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Contemporary Glacier Processes and Global Change: Recent Observations from Kaskawulsh Glacier and the Donjek Range, St. Elias Mountains

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ABSTRACT. With an extensive ice cover and rich display of glacier behaviour, the St. Elias Mountains continue to be an enviable natural laboratory for glaciological research. Recent work has been motivated in part by the magnitude and pace of observed glacier change in this area, which is so ice-rich that ice loss has a measurable impact on global sea level. Both detection and attribution of these changes, as well as investigations into fundamental glacier processes, have been central themes in projects initiated within the last decade and based at the Kluane Lake Research Station. The scientific objectives of these projects are (1) to quantify recent area and volume changes of Kaskawulsh Glacier and place them in historical perspective, (2) to investigate the regional variability of glacier response to climate and the modulating influence of ice dynamics, and (3) to characterize the hydromechanical controls on glacier sliding. A wide range of methods is being used, from ground-based manual measurements to space-based remote sensing. The observations to date show glaciers out of equilibrium, with significant ongoing changes to glacier area, volume, and dynamics. Computer models are being used to generalize these results, and to identify the processes most critical to our understanding of the coupled glacier-climate system.

Key words: Kluane Lake Research Station, St. Elias Mountains, glaciology, Kaskawulsh Glacier, Donjek Range, glacier mass balance, glacier change, glacier dynamics, glacier surges, glacier-climate interactions, subglacial processes

RÉSUMÉ. Grâce à leur importante couverture de glace et au riche étalage de comportement des glaciers, les monts St. Elias continuent de servir de laboratoire naturel enviable pour la recherche glaciologique. Des études récentes ont été motivées, en partie, par la magnitude et la vitesse des changements observés dans les glaciers de l'endroit, qui sont riches en glace au point que la perte de glace a une incidence mesurable sur le niveau général de la mer. La détection et l'attribution de ces changements de même que les recherches à l'égard des processus des glaciers ont servi de thème central à des projets qui ont été mis en œuvre au cours de la dernière décennie à la station de recherche du lac Kluane. Les objectifs scientifiques de ces projets consistent (1) à quantifier les changements récents relativement à l'aire et au volume du glacier Kaskawulsh, puis à les mettre dans une perspective historique, (2) à faire enquête sur la variabilité générale de la réaction du glacier vis-à-vis du climat et de l'influence modulatrice de la dynamique de la glace, et (3) à caractériser le contrôle hydromécanique par rapport au glissement du glacier. Une vaste gamme de méthodes est employée pour parvenir à ces fins, allant des mesures manuelles sur le terrain à la télédétection spatiale. Jusqu'à maintenant, les observations indiquent que les glaciers ne sont pas en équilibre et que d'importants changements se produisent quant à l'aire, au volume et à la dynamique du glacier. Des modèles informatiques sont utilisés pour généraliser ces résultats ainsi que pour cerner les processus les plus critiques à notre compréhension du système couplé glacier-climat.

Mots clés : station de recherche du lac Kluane, monts St. Elias, glaciologie, glacier Kaskawulsh, chaîne Donjek, bilan de masse des glaciers, changements caractérisant les glaciers, dynamique des glaciers, crues glaciaires, interactions glacier-climat, processus sous-glaciaires

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INTRODUCTION

With close to 46,000 km^2 of ice cover (Berthier et al., 2010), the St. Elias-Wrangell Mountains are home to one of the largest icefields outside the polar regions. For this reason alone, they are deserving of scientific attention and indeed have a distinguished scientific history (Clarke, 2014). Yet they also harbour an exceptional number of surge-type and

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tidewater glaciers (e.g., Post, 1969), which makes them a laboratory for researchers interested in all forms of glacier dynamics. Active geophysical and orogenic processes combine to produce high uplift and erosion rates (e.g., Enkelmann et al., 2009), resulting in a geography characterized by extreme elevation changes over short distances (Clarke and Holdsworth, 2002) and therefore strong gradients in environmental variables. Orographic blocking of moisture from the Gulf of Alaska by some of the highest peaks in North America (e.g., Mt Logan, 5959 m above sea level [asl]) creates sharp climate contrasts across the range (e.g., Marcus and Ragle, 1970), with a corresponding diversity of glacier attributes and flow and thermal regimes.

The St. Elias region has recently been profiled for its high rates of glacier mass loss and significant contributions to global sea level (e.g., Arendt et al., 2008; Luthcke et al., 2008; Berthier et al., 2010). Between 1968 and 2006, glaciers in the St. Elias and Wrangell Mountains, which straddle the Yukon-Alaska border, thinned at an average rate of 0.47 ± 0.09 m a^{-1} water-equivalent (w.e.) (Berthier et al., 2010). Estimates of the thinning rates of Yukon glaciers alone over the last several decades range from 0.45 ± 0.15 m a^{-1} w.e. (E. Berthier, pers. comm. 2010) to 0.78 ± 0.34 m a^{-1} w.e. (Barrand and Sharp, 2010). With the acknowledgment that glaciers outside of the Greenland and Antarctic ice sheets have a significant role to play in determining 21st century global sea level (e.g., Radić and Hock, 2011), increasing effort has been devoted to detection and monitoring of glacier change. The elucidation of general processes underlying these changes has remained a focus of glacier research in the St. Elias Mountains, with an emphasis on the roles of both surface mass balance processes and internal or subglacial dynamics.

Here we introduce contemporary glaciological research initiated over the past decade in the St. Elias Mountains and supported by the Kluane Lake Research Station (KLRS). This work covers a spectrum from process-scale studies of glacier bed mechanics to documentation of recent glacier change. The scientific methods are also varied, ranging from traditional mass-balance measurements to borehole instrumentation to satellite remote sensing.

STUDY REGION

Excluding ice-core studies and the long-running Trapridge Glacier project (Clarke, 2014), recent glaciological research based out of KLRS has been concentrated in and around the Donjek Range on the northeastern flanks of the St. Elias Mountains (Fig. 1). Framed by the Kaskawulsh and Kluane outlet glaciers, this sector of the Donjek Range represents a transitional region between the nearly ice-free Kluane Ranges to the northeast and the heavily glacierized Icefield Ranges to the southwest. It is situated in a prominent orographic rain shadow and thus experiences a continental climate similar to that of the Kluane Lake region. Ongoing projects initiated by the University of Ottawa in 2006 and by Simon Fraser University and the University of British Columbia from 2006 to 2008 have focused, respectively, on Kaskawulsh Glacier and on the smaller alpine glaciers of the Donjek Range. This area is readily accessible from KLRS and offers a variety of glaciological processes for scientific inquiry.

Kaskawulsh Glacier

Kaskawulsh Glacier is ~70 km long from its shared accumulation area with the upper Hubbard Glacier, at an elevation of ~2500 m asl, to its terminus ~25 km southwest of the Kluane Lake Research Station, at ~820 m asl (Fig. 1). It provides the source of the Slims River (Fig. 2), the primary water input for Kluane Lake to the northeast (which drains to the Bering Sea), and the source of the Kaskawulsh River to the southeast (which drains to the Gulf of Alaska). One of the most iconic and best studied outlet glaciers of the St. Elias Mountains, Kaskawulsh Glacier was the focus of much glaciological research during the Icefield Ranges Research Project between the 1960s and early 1970s (e.g., Wood, 1963; Bushnell and Ragle, 1969; Ragle, 1972). Isotope and near-surface temperature measurements, both historical (Macpherson and Krouse, 1969) and contemporary (L. Copland, unpubl. data), suggest that the glacier is temperate throughout. The current area of Kaskawulsh Glacier is ~1095 km^2 (Foy et al., 2011). Ice thicknesses range from 539 m near the topographic divide with the upper Hubbard Glacier (Clarke, 1969) and ~500 m at the confluence of the north and central arms at ~1750 m asl (Dewart, 1969) to 778 m at ~1600 m asl (Clarke, 1969). The equilibrium line altitude is estimated from 2007 late summer satellite imagery as 1958 m asl, and it appears to have changed little since the 1970s (Foy et al., 2011).

Donjek Range Glaciers

The Donjek Range is a partially glacierized, L-shaped mountain range bounded to the south by Kaskawulsh Glacier, to the northeast by the Duke River, and to the west by Kluane Glacier and the Donjek River (Fig. 1). This roughly 30 × 30 km area is home to over 30 individual valley glaciers, most of them less than 10 km long. The glaciers range in elevation from ~1800 to 3250 m asl, with the largest of these draining northwest toward the Kluane Glacier. Post (1969) identified evidence for surging behaviour in more than seven of these glaciers.

Two unnamed glaciers in the range (hereafter "South Glacier" and "North Glacier") have been the subjects of detailed study since 2006–07. South Glacier, with an area of 5.3 km^2, ranges in elevation from 1970 to 2960 m asl, while North Glacier is 6.9 km^2 and ranges from 1890 to 3100 m asl (Wheler, 2009). South Glacier is generally thinner than North Glacier, with a mean ice depth of 64 m compared to 77 m for North Glacier, but has a greater maximum ice thickness of 200 m compared to 180 m for North Glacier (Wilson, 2012). As their working names imply, North

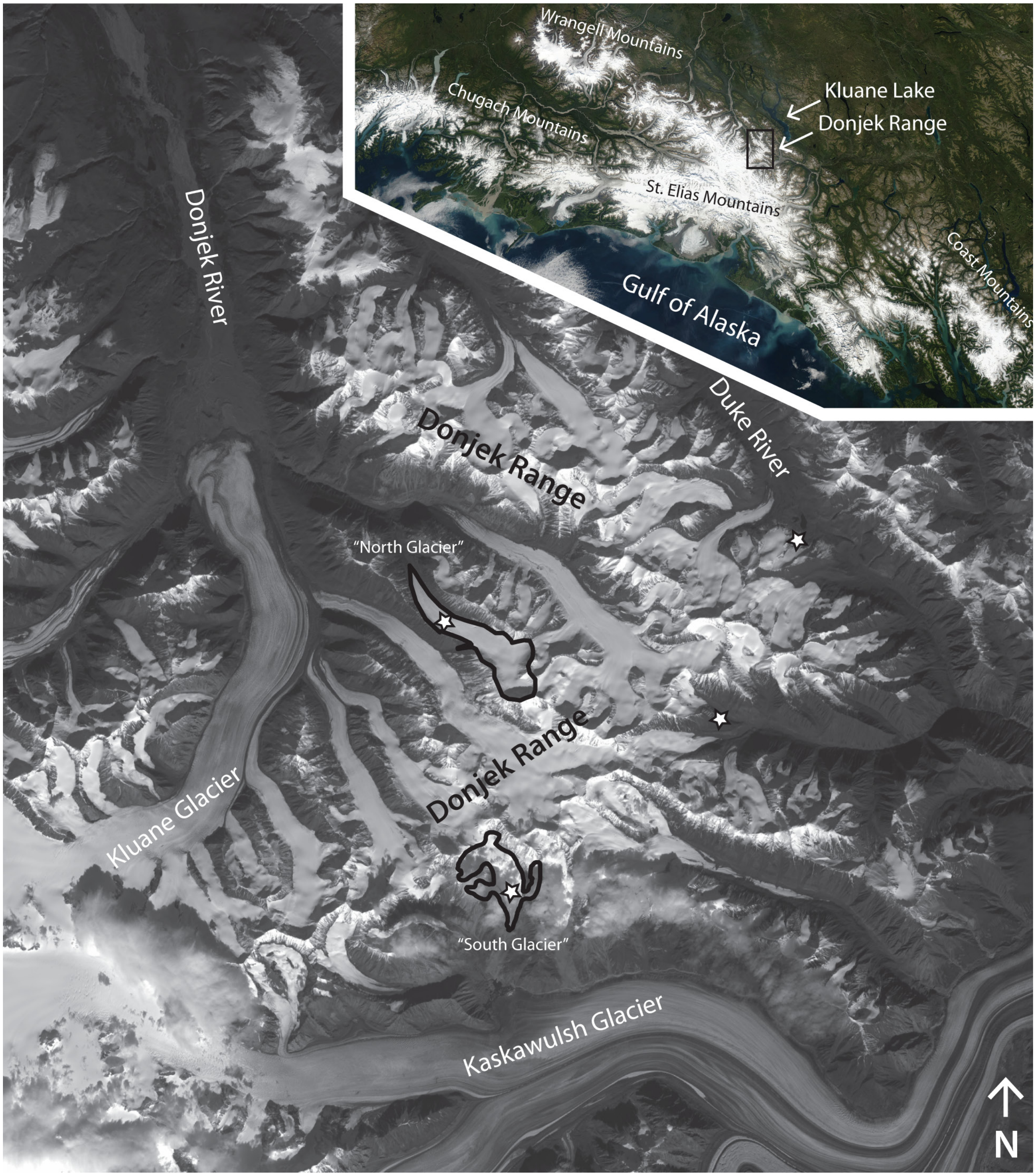

FIG. 1. The Donjek Range and environs (Geobase® image, 8 September 2008) within the St. Elias Mountains (NASA Aqua–MODIS image, 9 August 2003; http://visibleearth.nasa.gov/). North and South Glaciers are outlined, and locations of automatic weather stations operated since 2006–07 are marked with stars.

and South Glaciers have different aspects and are situated on opposite sides of the range crest. Despite these differences, both glaciers have equilibrium line altitudes around 2550 m asl (Wheler, 2009). South Glacier is a surge-type glacier (Fig. 3) within the Kaskawulsh drainage basin, and its proglacial area was previously studied by Kasper (1989) and Johnson and Kasper (1992). Direct measurements of englacial temperature, along with analysis of ice-penetrating radar data, suggest that both North and South Glaciers are polythermal (Wilson et al., 2013).

PAST AND PRESENT GLACIER VARIATIONS

The size of Kaskawulsh Glacier has varied considerably through time, with radiocarbon dating suggesting that it expanded by tens of kilometres into the Shakwak Valley (currently occupied by Kluane Lake) ~30 kya during the Wisconsinan Glaciation (Denton and Stuiver, 1969). In the historical past, Borns and Goldthwait (1966) mapped three sets of Little Ice Age moraines in the glacier forefield on the basis of distinctive variations in vegetation cover,

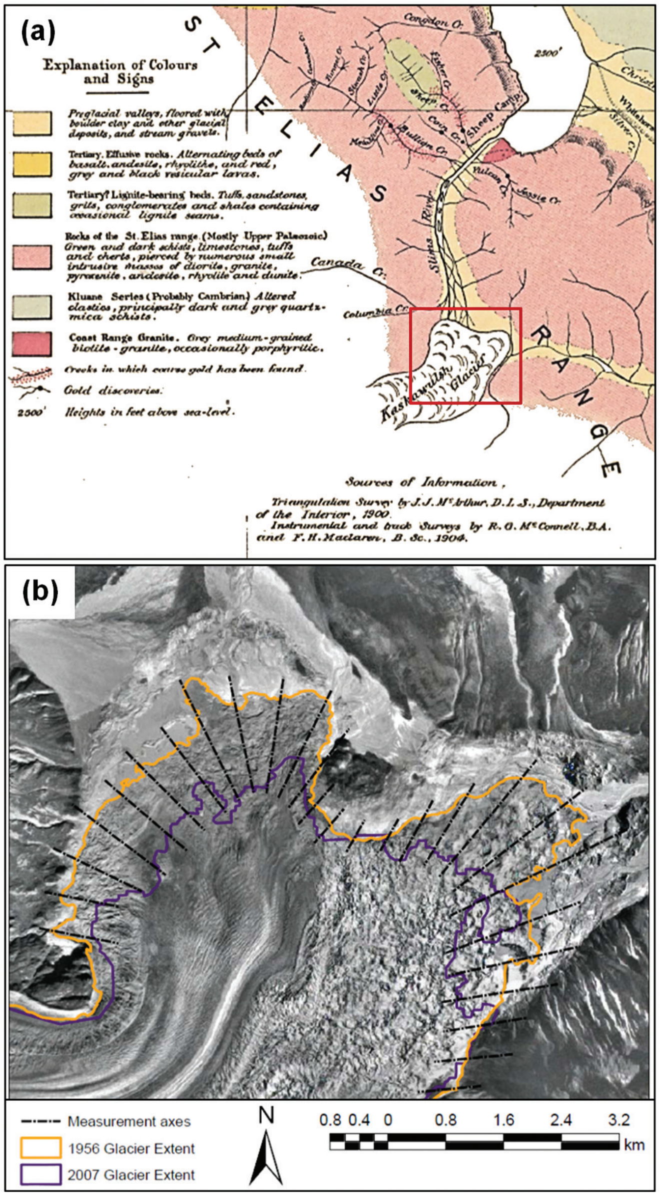

FIG. 2. Kaskawulsh Glacier. (a) One of the first known maps of Kaskawulsh Glacier (modified from McConnell, 1905); (b) Terminus positions of Kaskawulsh Glacier in 1956 and 2007, overlain on a 1956 aerial photograph (modified from Foy, 2009). Location of red box in (a) indicates approximate coverage shown in (b).

morphology, and the ages of trees and shrubs (Fig. 2b). Radiocarbon dating of trees found embedded in the outer end moraine has yielded radiocarbon ages of 450 ± 100 years (Borns and Goldthwait, 1966), 390 ± 80 years, and 110 ± 80 years (Denton, 1965). Dating of a buried spruce stump on an island near the terminus produced an age of 270 ± 60 years (Denton, 1965). Borns and Goldthwait (1966) interpreted these ages as meaning that Kaskawulsh Glacier was advancing by the early 1500s and reached its maximum recent position by approximately AD 1680. A recent study based on tree-ring dates suggests that the Slims River lobe reached its greatest Little Ice Age extent in the mid-1750s, whereas the Kaskawulsh River lobe reached its maximum extent around 1717 (Reyes et al., 2006). However, it appears

FIG. 3. South Glacier as seen during its 1986 surge (photo: P. Johnson) and in 2005 (photo: G. Flowers). To facilitate comparison, the black line in each photograph marks the same feature.

that the glacier did not start retreating from this position until the early to middle 1800s (Borns and Goldthwait, 1966). The recent discovery of a Geological Survey of Canada map of the glacier terminus from 1900 to 1904 (McConnell, 1905) indicates that the glacier was still in a forward position at that time (Fig. 2a), suggesting that most of the terminus retreat occurred in the 20th century.

Recent studies conducted by researchers at the University of Alaska (Arendt et al., 2002) and the University of Ottawa (Foy et al., 2011) indicate that ice losses from Kaskawulsh Glacier have continued through the latter half of the 20th century and first decade of the 21st century, although evidence for any recent acceleration in loss rates is equivocal. For example, Arendt et al. (2002) used repeat airborne LIDAR profiles taken along the centreline of the glacier in 1995 and 2001 to compute a mean change in thickness of -0.52 m a^{-1}. Comparisons between digitized maps from the 1950s and the 1995 LIDAR profile suggest that thickness changed by approximately -1.50 m a^{-1} during that earlier period. This pattern contrasts with most other glaciers in this region, the thinning rates of which have increased in the most recent period (Arendt et al., 2002).

Foy et al. (2011) used a combination of aerial photographs and satellite imagery to map changes in the position of the glacier terminus since 1956. Using measurements made along 27 axes that cross the terminus, they determined an average retreat of 655 m over this period (Fig. 2b), which equates to a total area loss of 8.20 km^2. The terminus retreated at a rate of ~10 – 15 m a^{-1} between 1956 and the late 1990s (with a short period of re-advance between 1986 and 1990), but this rate increased to 64 m a^{-1} between 2003 and 2007. These same authors also expanded upon the earlier LIDAR measurements of Arendt et al. (2002) by undertaking a scanning airborne LIDAR survey along the length of Kaskawulsh Glacier in August 2007. Using a method modified from Arendt et al. (2002) to compute vertical changes, they calculated a mean thinning rate along the glacier centreline of 1.2 m a^{-1} between 1995 and 2000, which declined to 0.7 m a^{-1} between 2000 and 2007. By comparing a Canadian Digital Elevation Dataset (CDED) digital elevation model from 1977 with the 2007 scanning LIDAR survey, they determined that the entire Kaskawulsh Glacier had lost a total of 3.27 – 5.94 km^3 water equivalent between 1977 and 2007. This mass loss was highly variable spatially, with thinning of up to 88 m at some locations near the terminus, but net thickening in the accumulation area at elevations above 2300 m asl. Overall, recent losses at Kaskawulsh Glacier have been driven primarily by changes in the height of the ice, rather than by changes in ice extent (Foy et al., 2011).

GLACIER-CLIMATE INTERACTIONS AND THE ROLE OF ICE DYNAMICS

Detection of recent glacier change raises the question of how glacier mass balance will respond to a future climate expected to produce warming of 3˚C – 4˚C in the region by 2100 (Christensen et al., 2007). In an area known for its abundance of surge-type glaciers, the additional question arises of the role of ice dynamics in modulating glacier response to climate. These overarching questions have motivated new research that aims to assess the local variability of glacier response to climate in the Donjek Range and to determine whether this variability is important when making more extensive regional projections of glacier change (e.g., Radić and Hock, 2011). The approach taken attempts to isolate variables by examining two similar glaciers within the range (Fig. 1) and then to (1) monitor the climate forcing, (2) measure the glacier mass-balance response, (3) characterize the glacier dynamics, and (4) model the interaction between climate, mass balance, and dynamics.

An intensive field-based program was launched in 2006 – 07 to accomplish the first three of these objectives. Four automatic weather stations were installed at similar elevations across the range (Fig. 1), and mass balance measurements were initiated on North and South Glaciers (Wheler, 2009; MacDougall, 2010). Surface velocities have been measured at South Glacier annually (Flowers et al., 2011)—and since 2009, continuously—using global positioning system (GPS) instrumentation mounted on structures embedded in the ice. Geophysical mapping was undertaken to determine the three-dimensional geometry of the study glaciers (De Paoli, 2009; Mingo and Flowers, 2010; Wilson, 2012) and, more recently, to infer their internal thermal structures (Wilson et al., 2013).

Glacier Mass and Energy Balance

Since the initiation of this measurement program, the mass balances of North and South Glaciers have been negative and of the order of decimetres of water-equivalent per year. The energy balances at both glaciers are dominated by net shortwave radiation (energy source), followed by net longwave radiation (energy sink), though the magnitudes of these fluxes are greater for South Glacier (MacDougall, 2010). Often (but not always), accumulation is also greater on South Glacier. The spatial patterns of accumulation and ablation are significantly more complicated on South Glacier, owing to the glacier's undulating surface morphology. This feature represents one feedback between glacier dynamics and mass balance; the undulations are a product of the sliding-dominated flow regime (Gudmundsson, 2003), as explained below.

The mass balance data have been used to assess the rigour of various approaches to modelling glacier melt where measurements may be sparse or absent, with the aim of improving our ability to model melt at regional scales. MacDougall et al. (2011) assessed the transferability of different melt models in space and time and found significant differences in the melt distribution and amount predicted by these models (Fig. 4). Simple models sometimes outperformed more complex models when sufficient data were available for calibration; but if data were absent, the more physically based (energy balance) model produced the most consistent results (MacDougall et al., 2011) (Fig. 4).

Energy balance models partition the heat sources that contribute to melt, and therefore are better able to isolate contributions from individual processes (see Hock, 2005). One such process is the conductive heat flux into and out of the glacier surface, responsible in part for lags between positive daily or seasonal temperatures and the onset of melt. Conductive heat loss into the ice is a significant energy sink early in the melt season and influences the timing and magnitude of glacier melt in the Donjek Range (Wheler and Flowers, 2011).

When evaluated against field measurements, the performance of the distributed energy-balance model developed by MacDougall and Flowers (2011) was found to be particularly sensitive to the treatment of ice albedo and snow accumulation, pointing to the need for site-specific estimates or measurements of these quantities. The data requirements to drive an energy-balance model can be burdensome and are not met in many places where estimates of melt are required. Simpler models are thus expected to remain in widespread use. Using data from North and South Glaciers

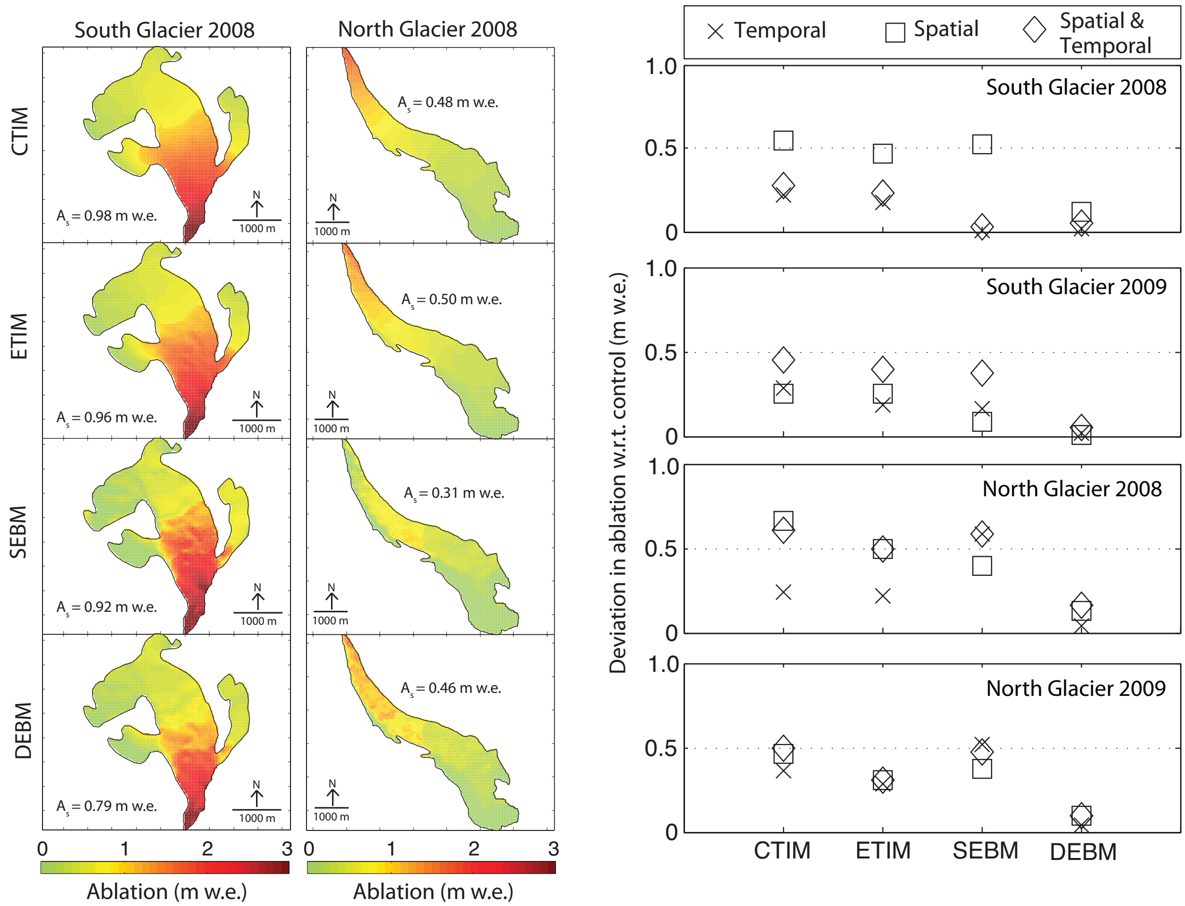

FIG. 4. Sensitivity of calculated glacier surface melt to type of melt model. Left: Distributed 2008 ablation for South and North Glaciers estimated with models of increasing complexity: the classical temperature-index model (CTIM), which correlates ice- or snowmelt linearly with positive air temperatures; the enhanced temperature-index model (ETIM) of Hock (1999), which includes potential direct solar radiation in the correlation coefficient; the simplified energy balance model (SEBM) of Oerlemans (2001); and the full energy balance model (DEBM) of MacDougall and Flowers (2011). Total modelled glacier-wide melt (A_s in each panel) varies from 0.79 to 0.98 m w.e. for South Glacier and from 0.31 to 0.50 m w.e. for North Glacier, depending on the model used. Right: Difference in estimated melt between simulations in which model parameters are calibrated with field data from the appropriate time and location ("control runs," represented by the horizontal axis) and simulations in which parameters are calibrated with field data from another year (crosses), another location (squares) or another year and location (diamonds). The clustering of symbols indicates consistency in model performance even when parameters are not recalibrated each year and for each site.

for 2006–07, Wheler (2009) experimented with driving several common empirical (temperature-index) models with air temperatures measured (1) on the glaciers themselves, (2) in ice-free locations within the range, and (3) at low-elevation stations outside the range. The provenance of the temperature forcing was found to have little influence on the total modelled melt amount, but temperatures collected outside of the regional glacier boundary layer best captured the daily variation in melt (Wheler, 2009).

Glacier Dynamics

Measurements of annual and short-term summer flow velocities at South Glacier reveal a consistent spatial pattern (Fig. 5): both summer and annual flow speeds peak in the central region of the glacier, where the ice is generally less than 100 m thick (De Paoli, 2009). Flow speeds over the lowermost third of the glacier, where the ice is thinner, are less than 10 m a^{-1}; flow speeds measured in the upper third range from ~10–30 m a^{-1} (Fig. 5). Speeds measured during the summer tend to exceed annual flow speeds by up to ~10 m a^{-1} over the upper two-thirds of the glacier. Simple calculations to estimate glacier flow rates (represented by the dotted line in Fig. 5a) do not predict the maximum flow speed over the central glacier, so the structure of the observed speeds is surprising.

One-dimensional geophysical inversion of the measured surface speeds revealed that basal motion (sliding or bed deformation) must account for 50% to 100% of the total motion year-round over the central region of the glacier (De Paoli and Flowers, 2009). This result has been corroborated by forward modelling (Flowers et al., 2011), which clearly shows the elevated flow speeds over the central glacier extending down to the bed (Fig. 5b). Figure 5b illustrates the contrast between a flow regime dominated by internal ice deformation (e.g., 0–1800 m along the flow line), in which flow speeds increase from bed to surface, and a sliding-dominated regime (e.g., 1800–3200 m along the flow line), in which flow speeds are nearly uniform through the ice column.

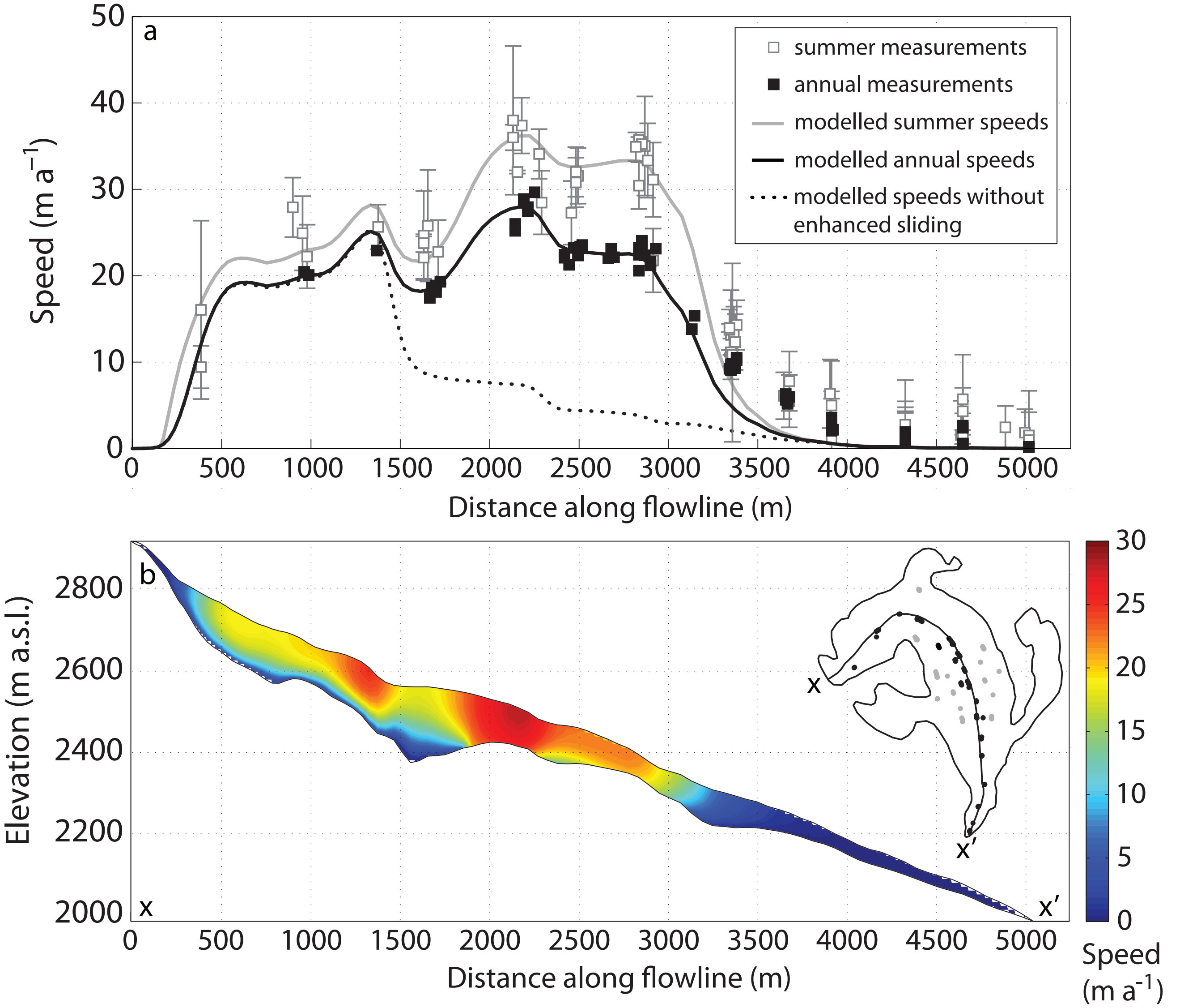

FIG. 5. Measured and modelled 2006–11 ice flow speeds along the South Glacier centreline. (a) Measured annual (filled squares) and summer (open squares) flow speeds can be modelled (solid lines) only when enhanced sliding is introduced in the central region of the glacier (cf. dotted line, which represents the result without enhanced sliding). Enhanced sliding is produced in the model by increasing basal water pressure over the region from 1900 to 3700 m along the flow line in annual simulations, and from 0 to 3700 m along the flow line in summer simulations. (b) Vertical cross-section of modelled annual flow speeds (colour). Inset shows profile location (line) relative to velocity measurement locations (grey and black dots). The black dots close to the centreline are those plotted in (a).

Balance velocity calculations show the present glacier flow regime to be unsustainable, while calculations of ice flux imply the propagation of a mass front into the nearly stagnant ice (De Paoli and Flowers, 2009). The evidence above, combined with observations of glacier surface morphology, has been interpreted to suggest that South Glacier is currently undergoing a "slow surge" (De Paoli and Flowers, 2009) as described for Trapridge Glacier by Frappé and Clarke (2007). Further modelling also hints at a potentially significant role for bed topography in building an ice reservoir between surges, as well as the possibility that sustained negative mass balances may spell the end of surges for this glacier (Flowers et al., 2011). The slow surge of South Glacier provides an opportunity to study basal hydromechanical processes in a context where they dominate the flow regime, ideally providing insight transferable to other glacier systems.

SHORT-TERM GLACIER FLOW VARIATIONS AND SUBGLACIAL DRAINAGE

The flow of South Glacier is marked by seasonal and shorter-term velocity fluctuations, most likely driven by surface water input to the glacier during the melt season. The response of subglacial drainage systems to water input is widely recognized not only as a driver of diurnal and seasonal velocity variations (Iken and Bindschadler, 1986; Jansson, 1995), but also as an essential component of some glacier surges (Kamb et al., 1985), with high basal water pressures seen as facilitating sliding.

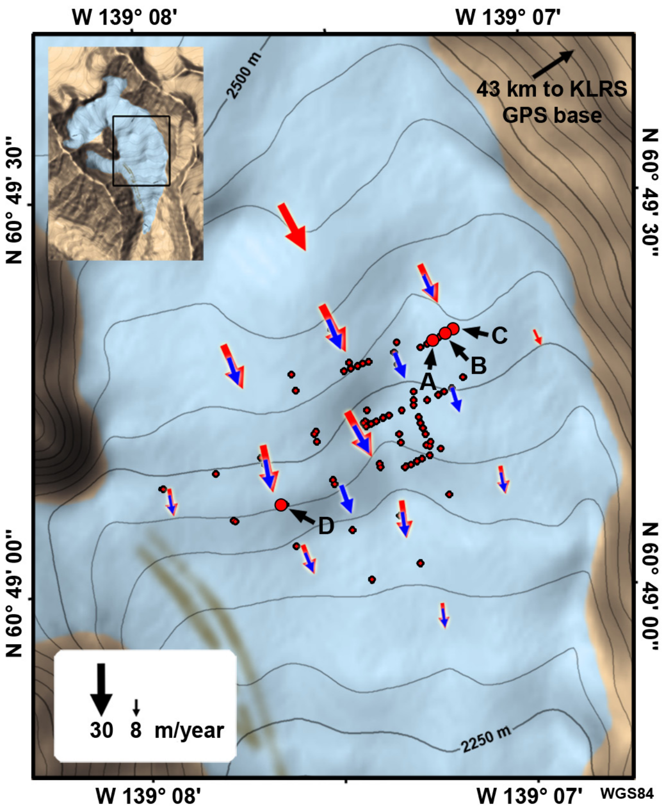

FIG. 6. The GPS array at South Glacier. The study area, shown as a black box in the inset image of the glacier, is roughly centred on the 3000 m mark of the flow line in Figure 5. Red arrows indicate velocities during the summer of 2010, and blue arrows, velocities in early spring 2011. Red dots show the location of all boreholes drilled to date. Pressure time series for the boreholes labeled A to D are shown in Figure 7.

The upper portion of the ablation area of South Glacier has been instrumented since 2008 with Global Positioning System (GPS) receivers and pressure transducers in an effort to study linkages between water input, evolution of the subglacial drainage system, and ice flow velocities. As of summer 2011, a total of 16 Trimble R7 differential GPS receivers have been monitoring glacier movement year-round, logging continuously for six hours per day (Fig. 6). More than 80 boreholes have also been drilled to the bed and instrumented with pressure transducers.

Borehole water pressure records reveal a drainage system that is highly heterogeneous spatially and is also experiencing strong temporal fluctuations in water pressure. Similar spatial and temporal variability is well known from other sites in Europe and North America (e.g., Gordon et al., 1998; Fudge et al., 2008). The spatial structure partially mimics that found under Trapridge Glacier (Murray and Clarke, 1995); some regions of the bed show evidence of strong diurnal pressure cycling in response to daytime surface melt, and hence connection to an active subglacial drainage system. Such connected regions can be found close to unconnected regions that may exhibit either no diurnal pressure variations or pressure variations in anti-phase with the connected system (Fig. 7). The morphology of connected and unconnected systems also evolves over time, and there is evidence that the connected system can both widen and become more efficient as the melt season progresses (see also Gordon et al., 1998; Nienow et al., 1998).

The velocity field exhibits not only marked seasonal speedup in the study area (Fig. 6) but also significant spatial structure, with higher mean velocities and more pronounced summertime acceleration at higher elevation (see also Fig. 5). A strong link between the seasonal evolution of a subglacial drainage system and glacier surface velocities has been observed at numerous glaciers (Iken and Bindschadler, 1986; Mair et al., 2003; Anderson et al., 2004) and more recently on the Greenland ice sheet (Bartholomew et al., 2010), though the relationship need not be trivial (Harper et al., 2005). Continued work on this study will aim to assess how these spatial variations in ice flow are related to differences in morphology of the drainage system at the glacier bed at our field site in the St. Elias Mountains.

DISCUSSION AND OUTLOOK

Of the 19 glacierized regions of the world identified by Radić and Hock (2011) outside of the ice sheets, the region including the St. Elias Mountains made the second highest glaciological contribution to global sea level during the period 1961 – 2000. Only Arctic Canada is expected to exceed this region in sea-level contribution over the 21st century (Radić and Hock, 2011). Our capacity to detect ongoing cryospheric change has improved over time, especially with increasing sophistication in processing spaceborne gravimetric (GRACE) data. For example, recent improvements in mass concentration (MASCON) solutions, including improved accounting of isostatic uplift rates, have allowed refinement of GRACE-derived mass losses from this region. For the period 2003 – 10, these losses (at a rate of -46 ± 7 Gt yr^{-1}) indicate that Yukon-Alaska made the largest glaciological contribution to sea-level rise outside of the Greenland and Antarctic ice sheets (Jacob et al., 2012). Combining multiple and independent data sources (e.g., time-variable gravity, repeat laser, or radar altimetry) has also increased the robustness of recent mass change estimates (Arendt et al., 2008).

The St. Elias Mountains exhibit high interannual variability in ice mass change (Luthcke et al., 2008), which is due in part to the abundance of surge-type and tidewater glaciers in different stages of their respective cycles (e.g., Arendt et al., 2008). Ice dynamics can be a confounding influence when attempting to isolate the effects of climate as an external driver of glacier change. For example, a surge-type glacier in the “quiescent” phase of its cycle may retreat even in a stationary climate (e.g., Meier and Post, 1969). Catastrophic retreat of a tidewater glacier may be triggered by climate, but it is largely controlled by glacier and fjord geometry (e.g., Vieli et al., 2001). Similar “flow instabilities” exist at larger scales in the form of ice streams and marine ice-sheets or outlet glaciers, the dynamics of which dominate the mass balances (and therefore sea-level

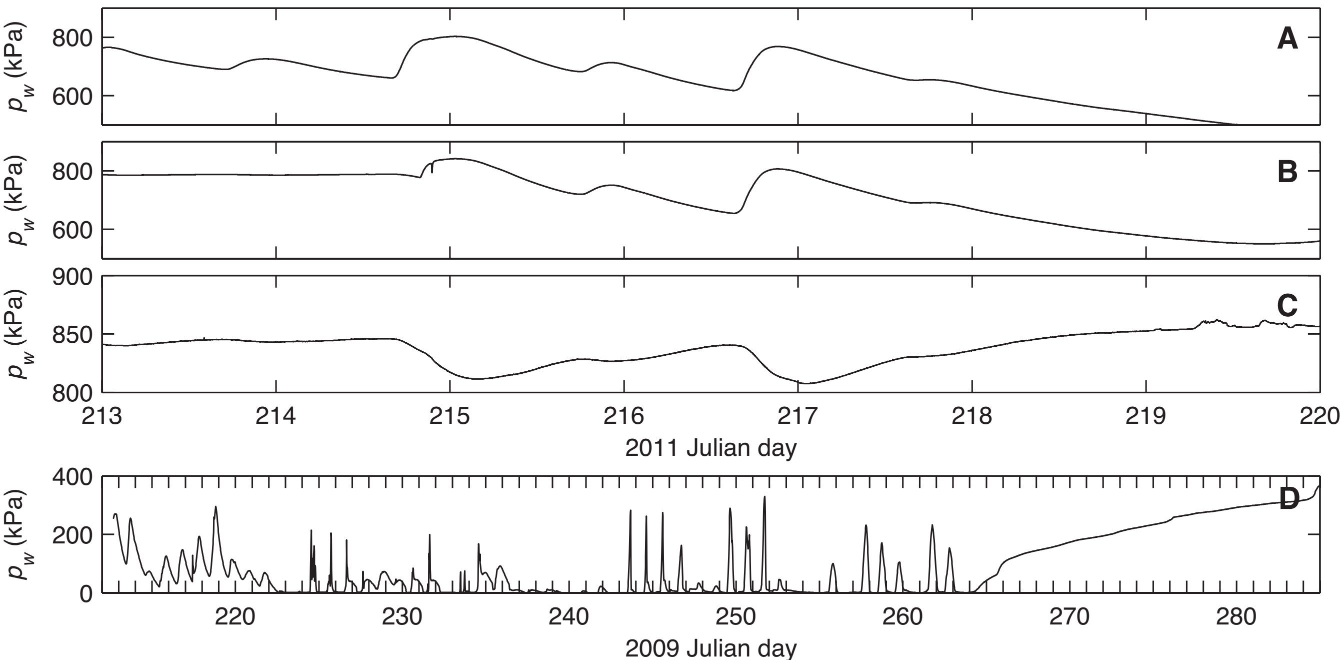

FIG. 7. Sample water pressure (p_w) time series for the boreholes labeled A to D in Figure 6. Boreholes A–C are closely spaced. A is connected throughout, while B becomes connected to the same drainage system at the end of day 214. C exhibits strong anticorrelation with A and B, which is probably due to normal stress variations caused by the active drainage system (Murray and Clarke, 1995). The longer time series for borehole D shows the seasonal evolution of a connected borehole as the drainage system becomes more efficient, with the borehole emptying completely at night after day 223 but exhibiting sharp pressure spikes during the day.

contributions) of large sectors of the modern ice sheets (e.g., Pritchard et al., 2009). Our ability to project future changes on short (sub-decadal to decadal) timescales therefore hinges on our understanding of internal glacier dynamics (Arendt et al., 2008), as well as our ability to project future climate in a given region and relate climate to glacier surface mass balance (e.g., Huss, 2012).

Detection of climate interference with the surge cycle or surge character of small glaciers in the region (Frappé and Clarke, 2007; Flowers et al., 2011) raises the question of whether climate might alter the surges of much larger glaciers, such as the Lowell, Kluane, Donjek, and Steele, whose catchments tap farther into the icefield interior. The present surge of South Glacier in some ways resembles a “Svalbard-type” surge, which proceeds more slowly and for a longer period than an “Alaska-type” surge owing to its thermal regulation (Murray et al., 2003). Whether climate has fundamentally altered the surging styles of Trapridge Glacier and South Glacier from the faster, shorter, more recognizable Alaskan style to the slower and more subtle Svalbard style is an interesting question. Many small polythermal glaciers, whose temperate ice content is largely controlled by meltwater entrapment and refreezing in the accumulation area, are expected to become colder under negative mass balance conditions (e.g., Rippin et al., 2011; Wilson and Flowers, 2013). It is therefore conceivable that thermal evolution over the course of decades can play a role in altering surge style. However, there is some evidence that both types of surges may be preceded by a prolonged—and until recently, unrecognized—period of acceleration (Sund et al., 2009; Jay-Allemand et al., 2011). Thus, a “slow surge” (Frappé and Clarke, 2007) or “partial surge” (Sund et al., 2009) may simply represent a truncation of the ordinary surge cycle that results from a deficit of mass (Frappé and Clarke, 2007), rather than a fundamental change in surge character. Mass deficits have manifested themselves differently on the well-studied and temperate Variegated Glacier, where the return interval between surges adapts itself in such a way that surges are triggered at a constant cumulative balance threshold (Eisen et al., 2001). The nature and timing of future surges of the large glaciers in the St. Elias Mountains will be instructive as we seek a more coherent understanding of the influence of climate on surging.

Previous research in the St. Elias region, particularly from the Trapridge Glacier project, has elucidated some of the thermal, hydrological, and mechanical processes that govern glacier surges in particular (e.g., Clarke and Blake, 1991) and basal dynamics in general (e.g., Fischer and Clarke, 2001; Clarke, 2005). Borehole instrumentation remains one of the only means of directly observing these processes at the glacier bed, and ongoing work increasingly aims to incorporate process-scale observations into theoretical models. Studies of small surge-type glaciers such as Trapridge Glacier and South Glacier therefore fulfill a dual purpose. They help to elucidate the fundamental mechanisms by which glaciers can exhibit large variations in flow velocity driven by changes at the base of the ice, and they also inspire the development of models that can be relevant to the dynamics of larger ice masses, such as ice sheets, where similarly detailed observations are much more costly to make (Schoof, 2010).

An important direction for future research lies in bridging the gap between the scales relevant to global climate models (GCM) and those accessible to local and regional observations. Assessment of GCM performance at regional scales (e.g., Radić and Clarke, 2011) and local downscaling of regional climate data (e.g., Jarosch et al., 2012) are productive steps in this direction. Regional glacier modelling requires creative treatment of quantities that are impractical to measure (e.g., Clarke et al., 2009) and informed judgments about optimal trade-offs between model performance and sophistication (e.g., MacDougall et al., 2011). Preliminary work, though limited in its scope, suggests that surface albedo and snow accumulation quantities are particularly important for accurate modelling of glacier mass balance (MacDougall and Flowers, 2011). Measurement and modelling of accumulation, and in particular its redistribution by wind, remain challenging and in need of further study (e.g., Dadic et al., 2010). Development of more physically based parameterizations of glacier albedo (e.g., Gardner and Sharp, 2010) represents a promising direction, especially if such models can be site-specifically validated over large spatial scales.

Though the fate of glaciers in the St. Elias Mountains is arguably of global significance, this area remains geographically remote and relatively little studied. Remote sensing is beginning to change this, allowing us to monitor vast and inaccessible areas from space. It also allows research to be more responsive to events such as glacier surges, and the archived imagery allows us to look back in time. However, ground-based measurements remain valuable for their high spatial and temporal resolution, for their ability to probe variables not accessible to space-borne instrumentation, and for the validation of the remote sensing products themselves. Both direct and indirect measurements have their place as we seek to quantify the impact of local ice mass loss on global sea level and to improve the predictive capability of models grounded in process-based science.

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