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Joint Geodetic and Seismic Analysis of Englacial and Subglacial Hydraulic Effects on Surface Crevassing near a Seasonal, Glacier-Dammed Lake on Gornergletscher, Switzerland

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JOINT GEODETIC AND SEISMIC ANALYSIS OF ENGLACIAL AND SUBGLACIAL HYDRAULIC EFFECTS ON SURFACE CREVASSING NEAR A SEASONAL, GLACIER-DAMMED LAKE ON GORNERGLETSCHER, SWITZERLAND

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Abstract

Glacial outburst floods are difficult to predict and threaten human life. These events are characterized by rapid draining of glacier-dammed lakes via the sub/englacial hydraulic network to the proglacial stream. The glacier-dammed lake on Gornergletscher in Switzerland, which fills and drains each summer, provides an opportunity to study this hazard. For three drainages (2004, 2006, and 2007), icequakes (IQ) are tracked as well as on-ice GPS movement. The seasonal seismic networks had 8 – 24 three-component stations and apertures of about 300 – 400 m on the glacier surface. The seasonal GPS arrays contained 4 – 8 GPS antennae on the glacier surface with spacings of 100 – 1,000 m. Using Rayleigh wave coherence surface IQ location, 2924, 7822, and 3782 IQs were located, in 2004, 2006, and 2007, respectively. The GPS data were smoothed using a nonparametric protocol, with average station velocities of 10 – 90 mm/day. In 2006, strains were calculated using five stations within 500 m of the lake, co-located with the seismic network. In 2007, strains were calculated using seven stations that were not co-located within the seismic network.

In 2006, there was no obvious increase in GPS speeds with slow (~21 days), supraglacial lake drainage. However, when drainage was subglacial as in 2007 (sub/englacial over ~11 days), GPS speed increased over 100% (6 to 13 cm/day). This speed increase is evidence for basal sliding induced by subglacial drainage. In general, when the strain increases on the principle extension axis that aligns with the crevasse opening direction, IQs are more prolific. A diurnal signal in both IQ occurrence and surface strain is observed, with peak strain occurring in the mid- to late-afternoon (15:00 – 19:00 local) across the study area in 2006. This time-shift in strain and spatiotemporal dependence of IQs is interpreted to be caused by diurnal variations in melt-induced sliding. This analysis highlights crevasse formation on short time scales where glacier flow is controlled by sliding variations in response to water input into the subglacial drainage system. Coupled seismic and GPS monitoring can thus make a key contribution to our understanding of brittle deformation and crevassing of glacier ice.

Introduction

Glacial outburst floods, also known as jökulhaups, are difficult to predict and threaten human life and property near glaciated regions. These events are characterized by rapid draining of glacier-fed lakes to the proglacial stream. These drainages have produced catastrophic floods in the recent and past times as evidenced by historical and geomorphological records (Clague and Evans, 2000; Bjornsson, 2002; Quincey et al., 2007). Therefore, the studying of jökulhaups is of importance to communities who live in their flood paths near glaciated regions.

Outburst floods occur by a variety of mechanisms: water overflowing an ice dam; rupture of subglacial, englacial and supraglacial water bodies; sudden breaching of a moraine or unconsolidated rock dam; rock falls or ice avalanches on to the glacier; periods of extreme ice melt; prolonged and heavy rainstorm events; glacier surges; and periods of subglacial geothermal activity or eruptions of subglacial volcanoes containing crater lakes (Clague and Mathews, 1973; Post and Mayo, 1970; Wilfried Haeberli, 1983; Owens, 2004; Roberts, 2005; Bjornsson, 2002; Clague and Evans, 2000; Quincey et al., 2007). They can cause centimeter scale displacements of the glacial surface over the period of days to weeks (Walter et al., 2008; Zwally et al., 2002; Magnusson et al., 2007). In the Greenland ice sheet, when the drainage of a large supraglacial lake occurred via the subglacial hydraulic network, an increase in seismicity, longitudal acceleration, and glacial uplift were observed (Zwally et al., 2002). Zwally concluded that the melt season speed up of the Greenland ice sheet surface could, in part, be due to the draining of multiple meltwater lakes to the base of the ice sheet throughout the season causing enhanced basal sliding.

Studies on alpine glaciers have shown that in the early melt season and during subglacial lake drainages, effective pressure averaged over some large area of the bed is inversely proportional to the sliding speed (Anderson, 2004). Anderson also showed that large drops in water pressure inferred by abrupt increases in proglacial discharge coincided with lowering of the surface of the glacier, and cessation of basal sliding. For temperate glaciers which have water in their systems, a basic relationship between water pressure and sliding can be shown (Paterson, 1994):

$$u_b \sim \tau_b^p / N^q \qquad (1)$$

Where u_b is the sliding velocity, τ_b^p is the basal shear stress, N^q is the effective pressure (overburden ice pressure minus the basal water pressure), and p and q are empirically derived constants. Previous studies have also shown that areas of high

water pressure at the glacier base correspond to "slippery" patches which facilitate basal sliding while areas of low water pressure correspond to "sticky" patches, which inhibit basal sliding (Iken and Truffer, 1997). As the melt season progresses, isolated, water-filled cavities from the slippery patches connect to form channels that drain the subglacial water more efficiently, lowering pressure build ups. This lowers the amount of basal sliding as the melt season progresses. In addition to cavity interconnection, erosional melting of more existing channels also lowers the amount of pressurization for a given water input (Bartholomaus et al., 2008; Anderson, 2004; Copland et al., 2003)**.** However, if there is period of lower water input such as an extended period of low temperatures, then the basal channels will creep closed, allowing the normal diurnal melt input to over pressurize the system and cause increased sliding when the temperatures return to their seasonal average (Copland et al., 2003). Both daily melt generation and lake drainage contributions to glacial accelerations will have mass balance and sea level rise implications as the global climate changes (Moore et al., 2013).

Furthermore, qualitative insight between fast and slow ice flow regimes can be provided by the orientation and type of crevassing (Vornberger and Whillans, 1990; Harper and Pfeffer, 1998). Crevasse fields have been used to identify surge events on alpine glaciers and recent speed ups at the Greenland Ice sheet (Herzfeld et al., 2013; Colgan et al., 2011). On decadal timescales, changes in crevassing measured by remote sensing can demonstrate changes in glacial thickness and slope which can be due to climatic forcing (Etzelmüller et al., 1993; Lliboutry, 2002; Colgan et al., 2011). Quantifying surface strain rates can identify regions of extensional and compressional flow that can lead to the opening and closing of crevasses can show how the glacier will behave with changing climates.

There is limited evidence that crevasse opening rates could have a diurnal cycle that could be due to thermal expansion and contraction (Meier and Mark, 1957). These crevasses would be further affected by daily meltwater routed to the crevasses where it can pool. If there is a large enough water supply to keep the crevasse filled to greater than approximately 92% of its depth, then a hydrofracture can propagate to the base of the glacier (Weertman, 1973; Colgan et al., 2016). These hydrofractured crevasses can deliver large amounts of meltwater to the base in regions without moulins (Boon and Sharp, 2003). Thus, glaciers that have crevasses with the increased potential for hydrofracturing will generally experience more basal sliding relative to that of nearby, uncrevassed glaciers (Colgan et al., 2011; Lampkin et al., 2013)

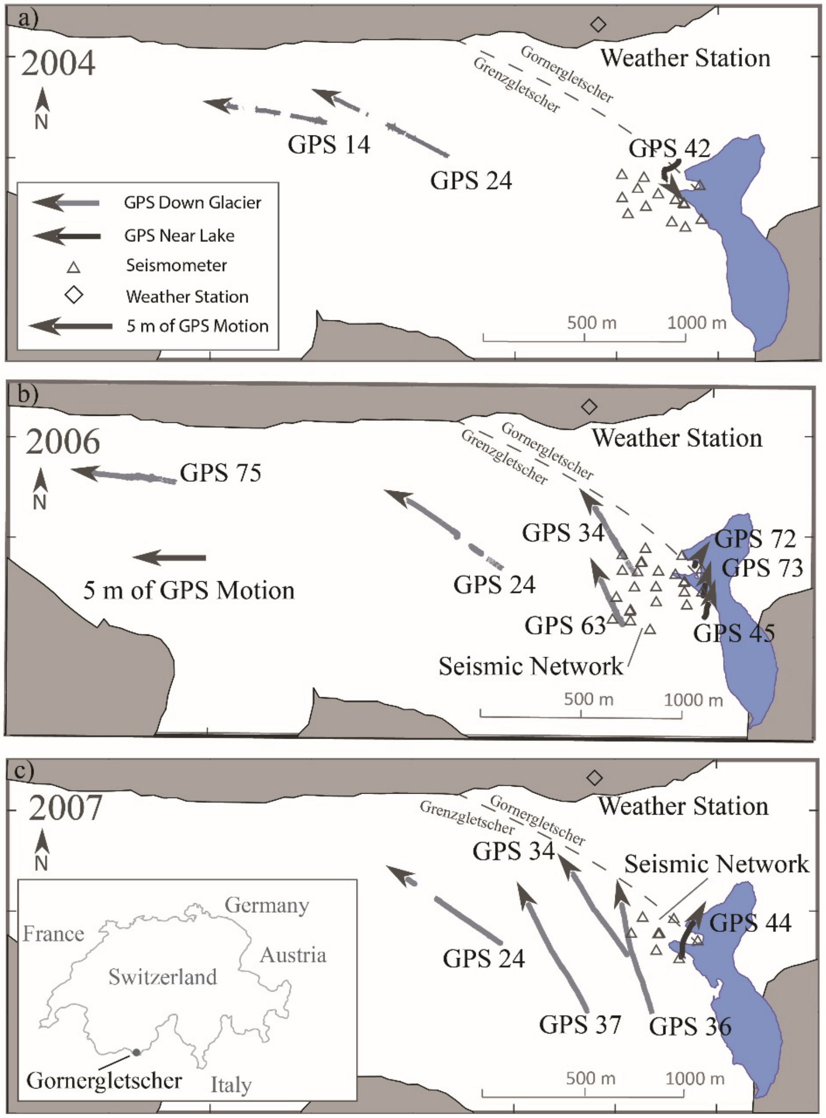

Figure 1 Study region. Maps of Gornergletscher and the deployed networks in (a) 2004, (b) 2006 and (c) 2007

Moreover, melt water entering the glacier has tremendous latent heat which causes cryohydrological heating within the bulk glacier. Cryohydrological heating represents an addition to the conventional three term heat equation consisting of advection, conduction, and strain heating (Phillips et al., 2010). As water passes through the glacier system and is refrozen or transported, large amounts of latent heat can transfer from the water to the surrounding ice. Ice viscosity varies nonlinearly with ice temperature, therefore small changes in temperature can result in large changes in effective ice viscosity (Glen, 1954). Cryohydrological heating appears to be most sensitive to the spacing of elements within the englacial hydraulic network, which is generally controlled by crevasse spacing. Therefore crevasses may ultimately govern the efficiency of cryohydrological heating within the glacier (Phillips et al., 2010). Because crevasses form in regions of high stress and strain, crevasse induced rheological changes in the ice either via cryohydrological heating or water infiltration can greatly

increase strain rates in these important regions of the glacier (Pfeffer and Bretherton, 1987). A potential feedback between crevasse, rheology, and deformation has been proposed whereby crevasse growth contributes to the efficiency of cryohydrologic warming and hydraulic weakening, which allows for higher strain rates in the ice, and then contributes to the further propagation of crevasses (Lampkin et al., 2013; Colgan, 2014). The impacts on ice rheology by cryohydrological warming and hydraulic weakening imply that crevasse extent may strongly influence the deformational velocity in high stress regions of the ablation and low accumulation zones of the glacier (Colgan et al., 2016). Crevassing and strain are interconnected and therefore the studying of strain and crevassing via GPS and seismic methods will further elucidate this relationship at the glacier surface.

2.1 Study site

Gornergletscher in southern Switzerland with its seasonal, ice-dammed lake, Gornersee (Figure 1), provides an ideal setting to study these phenomena. The study site is located at the coalescence of two large tributary glaciers, Gornergletscher and Grenzgletscher, at an elevations of 2600 m about 5 km from the terminus. The glacier experiences a change in direction from north to east and is highly crevassed in the study site. A synthesis study of over 50 years of water flow data at Gornergletscher's proglacial stream has shown long term and interannual fluctuations in outburst flood discharge rates (Huss et al., 2007). In the first half of the 20th century, outburst floods from Gornergletscher, Switzerland, were large enough to cause damage in the town of Zermatt, Switzerland located 20 km downstream. However, the volume of the lake and intensity of outburst floods has lowered in recent years (Huss et al., 2007).

During the 2004 – 2008 field seasons, annual lake drainages and their effect on glacial surface motion were studied on Gornergletscher. These five drainages fell into three categories though the author stated that these categories may not be relevant outside of Gornergletscher (Riesen, 2011):

Type O1: The onset of the drainage is very rapid as the water is routed through the basal hydraulic network. After this period, changing drainage intensity occurs at the diurnal scale. This type is usually initiated by the complete or partial floatation of damming ice which provides a conduit for large amounts of discharge relative to type O2.

Type O2: This type occurs when a glacier overspills the damming ice without floating it. The draining water then flows out over the surface of the ice at a slower rate than the type O1 or O3 drainages. The continuation of outflow is achieved by the erosion of larger and deeper channels as the lake drains.

Type O3: After initiation, the lake level progressively decreases with the largest discharge rate being near the end of drainage. The flow of water enlarging a subglacial channel is suspected to account for this progressive increase in flowrate.

2004 and 2007 which are studied in this paper are both type O1, while 2006 which is also studied here is type O2. 2005 and 2008, which are not studied here, are both type O3. Type O1 and O3 were observed to experience large increases in glacial motion and strain associated with the drainage whereas type O2 was not. For 2004 and 2007, strain and flow rates increased considerably across most of the area of Gornergletscher and propagated down glacier from Gornersee (Riesen, 2011). Even though the overspill water of the type O2 drainage of 2006 was routed to basal channels via a moulin, the flux of water from the drainage was not large enough to over pressurize the system above floatation levels as in 2004 and 2007. Riesen concluded that to initiate a large sliding event a sudden transfer of melt water to the base of the glacier is needed and type O2 drainages cannot supply enough water to generate sliding. Channel accommodation from lake drainages can also cause surface strain. In 2005, a GPS network placed on the surface of Gornergletscher during the drainage of Gornersee measured the inflation of the glacier surface to accommodate the enlarging basal channel from the discharged water. (Sugiyama et al., 2010). This flow pattern was analogous to the ground motion observed during a magma intrusion.

Furthermore, a crevasse field exists near the study site qualitatively showing that this is a region of high strain. The presence of this crevasse field will allow for the studying of how crevassing is affected by daily and seasonal scale water input. Also, the co-measurement of GPS with icequakes will allow insight into how the brittle and ductile processes of icequakes are affected on the seasonal and diurnal scales.

Studies on Gornergletscher and other glaciers in the Swiss alps have shown that daily meltwater generation can cause centimeter scale uplift and transient longitudal acceleration (Sugiyama et al., 2010; Sugiyama and Gudmundsson, 2004). In addition, it has been shown that basal icequake activity beneath Gornergletscher has a diurnal signal, with basal icequake productivity being highest in the early mornings as the basal water pressures are falling or at their lowest (Walter et al., 2008). While the surface icequakes comprise a large portion of the total icequake catalog, attention has been mostly focused on the basal icequakes on Gornergletscher (Walter et al., 2008).

Surface motion has been studied before on Gornergletscher via GPS networks (Walter et al., 2008; Riesen, 2011; Roux et al., 2010). Though, these studies focused mainly on the glacier response to daily meltwater generation immediately

before, during, and after drainage of Gornersee in 2004 and 2006. Seismic and geodetic methods have been used on the Greenland Ice Sheet to study uplift, longitudal acceleration, and increased seismicity during large lake drainages (Zwally et al., 2002). One study measured real time longitudal strain rate and seismicity of a marine terminating glaciers using GPS and seismic array and found that periods of increased strain corresponded with increased calving (Sunil et al., 2007).

This study incorporates strains calculated from GPS stations at the glacier surface and surficial icequakes of which a large percentage correspond to crevasse opening to study the hydraulic effects on temporal scales ranging from diurnal to seasonal over the 2004, 2006, and 2007 melt seasons.

Methods

Geodetic and seismic data for 2004, 2006, and 2007 were obtained by placing GPS and seismic arrays on the surface of Gornergletscher (Figure 1) during the summer ablation season (May to August). This data was originally acquired by Walter et al. (2008) and has been used in multiple studies (Sugiyama et al., 2010; Roux et al., 2010; Walter et al., 2009, 2008). The years 2004, 2006, and 2007 contained three, eight, and five GPS stations, respectively. Station

Table 1 Sampling rates for the geodetic network in 2004, 2006, and 2007

	2004	**2006**	**2007**
Sampling Interval	3 hours	3 hours to 8 seconds	2 minutes

placement varied each year (Figure 1) with 2004 and 2006 sampling a broader portion of the glacier while 2007 remained focused near the seasonal lake. Each measurement had an accuracy of +/- 0.3 cm (Sugiyama and Gudmundsson, 2004). Sampling rates varied during the study period and can be found in Table 1. Temperature and precipitation data were gathered from a meteorological station located on the unglaciated, northern margin of Gornergletscher (Figure 1). Lake levels were obtained from pressure transducers placed in the lake for the duration of the seasons.

The total distance traveled each year was dependent on station location. Stations positioned further west of Gornersee (brown arrows Figure 1) traveled an average of 8 – 10 m, while stations near the lake (green arrows Figure 1) traveled an average of 1 – 3 m throughout the melt season. Stations azimuths each year correspond to the flow directions of Gornergletscher and Grenzgletscher, with the exceptions of the stations closest to the lake of the two glaciers. For example, in 2004 station 42, which was closest to the lake (green arrow Figure 1a), is traveling upstream while the other stations travelling downstream (brown arrows Figure 1a). Similarly, in 2006 and 2007 the stations closest to the lake travelled partially upstream, while stations further west travelled downstream.

Table 2 Average speeds between Julian day 120 to 190

Year:	Down Glacier Average Speed:	Up Glacier Average Speed:	Station #24
2004	8.2 cm/day	0.8 cm/day	8.7 cm/day
2006	8.1 cm/day	1.5 cm/day	8.8 cm/day
2007	8.8 cm/day	1.4 cm/day	9.3 cm/day

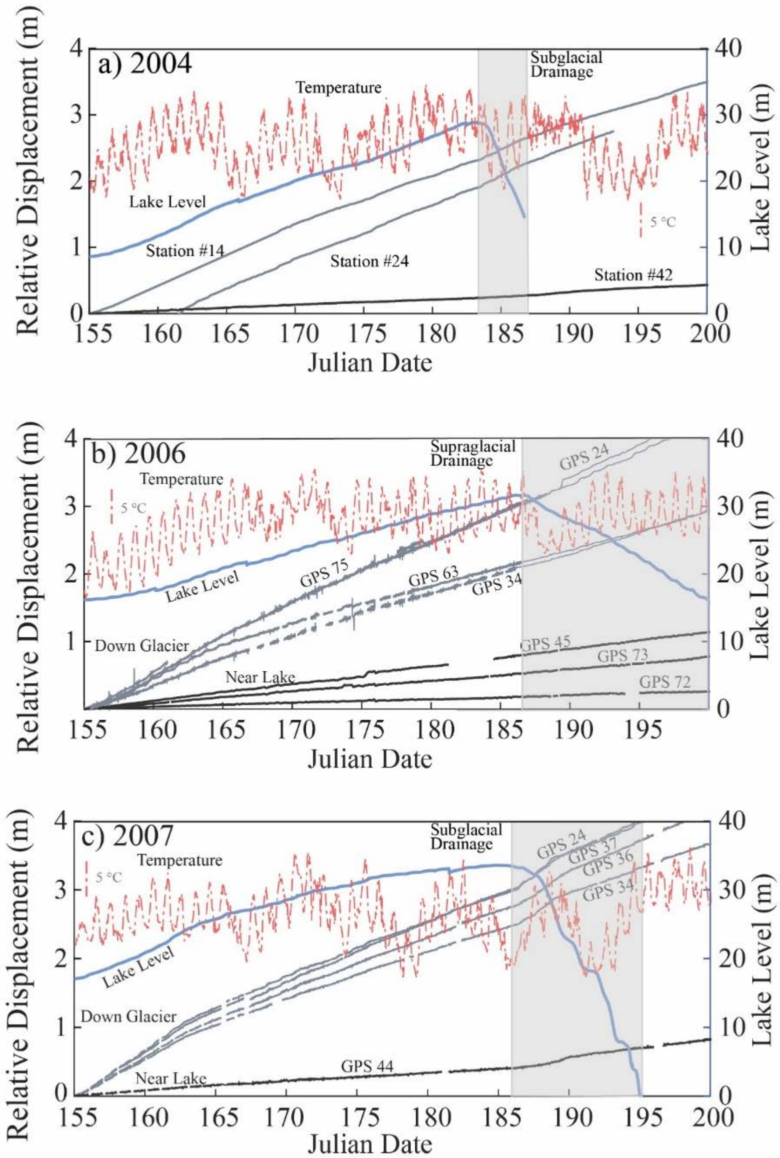

Figure 2 GPS displacements as a function of time for the melt seasons in (a) 2004, (b) 2006, and (c) 2007

Figure 2 shows variations in the glacier's horizontal surface displacement, relative lake level, and temperature from Julian day 120 to 220 (April 29th to August 7th) for each field season. A linear regression was used to fit the horizontal displacements for the duration of the season to obtain the velocities. The slowest moving stations are located near Gornersee, while the faster ones are located further down glacier (Table 2). Station #24 was the only station to be placed in the same location each year and does not show a significant change between seasons.

During the beginning of the season, the lake fill rate and GPS displacement are governed by the air temperature (red line Figure 2). For example, in Figure 2c near Julian day 160, an increase in the lake fill rate occurs synchronously with an increase in temperatures and speeds of all stations. The subsequent lowering of temperature and fill rate around Julian

Table 3 Speeds of GPS stations before, during, and after the lake drainage in 2004, 2006, and 2007

Station #:	**Speed Before Drainage (cm/day)**	**Speed During Drainage (cm/day)**	**Speed After Drainage (cm/day)**
2004			
Up Glacier:			
#42	0.8	1.1	1.5
Down Glacier:			
#14	7.0	10.0	6.6
#24	8.1	10.7	1.5
2006			
Up Glacier:			
#72	0.7	0.5	0.4
#73	1.8	1.6	3.2
#45	2.6	2.5	2.5
Down Glacier:			
#34	5.5	6.5	6.9
#75	9.9	9.7	9.8
#24	8.0	9.7	9.2
#63	5.3	5.8	5.7
2007			
Up Glacier:			
#44	1.2	3.0	2.9
Down Glacier:			
#36	7.4	13.0	9.3
#34	6.3	13.3	7.1
#37	8.0	14.2	9.6
#24	7.4	16.5	8.2

Day 162 is also accompanied by a decrease in speeds of all GPS stations relative to pre-warming levels.

Figure 3 shows the horizontal surface displacement during the period of drainage. This subset of the total season is indicated by the grey boxes in Figure 2. 2004 and 2007 experienced subglacial or a combination of subglacial, englacial, and supraglacial draining, whereas 2006 only exhibited supraglacial drainage (Table 3). During the period of fastest drainage, increased glacial motion was observed in 2004 and 2007 but not in 2006. Table 4 shows the speeds of all stations before, during, and after this period of intense draining. Speeds were averaged over time periods as follows: for 2004 and 2007 (Figures 3a and 3c) the periods chosen were seven days before the observed acceleration, the period of the acceleration, and seven days after. For 2006 (Figure 3b), a period of seven days centering on the interval of lake drainage was used to calculate the speed during drainage, with speeds before and after corresponding to seven-day periods before and after the window.

To identify diurnal signals caused by rising water pressures above floatation levels, times of minimum and maximum vertical displacements were calculated from the GPS data. However, because the vertical data were noisy, displacements were first detrended and smoothed using a non-parametric method over 24-hour periods. The smoothed data was then averaged over seven days to obtain average hourly vertical displacements for a given week (Figure 4).

In the weeks leading up to the drainage in 2007 (Figure 4a - c), we observed a daily vertical and horizontal displacement low centering around 10:00 UTC and a high around 18:00 UTC in most stations. In the weeks after drainage (Figure 4d - f), the daily vertical high shifted to center around 02:00 UTC with a smaller magnitude of uplift. These times correspond to when the water pressures are at or near their minimum and maximums as was measured by Walter et al (2008).

The ability of strain to show the principle axes of compression and extension allows for the comparison of crevasse opening to the changing deformation occurring at the glacier surface and for the inference of the changing stress field at the

Table 4 Duration and mode of drainage for each season

Year:	Drainage Duration:	Drainage Mode:	Rapid Glacial Motion:
2004	6 days	Subglacial	Yes
2006	21 days	Supraglacial	No
2007	11 days	Subglacial, Englacial, Supraglacial	Yes

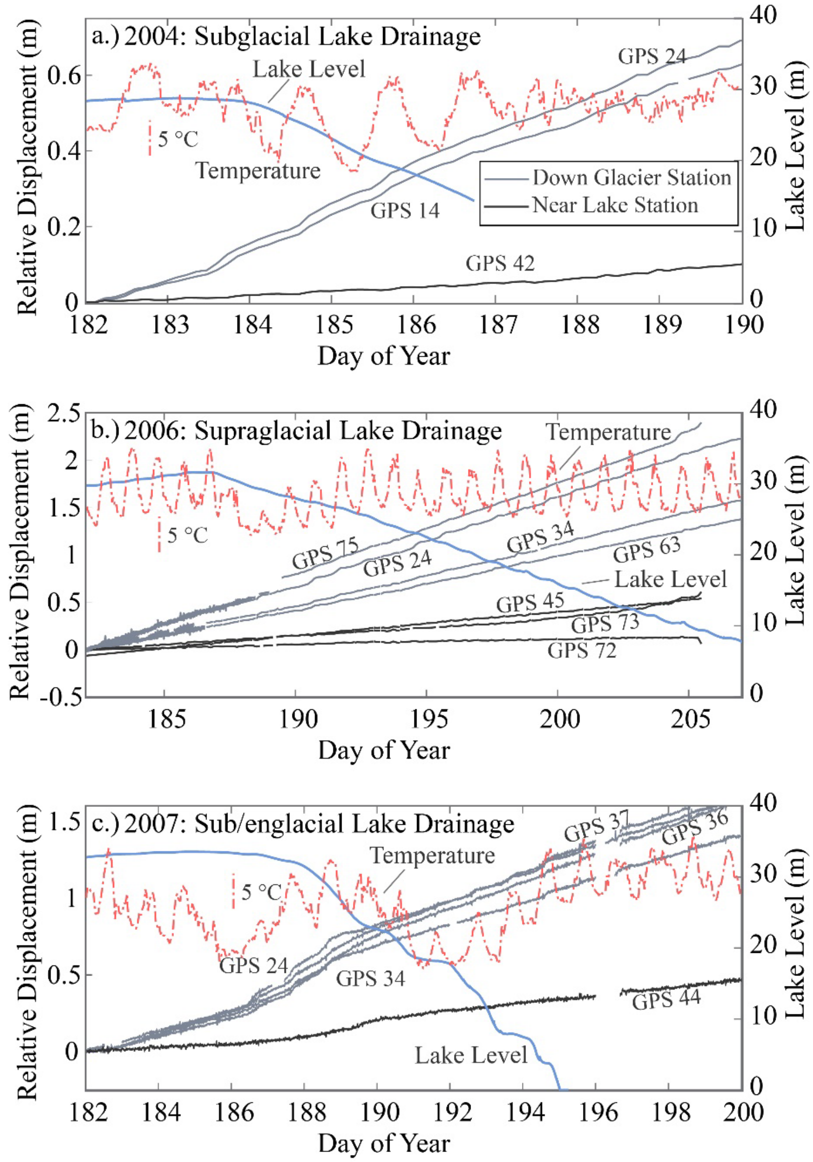

Figure 3 Relative displacement during lake drainage for a) 2004, b) 2006, and c) 2007

surface of the glacier. Before strains were calculated, GPS data were passed through the above non-parametric smoothing protocol with a seven-hour window and one-hour timestep for times of high rate data and a 13-hour window with a three-hour timestep for low rate data. This protocol down sampled the high rate data and up sampled low rate data. For example, in 2007 stations 75 and 34 were down sampled from 1 point every 30s to 1 point per hour while stations, 45, 73, and 72, were up sampled from one point every three hours to one point per hour. These stations were slow moving, and the data

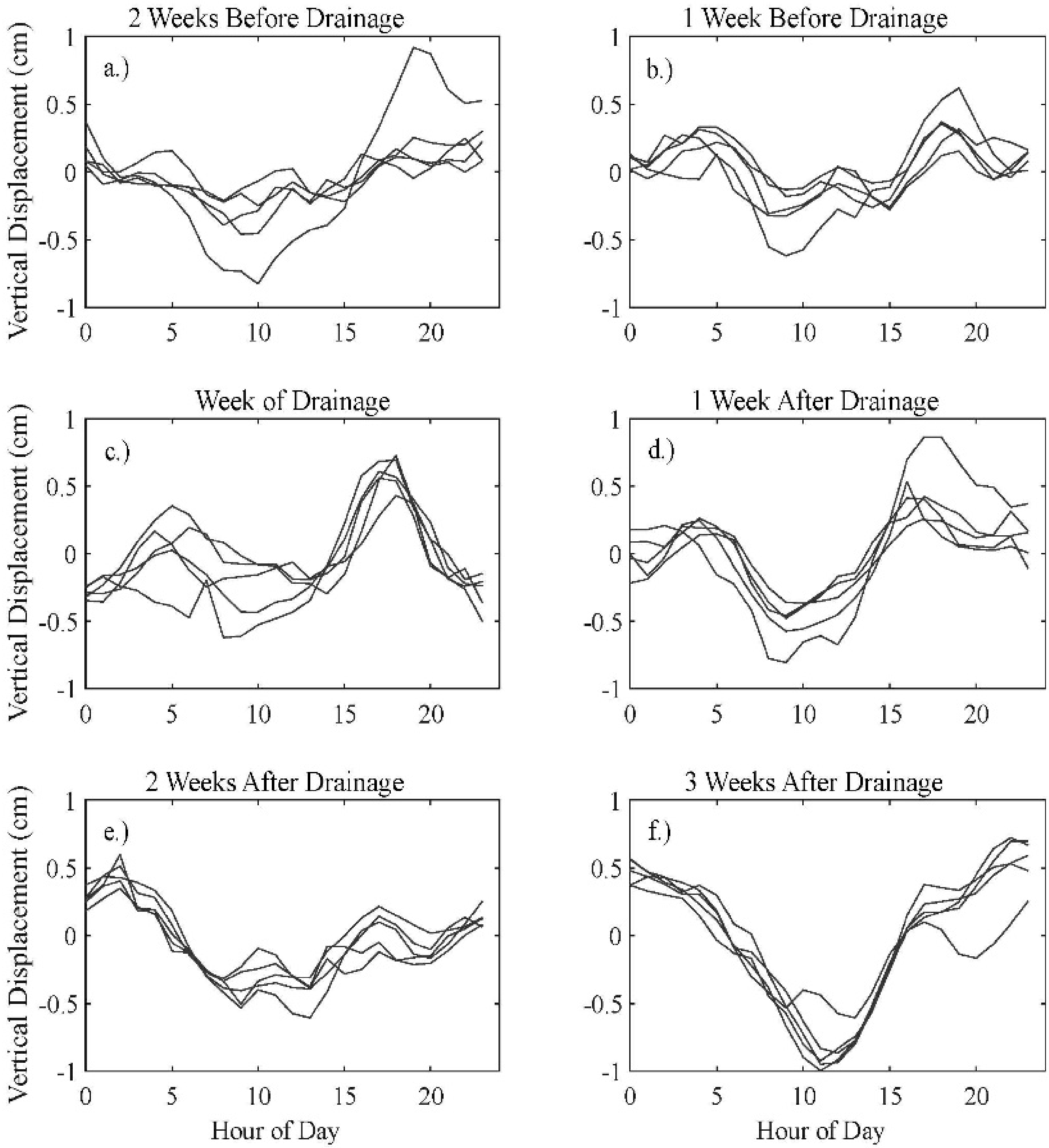

Figure 4 Stacked Vertical Displacements for GPS stations for selected weeks before and after drainage in 2007

were not noisy. Data gaps larger than four hours were omitted from the strain analysis to prevent the introduction of artifacts. Once the raw GPS data were smoothed, displacements were calculated at one to three-hour intervals.

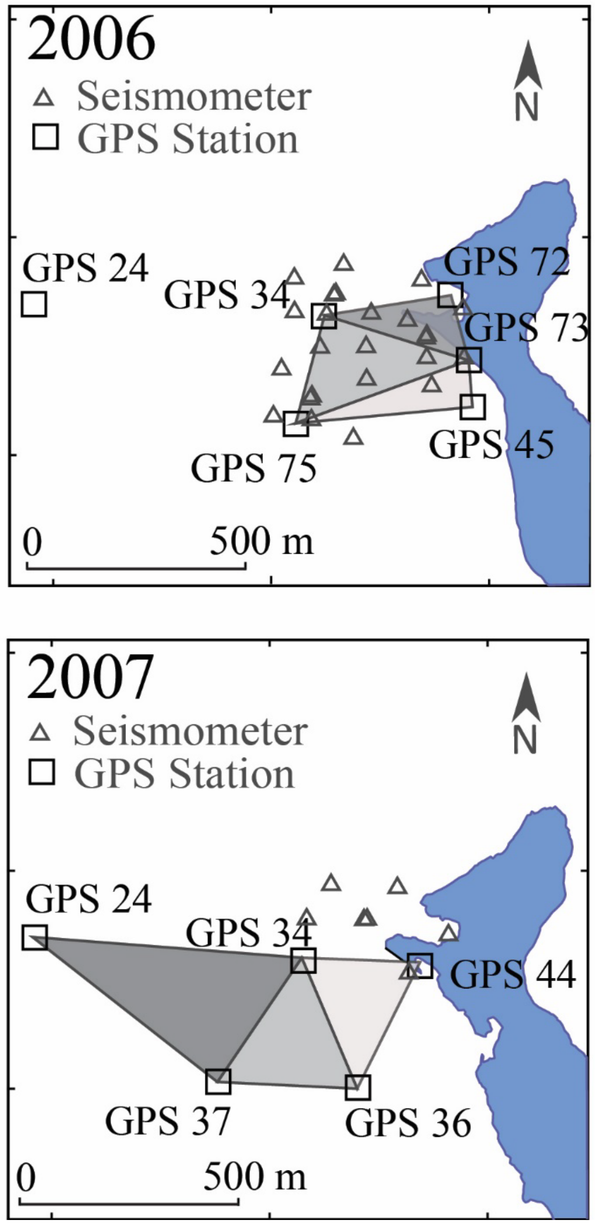

Figure 5 Station configuration for: (a) data recorded in 2006 and (b) data recorded in 2007

The stations were arranged into the three strain areas which shared GPS stations (Figure 5). The displacement of the GPS stations which comprised the strain areas were used to calculate strain rates based on the method presented in Savage et al., (2001).

The seasonal seismic networks had 8 - 24 three-component stations and apertures of about 300 – 400 m on the glacier surface located within 400 m west of Gornersee. The recording instruments operated at sampling frequencies as high

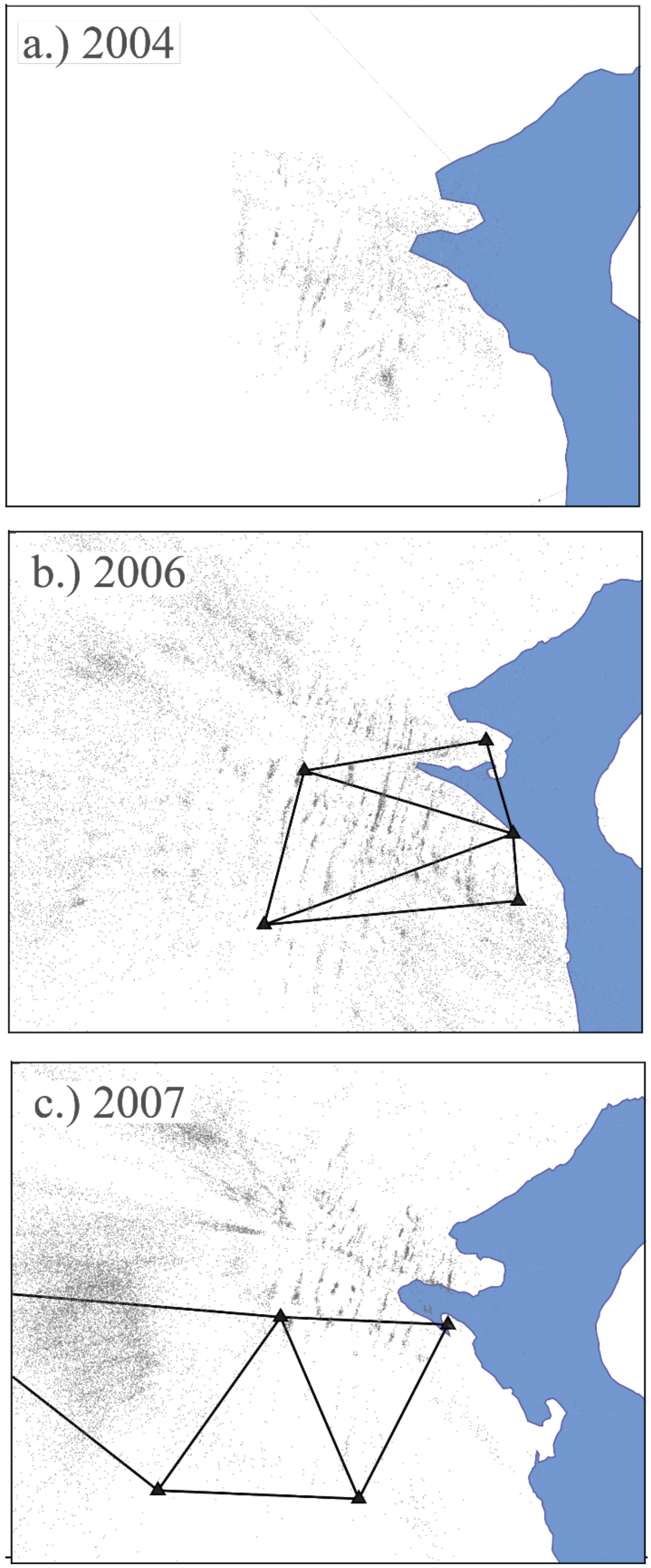

Figure 6 Map view of icequakes locations used in this work for data recorded in years: a) 2004, N=2924 events; b) 2006, N=7822 events; and c) 2007, N=3782 events

as 4000 Hz and the deployment spanned one to two months each summer. The 2004 and 2006 recording were based on event recognition using a trigger algorithm at the recording stage (Walter et al., 2008), whereas in 2007 the glacier motion was recorded continuously and a short-term average to long-term average (STA/LTA) trigger algorithm was applied to the data at the processing stage (Walter and others, 2009; see Appendix A). For these deployments the seismometers had eigenfrequencies between 1 and 28 Hz. Because icequake activity is pervasive within our study region we were able to record between 30,000 and 200,000 events each summer season. The vast majority of these events are surface crevasse openings, although intermediate-depth as well as basal events were also recorded (Walter et al., 2008, 2009). Using a Rayleigh wave coherence surface icequake location method (Roux et al., 2010), 2924, 7822, and 3782 icequakes were located, in 2004, 2006, and 2007, respectively. For more information of the seismic instrumentation the reader is referred to (Walter et al., 2008). Figure 6 shows all icequakes detected for each campaign in map view. In all years, a large portion of the icequakes occurring near the lake correspond to crevasse opening. Icequakes were then spatially sorted by which strain area they occurred in. Icequakes occurring outside these areas were excluded from this analysis.

Results

4.1 2006

Figure 7 shows strain, temperature, and icequake rate plotted against Julian day for the northern, central, and southern strain areas in 2006 (Figure 5a). Strain, temperature, and icequake rate appear to be correlated in the beginning of the 2006 melt season. As the temperature increases from day 152 to 164, the diurnal strain rate fluctuations and background strain rates increases (~100 – 200 micro-strain per day). Icequakes productivity is highest in the beginning of the time series while temperatures are rising (up to 60 icequakes per hour). The icequakes occurring in the central and southern areas appear to be in phase with the strain rate and temperature fluctuations. One episode of high icequake activity occurs during high temperatures on day 163, but strain rate data are not present during this time due to GPS network outages.

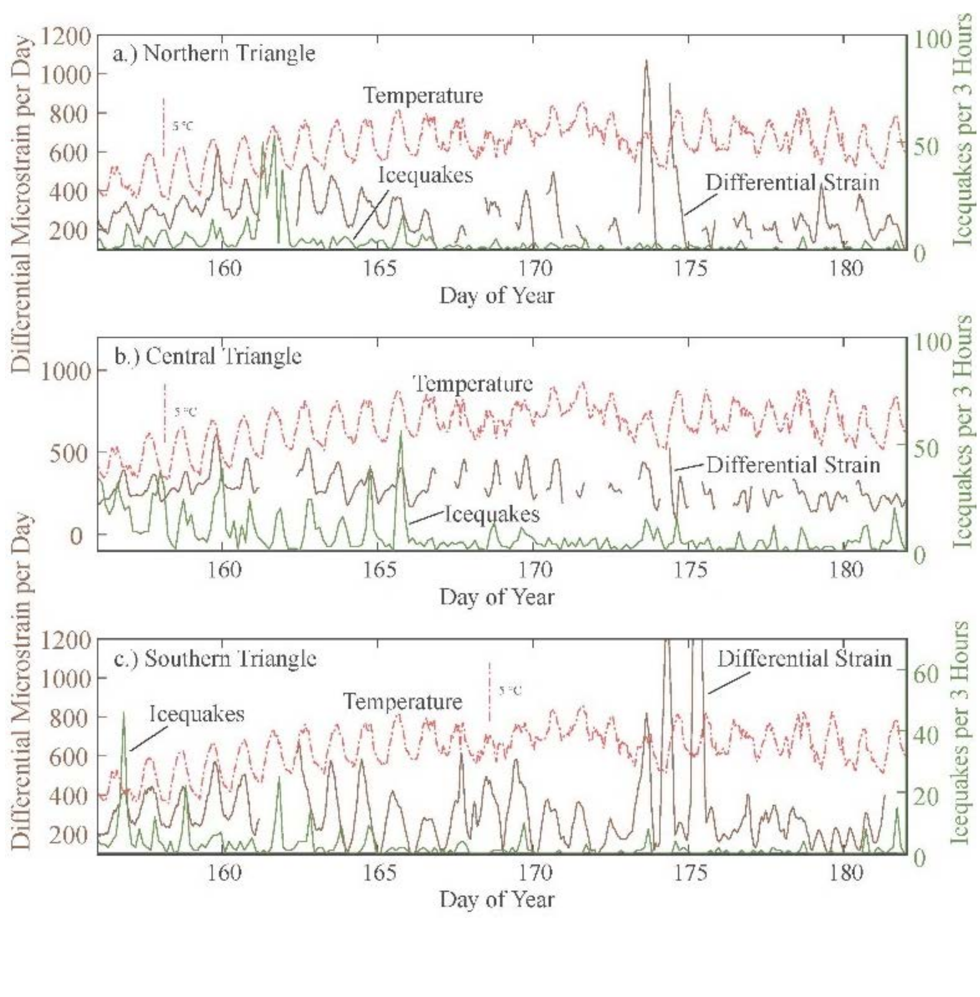

Figure 7 The differential strain rate (microstrain per day), hourly temperature (C), and icequakes per three hours are plotted against the day of year in the 2006 early season

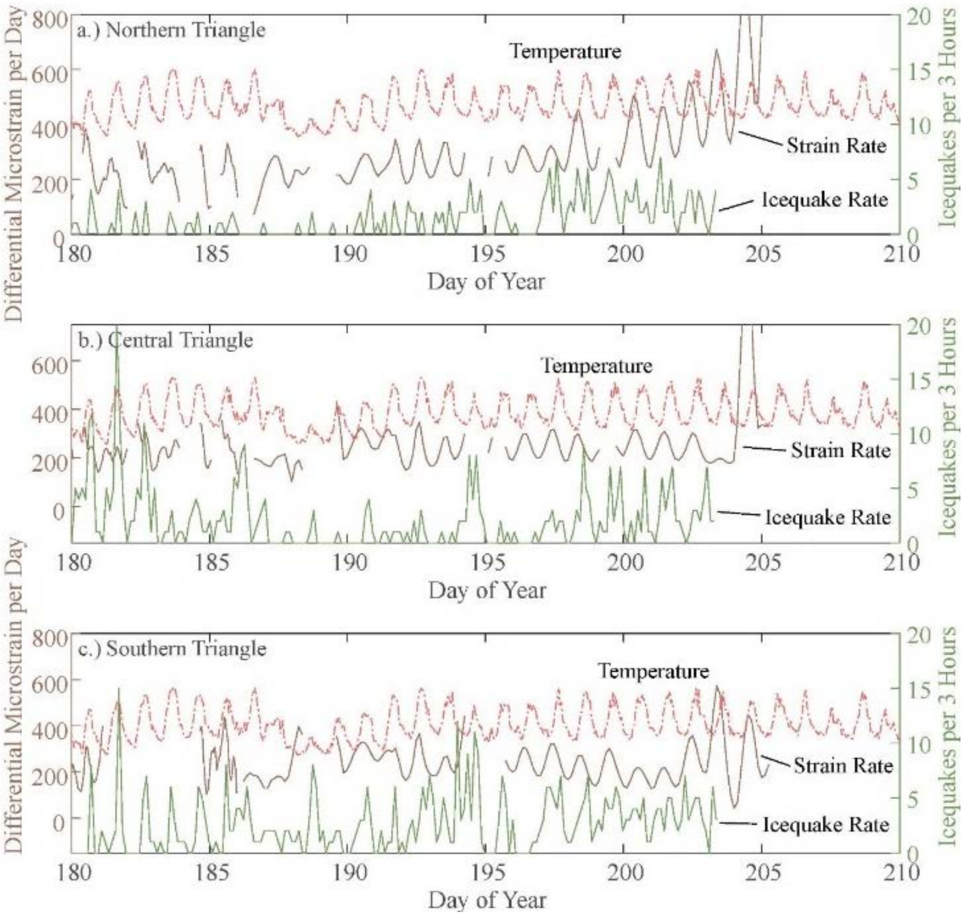

Figure 8 The differential strain rate (microstrain per day), hourly temperature (C), and icequakes per three hours are plotted against the day of year during the 2006 lake drainage

By day 167, both the icequake rate and strain rate begin decreasing for all areas. The northern and central areas see a decrease in both background (~150 micro-strain per day) and daily fluctuations (from 300 to 100 micro-strain per day) in strain rate while the southern area only sees a drop in the background strain rate (~100 micro-strain per day).

During a 7.5 mm precipitation event in 2006 on day 173, the strain rates in the northern and southern areas increase by 1000 microstrain per day. We are unable to assess if the signal is present in the central area due to network outages during this period. There is no increase of icequakes above the background rate in any of the areas during or after the precipitation event.

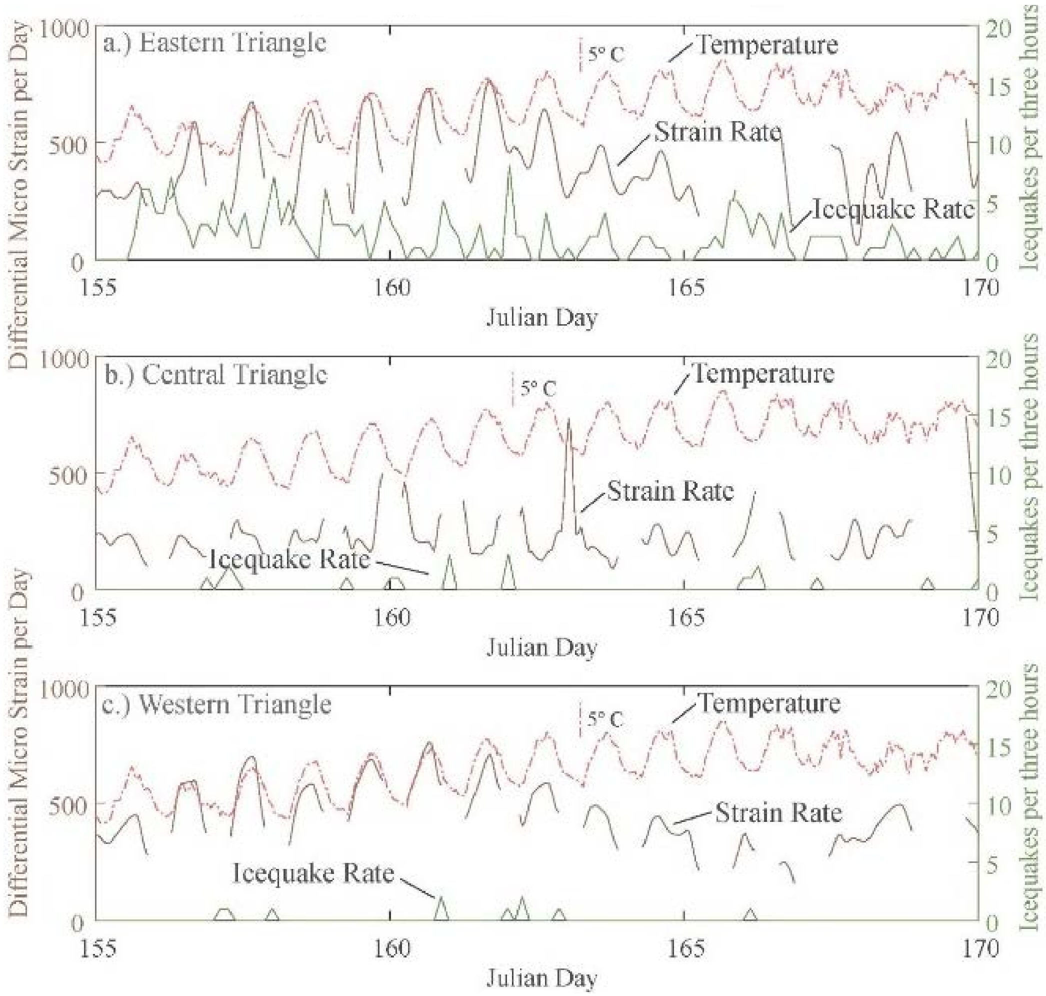

Figure 9 The differential strain rate (microstrain per day), hourly temperature (C), and icequakes per three hours are plotted against the day of year in the 2007 early season

No strain rate increase is seen during the supraglacial lake drainage (type O2) of 2006 (Figure 8, day 187). Icequake rates increase by 5 – 10 icequakes per hour, however this is below the early season rates (30 to 50 icequakes per hour). From about day 202 to the end of the timeseries, the diurnal and background strain rates increase in the northern and southern areas, whereas an increase in diurnal strain rate is only seen on day 204 in the central area.

4.2 2007

Figure 9 shows the differential strain rate, temperature, and icequake rate plotted against Julian day for the eastern, central, and western areas in 2007 (Figure 5b). Detected icequake productivity is less than 2006 due to the location of the

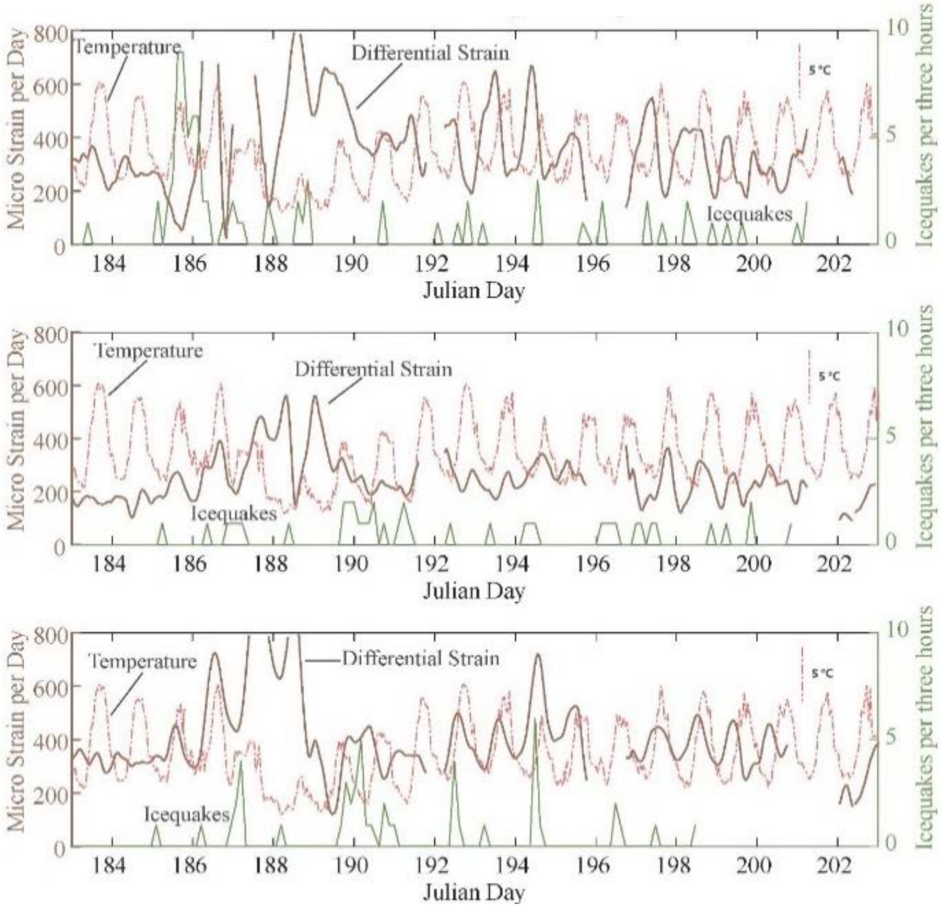

Figure 10 The differential strain rate (microstrain per day), hourly temperature (C), and icequakes per three hours are plotted against the day of year during the 2007 lake drainage

seismic network outside of the strain network in 2007. In the beginning of the 2007 melt season (day 155 - 162), the strain rate appears to be correlated to daily temperature fluctuations. In the western and eastern areas, the strain rate and temperature are in phase, while the strain rate and temperature are phase shifted on the central area. After day 162 there is a decrease in the both the background (~250 micro-strain per day) and the diurnal strain rates (~500 micro-strain per day to ~200 micro-strain per day) in the eastern and western areas.

The mode of drainage in 2007 was observed to be a combination of a sub/supra/englacial (type O1). When the drainage initiated around day 186 all areas show an increase in strain rate of 400 – 700 micro-strain per day (Figure 10). The largest strain increases are seen in the eastern and western areas from day 185 – 190. During this period, the strain rate still appears to be in phase with the temperature variations.

In the eastern area, there is an increase in icequakes when the strain rate is at its lowest which is centered around day 186. It should be noted that the icequake productivity remains low (~10 icequakes per hours) with respect to the 2006 data. After the most intense drainage (day 192), the strain rate appears to be out of phase with respect to daily temperature fluctuations. In contrast, in the central and western areas, the strain rate appears to stay in phase with respect to the temperature.

Discussion

In all years, the study site was in a high velocity gradient region at the coalescence of the two tributaries of Gornergletscher. With nearly an order of magnitude difference between the slowest and fastest moving stations, this region of the glacier experiences more strain than other regions of the glacier. This is evidenced by the crevasse field in the study region which is a morphological representation of high strain regions (Herzfeld et al., 2013; Mayer and Herzfeld, 2000).

5.1 Beginning of season

The correlation in 2006 and 2007 of strain and icequake rates to temperature in the beginning of the melt season (Figure 7 day 152 – 160 and Figure 9 155 - 162) suggests that daily meltwater is percolating down to the glacial base raising subglacial water pressures and increasing basal sliding. This pressure increase is caused by the influx of melt water being greater than the amount of water the subglacial hydraulic network can accommodate, which causes the flowing fluids to increase in pressure (Anderson, 2004; Iken and Truffer, 1997). As the pressure increases to the flotation level, the glacier will decouple from the bed, lowering friction and increasing basal sliding (Figure 11a,b) (Iken and Truffer, 1997). As can be seen in Table 2, the stations near the lake are moving slower than the stations downstream, creating a velocity gradient. This velocity gradient causes the relatively cold brittle surface ice to strain and crack to produce the large amounts of icequakes that are seen in this time.

In the following period (Figure 7 after day 160 and Figure 9 after day 162), both the background and diurnal strain rates decrease. This indicates that the draining water has eroded larger subglacial channels that can accommodate more melt water. These larger channels lower diurnal pressure fluctuations, by draining the water in the network faster, and lower pressure build up, basal sliding, and background strain rates (Figure 11c, d) (Anderson, 2004).

The icequake productivity also decreases over this period (Figure 7 after day 160 and Figure 7 after day 162). This may be due to two main mechanisms: 1.) decreases in strain rate and 2.) changes in ice rheology from increased crevasse propagation and cryohydrological heating (Glen, 1954; Phillips et al., 2010). Cryohydrological heating occurs because the inflowing water has large of amounts of latent heat that can be efficiently delivered to the bulk of the glacier via the heavily crevassed surface, changing the rheology of the glacier. This change in ice rheology would allow the glacier surface to accommodate more ductile strain (Pfeffer and Bretherton, 1987).

5.2 Precipitation event in 2006

The precipitation event on day 173 in 2006 (Figure 7) shows a strain increase of almost an order of magnitude following 7.5 mm of rainfall. This input of water would percolate down to the base and cause additional melting of the glacier to generate a large pulse of water to the basal hydraulic network. This pulse will increase basal water pressures and initiate surface acceleration and straining. However, during this increase in strain, there is not an associated increase in icequake activity. This is likely due to a previously proposed cryohydrological heating. By this point in the season, the crevasse system in this region of the glacier would be well formed, allowing for the efficient transmission of heat to the surrounding ice (Phillips et al., 2010). The rain water falling at the surface of the glacier would have a tremendous amount of latent heat that would both warm the bulk of the ice and continue the melting of the glacier (Pfeffer and Bretherton, 1987; Lampkin et al., 2013). This continued melting overwhelming the glacier hydraulic network along with a more ductile glacier surface and interior could allow for the large, aseismic surface strain.

5.3 Drainage events in 2006 and 2007

In the period leading up to the supraglacial drainage (type O2) in 2006, there are increases in icequake productivity, though at lower levels than the beginning of the season (< 20 icequakes per hour). After the initiation of drainage, there are no significant increases in strain in any of the areas (Figure 8). Though the water from this drainage is routed to the base through a moulin, there is no increase in surface speed or strain due to relatively low flux of water to the base not overpressurizing the system (Figure 11f) (Riesen, 2011). The lack of an increase in strain rates and the previously mentioned effect on ice rheology from cryohydrologic heating can explain the constant rates of earthquakes during the type O2 drainage in 2006.

In contrast, the 2007 sub/en/supraglacial lake drainage (type O1) shows a very large increase in strains in all three areas and an associated increase in icequakes in the Eastern area (Figure 10). The cold spell in the period leading up to the drainage would have suppressed melt generation and allowing for creep closure of the subglacial hydraulic network (Copland et al., 2003). This decreased subglacial capacity and increased water input from lake drainage, overwhelmed the subglacial network and caused the water pressures to raise above the flotation level (Walter et al., 2008). This increase in water pressures then caused increased basal sliding, a change in the velocity gradient, and therefore strains (Figure 11e).

While the lake was still draining, the strains decreased (Figure 10 after day 190) due to channel enlargement and decreased basal water pressures (Anderson, 2004). In addition, as the lake drained, the overburden pressure of the lake

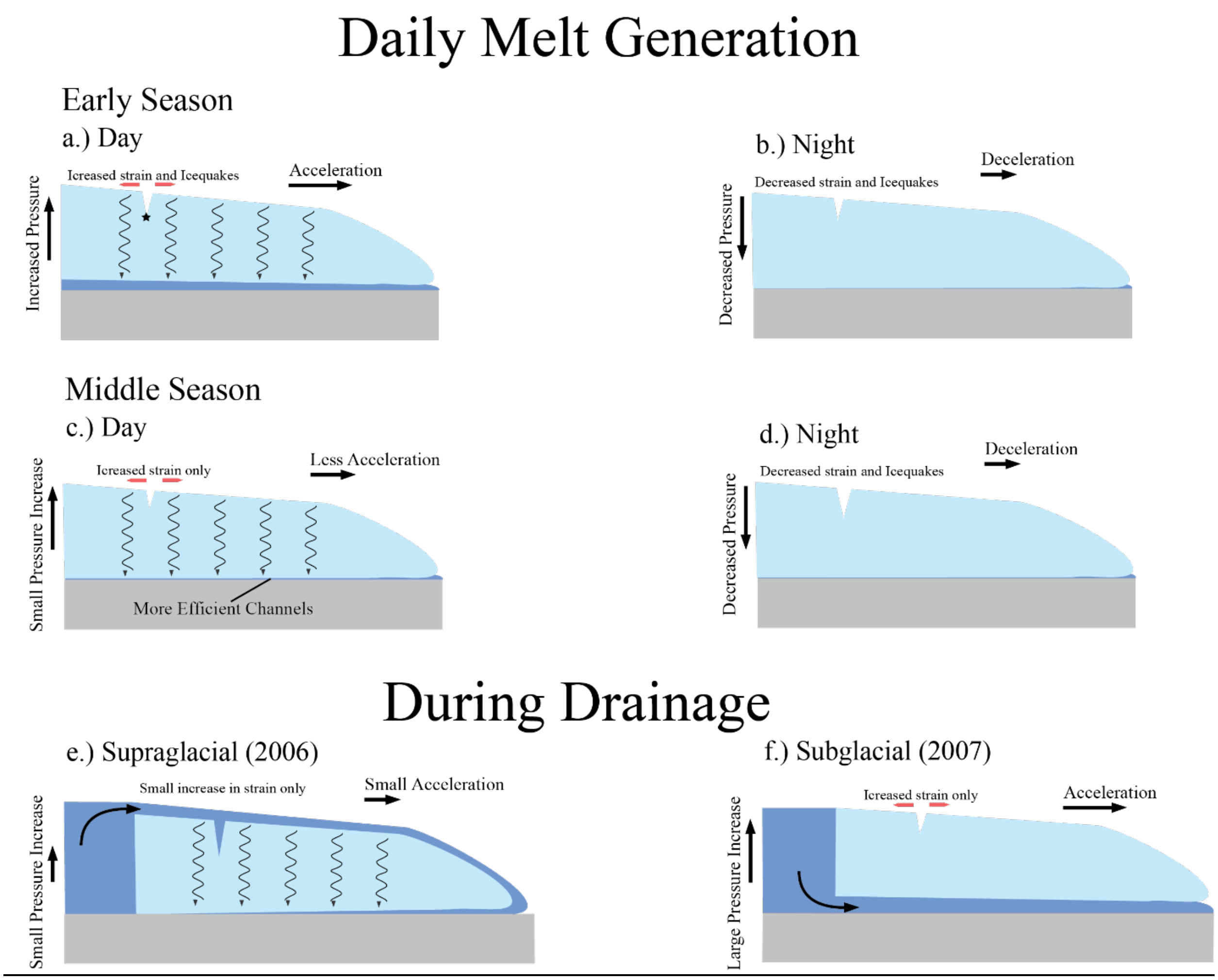

Figure 11 Cartoon of daily melt generation scenarios, depicting what might potentially happen during different parts of the season

water decreased with falling lake level which could lower the hydraulic input rate (Riesen, 2011). The combination of these two mechanisms could explain the decreases in strains that are observed in this period.

During and after the time of increased water input from the lake drainage, the strains are in phase with the daily temperature fluctuations. The diurnal modulation by the daily meltwater suggests that daily melt is on the same order as the lake input. Whereas if this were not true, then there would not be any daily fluctuation because the daily melt input would negligibly perturb the basal water pressures and consequently strain rates.

5.4 Seasonal picture

In the beginning of the melt season, the relatively cold ice is brittle and has yet to form an efficient basal hydraulic network. As the snow and firn begin to melt at the glacier surface, the meltwater being routed to the base overpressurizes the basal hydraulic network causing uplift and lowering of friction at the base of the glacier and increased sliding. As the base slides, the top of the glacier will also move and deform. This will open new crevasses and propagate existing ones in zones of high strain and because the ice is still relatively cold and brittle, it will crack to generate icequakes. As the melt season progresses, the daily melt that is generated erodes the basal hydraulic network to allow for the accommodate for larger water input. This will keep the system from overpressurizing and will lower the basal sliding and decrease the diurnal fluctuations in strain that are seen in 2006 and 2007. In addition, with the propagation of the crevasse field, melt water with large amounts of latent heat are routed through the crevasse and deliver heat to the bulk glacier which changes the rheology of the ice. This change in rheology with the lowering of strain rates could account for the lower icequake productivity that is seen as the melt season progresses.

If in the middle season we see a significant amount of water input from events like rain or lake drainages, this can lead to increased melting of and water input into the glacier, which can overwhelm these more efficient meltwater channels. However, most events will not be large enough to do this outside of rapid lake drainages. As the seasonally dammed Gornersee drains, the type of drainage is important to the behavior at the surface of the glacier. For type O1 and O3 drainages, the glacier surface will experience increased motion and strain, however for type O2 drainages the surface will not as shown in the 2004 and 2007 type O1 drainages vs the 2006 type O2 drainage. Another important factor to the behavior of the surface is the ambient temperature leading up to the drainage as is demonstrated between 2004 and 2007. In 2007 there was a sustained temperature drop of 10 – 15 °C before the drainage which would allow for creep closure of the basal network, increased overpressurization and basal sliding when compared to the constant mean temperatures seen in 2004.

Conclusions

A GPS and seismic network were placed on the surface of Gornergletscher, Switzerland near a seasonal dammed lake to study the relation between strain rate, icequakes, and crevassing during outburst floods and seasonal changes in melt generation for the summers of 2004, 2006, and 2007. Three to eight GPS arrays and 8 – 24 seismometers with apertures of 300 – 400 m were deployed. An icequake catalog was calculated based upon Rayleigh wave coherence and two-dimensional strains were calculated from the GPS displacements.

In the beginning of melt seasons on Gornergletscher, Switzerland, daily meltwater percolating to the glacier base is the main driver of straining and icequakes at the glacial surface. This is caused by the influx of water being greater than the amount of water the subglacial hydraulic network can accommodate, increasing water pressures beneath the glacier. As the pressures increase and the glacier reaches the flotation level, friction between the base of the glacier and its bed lowers and allows increased basal sliding. This basal sliding increases motion at the surface with the stations near the lake moving slower than the stations downstream, which leads to straining and crevassing. Because the ice is still relatively cold and brittle, brittle crevassing occurs as evidenced by increased seismicity during this period.

Later in the season, strain decreases from the erosion of more efficient basal meltwater channels, lowering the basal pressures. This lowering of the pressures causes the friction between the base of the glacier and its bed to increase, slowing the motion of the glacier. During this time, a decrease in seismicity is also observed. This is attributed to the lowering of the surface strain and the cryohydrological warming of the ice. This warming is from melt water containing high latent heat infiltrating the laterally and vertically propagating crevasse field allowing for the warming and changing of rheology of the ice.

When the lake drained subglacially in 2004 and sub/en/supraglacially in 2007 (type O1), increases in surface motion seen in 2004 (up to 40%) and 2007 (up to 100%) and therefore strains. However, this increase in surface motion and strains was not seen in 2006 when the lake drained supraglacially (type O2). Only an increase in surface seismicity was seen in the 2004 drainage, however, the authors do not have explanation of why the icequake productivity is higher in 2004 than in 2007 when the strains are higher. In 2007, a cold period just before the drainage period would have allowed for the partial creep closure before the drainage which would make the basal drainage system more inefficient. The increased input from the lake drainage would then overpressurize the less efficient hydraulic system beyond the sTable temperature case in 2004.

This would cause greater uplift of the glacier and sliding which is evidenced by the increased strain rates and displacements over this period for 2007.

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Vita

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