High basal melting rates within high-precipitation temperate glaciers

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ABSTRACT. The role of basal melting within high-precipitation temperate glaciers represents a significant gap in understanding glacier melting processes. We use a basal melt equation to calculate geothermal and frictional heat-induced basal melt and develop an equation to calculate the rainfall-induced basal melt for Franz Josef Glacier, New Zealand, a high-precipitation, temperate glacier. Additionally, we calculate basal melt due to heat dissipation within water and ice. Data collated from published information on glacier dynamics and climate station readings show that total basal melt contributes on average $\sim$2.50 m a^{-1} over the lower to mid-ablation zone (300–1500 m a.s.l.), which is equivalent to >10% of the total ablation for the glacier. This indicates that basal melting is an important component of mass balance for high-precipitation, temperate glaciers.

INTRODUCTION

Ablation refers to the processes that remove snow and ice from a glacier. Snow and ice are ablated from a typical temperate glacier through melting, ice avalanches and sublimation. Glaciers whose termini reach a proglacial lake or the sea will also lose mass through ice calving. The predominant ablation process on temperate glaciers is melting (Cuffey and Paterson, 2010). While ablation predominantly occurs in the ablation zone – in which annual snow and ice loss exceeds annual snow and ice gain – it also occurs in the accumulation zone and this can contribute significantly to the overall ablation. With new technologies, annual mass balance is commonly measured by satellite remote sensing (e.g. Hubbard and others, 2000) and airborne laser profiling (e.g. Krabill and others, 1995).

Net surface mass balance is typically measured by placing stakes at spatially consistent intervals over the surface of a glacier to monitor changes in stake height against surface level. This technique takes into account sublimation and surface melting. Crucially, however, this technique for measuring ablation does not take into account local surface ablation processes, such as slushflows and snowdrifting, which can be missed by stake (point) measurements, as well as basal melting due to thermal erosion (Alexander and others, 2011). Knight (1999) suggests that thermal erosion of ice occurs in the subglacial zone due mainly to geothermal heat input and friction through basal sliding, henceforth referred to as 'geothermal and frictional heat-induced basal melting'. Additionally, Shulmeister and others (2010) note that advection of heat from water passing through the glacier during heavy rainfall events can contribute significantly to the overall ablation rate of a glacier; this is henceforth referred to as 'rainfall-induced basal melting'. The rainfall-induced basal melt that we describe occurs both en- and subglacially, but we refer to it as basal melting because most of the melt will occur in the subglacial zone. We also consider other basal melting components, such as the dissipative heat produced as potential energy which is lost from water flow through the glacier, as well as heat production within the ice through ice deformation.

RATIONALE

While measurements and estimates of basal melting have been carried out for many years in polar glacier environments, particularly in Antarctica (e.g. Budd and others, 1970; Joughin and others, 2003; Wen and others, 2010) and to a lesser extent Greenland (e.g. Rignot, 1997; Fahnestock and others, 2001; Buchardt and Dahl-Jensen, 2007), there is very little known about basal melting processes beneath temperate glaciers. This represents a significant gap in understanding glacial melting processes. Kaser and others (2003, p. 10) noted that 'on mountain glaciers [subglacial ablation] is usually insignificant in comparison to surface losses' and that 'mass changes on the glacier surface dominate the mass balance and the internal and subglacial processes are, in most cases, ignored'. However, it is difficult to validate this comment when measurements or even estimates of subglacial melting are absent for temperate glaciers. The objective of this paper is to derive first-order estimates of basal melt at Franz Josef Glacier, New Zealand, and to investigate whether basal melt is a significant component of mass balance for high-precipitation temperate glaciers. These glaciers are often referred to as high mass-turnover glaciers due to the steep mass-balance gradient created by high levels of precipitation and ablation. Franz Josef Glacier is selected as a case study based on the availability of published, peer-reviewed field measurements relevant to calculating basal melt rates.

METHODOLOGY

Location

New Zealand glaciers are located in the mid-latitudes of the Southern Hemisphere, a zone of persistent moist westerly winds known as the 'roaring forties'. In the South Island of New Zealand, glaciers are confined to a narrow 30 km zone running parallel to the $\sim$3000 m high Southern Alps, a southwest- to northeast-trending axial mountain range. On the windward side of the Southern Alps, high-altitude areas can experience extremely high precipitation

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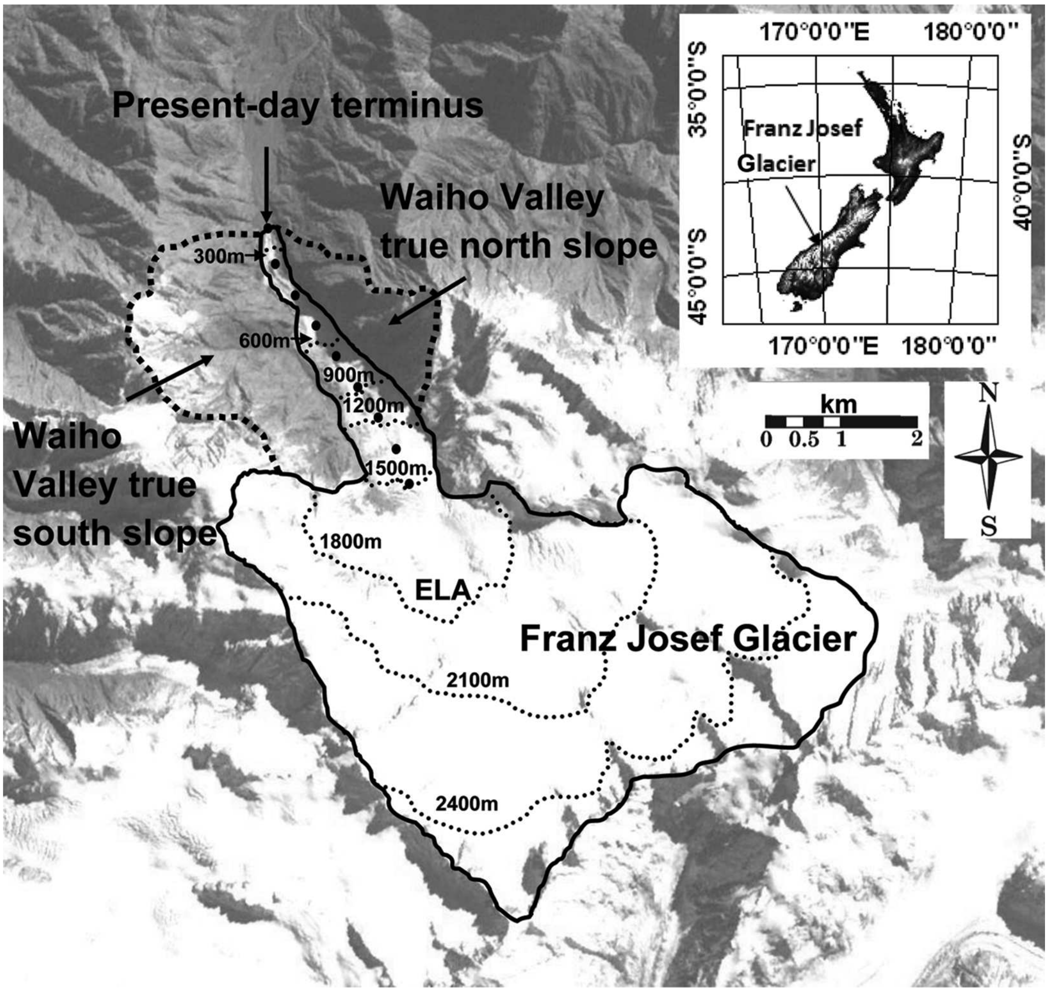

Fig. 1. Location, topography and points of interest at Franz Josef Glacier, New Zealand. The black dots in the lower to mid-ablation zone represent 500 m intervals from the terminus at 300 m a.s.l. to the top of the confined valley at 1500 m a.s.l. These locations are used to obtain point estimates for basal melting. The ELA is located at ~1800 m a.s.l.

of up to 14 m w.e. a^{-1} (Griffiths and McSaveney, 1983; Henderson and Thompson, 1999). Franz Josef Glacier has a high-elevation catchment accumulation zone of 27 km^2 originating at the top of the main topographic divide of the Southern Alps, and a small, narrow ablation zone of 8 km^2 extending to ~300 m a.s.l., yielding a very high accumulation–area ratio (AAR) of 0.8. The equilibrium-line altitude (ELA) is located at ~1800 m a.s.l. (personal communication from T. Chinn, 2009; Fig. 1). Measured surface ablation rates of ≥20 m w.e. a^{-1} on the lower ablation zone of the glacier are some of the highest in the world (Anderson and others, 2006). In fact, the ablation rates on Franz Josef Glacier are almost twice as high as the highest reported ablation rates of any glacier reported to the World Glacier Monitoring Service (WGMS, 2001). Franz Josef climate station data indicate that mean summer temperatures are ≥15°C at the terminus, with daily maxima often reaching >20°C, yielding extremely high surface ablation during the summer melt season.

Geothermal and frictional heat-induced basal melt

Based on the basal melt equation of Paterson (1994), we use published measurements and, where necessary, realistic estimates of various parameters for Franz Josef Glacier to calculate the geothermal and frictional heat-induced basal melt, m_r, as

$$m_r = \frac{G + \tau_b u_b - k_i \Theta_b}{L_i \rho}, \tag{1}$$

where G is the geothermal heat flux, τ_b is the basal shear stress, u_b is the basal sliding velocity, k_i is the thermal conductivity of ice, Θ_b is the basal temperature gradient within ice, L_i is the latent heat of fusion of ice and ρ is the density of ice. For temperate glaciers with basal temperatures close to the pressure-melting point, it can be assumed that k_i and ρ are constants with values of 2.10 W m^{-1} K^{-1} and 917 kg m^{-3} respectively, while L_i is 333.5 kJ kg^{-1} (Cuffey and Paterson, 2010).

Data are collated from published information on glacier dynamics and climate station readings in order to calculate a mean annual melt rate for all types of basal melt discussed herein by averaging the annual melt at 500 m intervals from the terminus (300 m a.s.l.) to the end of the confined valley (1500 m a.s.l.) as shown in Figure 1. All variables used to calculate annual geothermal and frictional heat-induced basal melt are kept constant throughout the year apart from the ice-flow velocity, which is reduced linearly by 30% from a maximum in January to a minimum in July. We base this reduction on measurements from the adjacent Fox Glacier, which indicate winter velocities are ~30% less than

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summer velocities (Purdie and others, 2008). Basal sliding velocities are approximated as 75% of the surface velocities at Franz Josef Glacier (Anderson, 2003), which are an average of 1.2 m d^{-1} at the lower surface elevations of the glacier (McSaveney and Gage, 1968; Anderson, 2003; Purdie and others, 2008). We use the estimated basal shear stress (τ_b) value of 150 kPa from Anderson and others (2008) for Franz Josef Glacier, determined by radio-echo sounding on the accessible parts of the glacier. While the 150 kPa basal shear stress is at the high end of recognized values for valley glaciers (Knight, 1999; 50–150 kPa), this value is realistic for high mass-turnover glaciers like the Franz Josef (Oerlemans, 1997).

Average geothermal heat fluxes range from 77 mW m^{-2} for Cenozoic volcanics to 46 mW m^{-2} for Precambrian rock (Sclater and others, 1980), and the average is ~60 mW m^{-2} (Paterson, 1994). Franz Josef Glacier is likely to experience a slightly higher than average geothermal heat flux of 65 mW m^{-2} due to the presence of heat generated by the Alpine Fault, which runs adjacent to the main divide and is associated with rapid advection of crustal rock from depth. Since high snowfield cores in the Southern Alps indicate basal ice temperatures of close to 0°C (personal communication from U. Morgenstern, 2010) and it is well recognized that temperate ice has a basal temperature close to 0°C (Cuffey and Paterson, 2010), we do not include a temperature gradient within the ice.

Rainfall-induced basal melt

It has been well established that rainfall melts ice on the surface of a glacier due to the transfer of heat from water to ice (e.g. Hay and Fitzharris, 1988; Konya and Matsumoto, 2010), but the influence of rainfall melting basal ice has not been investigated previously. For glaciers such as Franz Josef Glacier that have moderately to heavily crevassed regions in the ablation zone, which reach near or fully to the glacier bed, the amount of rainwater able to reach the subglacial drainage system, and in turn melt subglacial ice via advection of the relatively warm water, will be high. Ultimately, the concept of rainfall-induced basal melt is dependent on the assumptions that rainfall in the glacier catchment (valley sides and glacier) will reach the subglacial drainage system, that ice temperatures are at the melting point and that rainfall rates are high. Since most of the >6 m a^{-1} of rain that falls onto Franz Josef Glacier reaches the subglacial drainage system via water flowing down the glacier sides and a heavily crevassed ablation zone, the potential for significant rainfall-induced basal melting is high given the high temperature of rainfall, and ice temperatures close to 0°C.

The rainfall-induced basal melt, R, can be calculated as

$$R = P(A_c)\frac{C_v(T_r - T_w)}{L_i}, \tag{2}$$

where C_v is the specific heat capacity of water (4182 J K^{-1} kg^{-1}), T_r is the temperature of rainfall and T_w is the temperature of the water exiting the terminal cave. The amount of annual precipitation that falls as rain, P, over the area of the Franz Josef Glacier catchment, A_c, is calculated as a mass (kg) and is determined according to both the annual frequency and intensity of daily rainfall events, r, where $r \geq 25$ mm d^{-1} (Table 1).

Since measuring the temperature of rainfall is difficult, it is often estimated using the wet-bulb temperature (e.g. Anderson, 1976; Marcus and others, 1985). This is appropriate to apply to the west coast of New Zealand given that rainfall is associated with low-elevation clouds, meaning the moisture in the clouds is relatively warm and will be the same as the temperature of the air mass. Mean 1980–2009 temperature data from the Franz Josef climate station based on daily readings indicate a mean annual air temperature and wet-bulb temperature of 8.5°C and 8°C respectively. These measurements are taken at 0900 h, however. The daily mean temperature over a 24 hour period is 11.5°C, which is higher than the 0900 h mean temperatures. Since the estimated wet-bulb temperature is only slightly less than the air temperature due to very high annual mean relative humidity (90%), it is highly likely that the mean annual wet-bulb temperature will be 10.5–11°C. If we then take into account the climate-station elevation of 155 m a.s.l. by factoring in a realistic saturated adiabatic lapse rate of 4.5°C km^{-1} (Wallace and Hobbs, 2006), the mean temperature of rainfall will be very close to 10°C at the terminus (~300 m a.s.l.).

Not all energy is used up through the transfer of heat from the water to the ice as it travels through the glacier, so the temperature of the water exiting the terminal cave, T_w, is introduced to take into account the actual cooling possible during rainfall events. During a 30 mm d^{-1} rainfall event in August 2010, the air temperature, T_a, was 10°C and T_w was 1°C at the terminus, indicating that a substantial amount of energy was used to melt ice as the water passed through the glacier. On a clear day with no rain in the previous 24 hours, T_w was measured as 0.2–0.5°C due to surface and geothermal and frictional heat-induced melt, as well as dissipative heat production within water. We use $T_w = 1$°C for basal melt calculations. While we expect some cooling effect to originate from the initial cooling of rain as it comes into contact with surface ice, the rainwater will flow via streams almost immediately into the englacial and subglacial drainage system through crevasses and moulins.

We assume 100% of all rain that falls on the glacier catchment sides reaches the subglacial system from the very steep, generally non-vegetated and poorly permeable rock slopes. Above these elevations, most of the precipitation will fall as snow (Rother and Shulmeister, 2006), and even when precipitation falls as rain there, it will have difficulty reaching the basal system due to the lack of significant crevassing in the accumulation zone. In addition, the lower temperatures will fail to provide suitable conditions for any notable amount of ice melt. We use a realistic saturated

Table 1. Classification scheme for different-intensity daily rainfall events for Franz Josef Glacier

Rainfall category	Rainfall	Number of occurrences	Mean rainfall within categories
	mm d^{-1}	a^{-1}	mm d^{-1}
r_i	25–49	35	35
r_{ii}	50–74	17	61
r_{iii}	74–99	8	85
r_{iv}	100–124	4	111
r_v	125–149	3	136
r_{vi}	150–199	3	173
r_{vii}	200+	1	258

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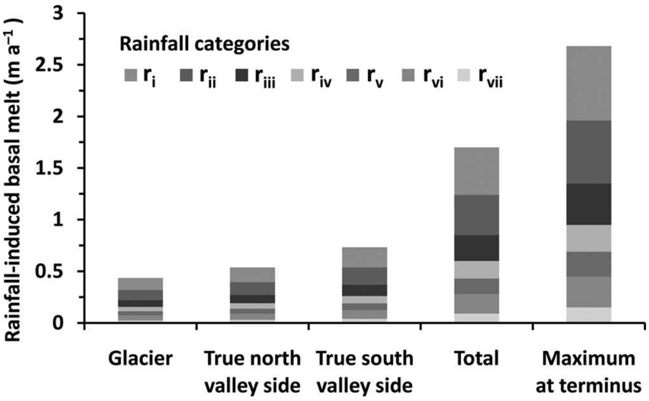

Fig. 2. Mean rainfall-induced basal melt (m a^{-1}) produced at 300–1500 m a.s.l. caused by rain falling directly onto the glacier and true north and south valley sides of Franz Josef Glacier (see Fig. 1). The total mean rainfall-induced basal melt is graphed alongside the maximum rainfall-induced basal melt at the terminus (300 m a.s.l.). Columns are partitioned according to melt contributed by different rainfall intensities (categories).

adiabatic lapse rate of 4.5°C km^{-1} (Wallace and Hobbs, 2006) to determine the temperature of rainfall at a specific elevation. This lapse rate represents a wet air mass, typical of air masses coming off the Tasman Sea. Since data do not exist for daily rainfall distributions as functions of elevation at Franz Josef Glacier, the amount of precipitation from a single event at any given elevation, $P(e_z)$, can be calculated based on a ratio between annual precipitation at the terminus, $P(a_t)$, and the precipitation from a single event at the terminus, $P(e_t)$. This assumes the annual precipitation distribution as a function of elevation, $P(a_z)$, has been modelled (e.g. Griffiths and McSaveney, 1983):

$$P(e_z) = \frac{P(e_t)}{P(a_t)} P(a_z). \tag{3}$$

Mean 1980–2009 precipitation data were taken from the Franz Josef climate station. We assume that rainfall values measured at this location are the same as at the terminus, although in reality the terminus is likely to have slightly more rainfall than recorded at the station due to its higher elevation and proximity to the range front.

Dissipative heat production within water and ice

Water that flows from the glacier surface through a glacier to the terminus loses potential energy to heat, leading to the melting of ice adjacent to the passageways transporting the water (Cuffey and Paterson, 2010). We take the average surface elevation of the lower to mid-ablation zone ranging from 300 to 1500 m a.s.l., meaning the average elevation drop from water entry at the glacier surface to the terminus will be 600 m (900 m a.s.l.). In addition, meltwater originating from surface melt at the average elevation of 900 m a.s.l. is 10 m a^{-1} (Alexander and others, 2011). Dissipative heat production within water, H, can be calculated as

$$H = [P(A_c) + M_s]\frac{gh}{L_i}, \tag{4}$$

where g is the acceleration due to gravity (9.81 m s^{-2}) and h is the elevation change between the glacier surface and the terminus. The precipitation falling as rain in the glacier catchment, $P(A_c)$, and the surface meltwater, M_s, is calculated as a mass (kg).

Dissipative heat production within ice occurs through ice deformation, causing the production and meltout of water within the matrix, occurring mainly in the basal zone where stresses and deformation rates are high, but also wherever the ice is temperate, thick and deforming rapidly (Cuffey and Paterson, 2010). Meltwater production in a temperate ice layer, b_e, can be calculated (Cuffey and Paterson, 2010) as

$$b_e = \frac{S_E Z_t}{L_i}, \tag{5}$$

where S_E is the strain heating rate and Z_t is the basal ice thickness. We assume a typical temperate glacier strain rate of 0.2 a^{-1} (Cuffey and Paterson, 2010) and calculate melt for the mean glacier thickness (~200 m; Anderson and others, 2008) by estimating the basal shear stress through the ice column, keeping all factors constant apart from ice thickness. Since shear stress and strain rate are related, the strain rate is estimated to vary proportionally to the basal shear stress.

RESULTS

The total mean basal melt rate at elevations between 300 and 1500 m a.s.l. of Franz Josef Glacier is 2.47 m a^{-1}. The mean geothermal and frictional heat-induced basal melt is 0.20 m a^{-1}, with geothermal heat contributing basal melt of 0.01 m a^{-1} and frictional heat contributing basal melt of 0.19 m a^{-1}. Rainfall-induced basal melting results are shown graphically in Figure 2. Mean rainfall-induced basal melt for elevations between 300 and 1500 m a.s.l. is 1.71 m a^{-1}, when rainfall inputs are considered directly into the glacier (0.44 m a^{-1}) and indirectly into the glacier from the true north and south Waiho Valley sides (0.54 and 0.73 m a^{-1} respectively). It is the high frequency of moderate (by West Coast New Zealand standards)-intensity rainfall events, r_i = 25–49 mm (35 events a^{-1}) and r_{ii} = 50–74 mm (17 events a^{-1}), that contributes in the most significant way to mean rainfall-induced basal melting (0.46 and 0.39 m a^{-1} respectively). Maximum rainfall-induced basal melting of 2.67 m a^{-1} occurs at the terminus of the glacier (Fig. 2). Dissipative heat production within water occurring between 300 and 1500 m a.s.l. produces mean melting of 0.55 m a^{-1}, 0.37 m a^{-1} of which is contributed by rainfall and 0.18 m a^{-1} by surface melt. In addition, melting produced through ice deformation accounts for a negligible 0.006 m a^{-1}.

DISCUSSION

Sensitivity analyses

Sensitivity analyses show that for geothermal and frictional heat-induced basal melt the most sensitive parameters are the basal shear stress, τ_b, and basal speed, u_b, which are directly used to calculate basal friction (Table 2). For example, a change in τ_b of 100 kPa results in a 0.073 m a^{-1} change in the basal melt rate, while a change in u_b of 0.3 m d^{-1} results in a 0.06 m a^{-1} change in the basal melt rate. Both of these parameters have been measured either directly or indirectly over the lower elevations of the glacier, so the amount of variation is unlikely to be large. The geothermal heat flux, G, and basal temperature gradient, Θ_b, appear to have a negligible impact on results. Table 2 shows that a change in G of 25 mW m^{-2} results in a 0.003 m a^{-1} change in the basal melt rate, while a value for Θ_b of 0.05°C results in a 0.012 m a^{-1} reduction in the basal melt rate.

Table 2. Sensitivity of the basal melt rate to changes in variables at the terminus of Franz Josef Glacier

Type of basal melt	Variable	Value used	Range tested	Max. change in melt rate $m\,a^{-1}$
Geothermal and frictional heat-induced basal melt	Basal shear stress	150 kPa	50–250 kPa	0.073
	Basal sliding velocity	$0.8\,m\,d^{-1}$	$0.5–1.1\,m\,d^{-1}$	0.060
	Geothermal heat flux	$60\,mW\,m^{-2}$	$40–80\,mW\,m^{-2}$	0.003
	Basal temperature gradient	$0°C\,m^{-1}$	$0–0.05°C\,m^{-1}$	0.012
Rainfall-induced basal melt	Rainfall reaching subglacial system	100%	100–75%	0.320
	Temperature of rainfall	10°C	7.5–12.5°C	0.625
	Lapse rate	$4.5°C\,km^{-1}$	$0.3–0.6°C\,km^{-1}$	0.160
Heat dissipation within water	Mean water elevation change from glacier surface to terminus	600 m	500–700 m	0.091
Heat dissipation within ice	Basal shear stress	150 kPa	50–250 kPa	0.004
	Strain rate	$0.2\,a^{-1}$	$0.1–0.3\,a^{-1}$	0.003

The rainfall-induced basal melt rate is most sensitive to the temperature of rainfall, T_r, and the amount of water that reaches the basal system from the Waiho Valley sides. Table 2 shows that if only 75% of the rainfall on the valley walls contributes to basal melt of subglacial ice, then the basal melt rate will decrease by $0.32\,m\,a^{-1}$. The other major influence on basal melt sensitivity is the temperature of the rainfall. An increase or decrease from $T_r = 10°C$ of 2.5°C results in a $0.64\,m\,a^{-1}$ change in the basal melt rate. The 10°C used in calculations will vary throughout the year. However, given heavy rainfall events are most common during spring and summer, with high air-temperature maxima at the terminus of >20°C in summer, 10°C would appear to be a conservative estimate of T_r. The lapse rate has a minimal sensitivity to change. A lapse rate change of $1.5°C\,km^{-1}$ yields only a $0.16\,m\,a^{-1}$ change in the basal melt rate.

Basal melting caused by heat dissipation within water has a low sensitivity to change in mean elevation (Table 2). An elevation change of $500 \pm 100\,m$ between the glacier surface and the terminus results in only a $0.09\,m\,a^{-1}$ change in the basal melt rate. Basal melt produced due to heat dissipation within ice is highly sensitive to variation in basal shear stress and strain rate (Table 2). However, the basal melt produced is negligible ($0.006\,m\,a^{-1}$), so the effect of a $0.004\,m\,a^{-1}$ and $0.003\,m\,a^{-1}$ change in melt rate due to a change in τ_b of 100 kPa and change in strain rate of $0.1\,a^{-1}$ respectively is insignificant in terms of total basal melting on Franz Josef Glacier.

Geothermal and frictional heat-induced basal melt

The basal melt rates for geothermal and frictional heat-induced basal melt calculated herein for Franz Josef Glacier of $0.20\,m\,a^{-1}$ are several orders of magnitude greater than those reported for polar ice sheets (e.g. $0.005–1.5\,m\,a^{-1}$, central Greenland ice sheet (Fahnestock and others, 2001); $<0.001\,m\,a^{-1}$, West Antarctic ice sheet (Budd and others, 1970); $0.006\,m\,a^{-1}$, north Greenland ice sheet (Buchardt and Dahl-Jensen, 2007)). The geothermal heat flux has been shown to have a significant influence on basal melt rates in locations with highly elevated geothermal heat flow caused by volcanic phenomena, such as in the central Greenland ice sheet, where the $100\,mm\,a^{-1}$ of basal melt requires a geothermal heat flux of $970\,mW\,m^{-2}$ (Fahnestock and others, 2001). However, our results suggest that the basal shear stress and ice-flow velocities are significantly more influential than the geothermal heat flux for temperate glaciers, most likely due to their high mass turnover, yielding high ice-flow and basal shear stress values.

Rainfall-induced basal melt

The rainfall-induced basal melt rate calculated herein is more than an order of magnitude greater than geothermal and frictional heat-induced basal melt rate. The $>2\,m\,a^{-1}$ of basal melt produced through heat advection and heat dissipation of water indicates that precipitation is not just important in contributing to accumulation on high-precipitation, temperate glaciers, but also significantly contributes to ablation. While the flow of water will be most concentrated through the subglacial conduits, the total melt will be the same to a first-order approximation irrespective of the location of the drainage paths, assuming water remains in contact with ice. This is likely given that flow of water in the subglacial drainage system will be turbulent, meaning that the entire volume of water will be in contact with the ice at some stage as it travels through the glacier. Water entering the glacier has the same potential to melt ice regardless of its location within the glacier. The mean basal melt of $\sim 2.50\,m\,a^{-1}$ on the lower to mid-ablation zone of Franz Josef Glacier is an extremely significant contribution to the overall ablation rate when it is considered that measured surface ablation at the terminus is $\geq 20\,m\,w.e.\,a^{-1}$ (Anderson, 2003), which corresponds to a total ablation rate of $\sim 23\,m\,w.e.\,a^{-1}$ at the terminus. This ablation rate fits quite well with recent mass-balance modelling of Franz Josef Glacier by Alexander and others (2011), which required $26\,m\,w.e.\,a^{-1}$ at the terminus for a steady-state glacier.

Effects and implications

Basal melting is not currently considered in mass-balance calculations for temperate glaciers. This would be acceptable if there were actual measurements to indicate that basal melting did not occur or, at the very least, was not influential on temperate glacier melting rates, but there is no justification for not including a basal melt component in measurements and estimates of mass balance. Basal melting appears to account for >10% of the ablation at Franz Josef Glacier, which is a significant contribution to the overall ablation rate. This is important given that temperate glaciers are regarded as high-quality indicators of climate change (e.g. Anthwal and others, 2006; Haeberli and others, 2007). Interpretations of annual mass balance are likely to be incorrect due to underestimations of the total ablation rate if a basal melt component is not included. Thus, glacier mass-balance measurements should include both surface and basal components of ablation on high-precipitation, temperate glaciers. We note that the most significant factor leading to basal melting on Franz Josef Glacier is rainfall, and while annual rainfalls on New Zealand glaciers are some of the highest in glacial environments worldwide, rainfall-induced basal melt is still likely to be relevant to glaciers in similar temperate environments with high precipitation rates, such as North America, Patagonia and New Zealand (Oerlemans, 2001). Since the majority of the basal melt is from mass convection of heat to the glacier by rainwater and subsequent heat exchange by contact, changes in precipitation will change the mass balance significantly, potentially confounding simplistic temperature-related estimates of climate change.

CONCLUSION

The role of basal melting within the subglacial zone of temperate glaciers represents a significant omission in our understanding of glacier melting processes. Over the lower to mid-ablation zone (300–1500 m a.s.l.), mean rainfall-induced basal melt ($1.71\,\mathrm{m\,a^{-1}}$) is approximately an order of magnitude more significant than basal melt produced by geothermal and frictional heat ($0.2\,\mathrm{m\,a^{-1}}$) on high mass-turnover temperate glaciers, due to high amounts of warm rainfall. The high amounts of rainfall and surface melt also contribute to high production of heat dissipation within water ($0.55\,\mathrm{m\,a^{-1}}$), while melting due to ice deformation is negligible ($0.006\,\mathrm{m\,a^{-1}}$). Since total mean basal melting has been shown to contribute $\sim$$2.50\,\mathrm{m\,a^{-1}}$ or the equivalent of $\sim$10% of the total glacier ablation rate to Franz Josef Glacier, accurate mass-balance ablation measurements on high-precipitation, temperate glaciers must include ablation in the subglacial zone in addition to typical surface ablation measurements.

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