku Glacier have a larger impact on its behavior than accumulation zone conditions, and that Taku Glacier advance is still dominated by post-tidewater glacier dynamics.

Future work will rely on continued annual measurements of surface height along established survey profiles and mass balance measurements. Ideally, *in situ* temperature and precipitation data will be recorded in the accumulation and ablation zones of Taku and Lemon Creek Glaciers. In addition, a long-term mass balance record on Llewellyn Glacier (Fig. 1) should be established because it is located at the northern end of Juneau Icefield in a continental climate and is not a tidewater glacier, and should therefore allow for an analysis of the link between mass balance and PDO. Future studies should employ the use of models such as that developed by Bhatt et al. (2007) to predict future mass balances of Taku and Lemon Creek Glaciers.

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