Recent high-resolution surface velocities and elevation change at a high-altitude, debris-covered glacier: Chacraraju, Peru

Bryn HUBBARD, Samuel CLEMMENS

Centre for Glaciology, Institute of Geography and Earth Sciences, Aberystwyth University, Aberystwyth SY23 3DB, UK
E-mail: byh@aber.ac.uk

ABSTRACT. Surface-elevation change and ice velocities have been measured over the debris-covered tongue of Chacraraju, Peru. Elevation change was measured by reflectorless survey at a 1 m horizontal resolution over three separate areas of the glacier between 2004 and 2005. Area-averaged change revealed general lowering, with two of the surveyed areas experiencing surface lowering of 0.58 and 0.77 m, and the third a rise of 0.07 m. Combining all three areas (43 216 m^2) resulted in a mean net lowering of 0.43 m a^{-1}, which is at the higher end of the range of long-term studies in the region. Velocity was measured over 7 days by the repeated optical survey of 12 prisms attached to stakes inserted directly into the glacier's surface. Results indicate that velocity increases approximately with distance squared from the glacier's terminus, from <10 mm d^{-1} near the terminus to approaching 100 mm d^{-1} at the base of the glacier's icefall, located ~1.7 km up-glacier. Velocity vectors also changed systematically along the glacier, from a consistent down-glacier orientation near the icefall to more variable orientations within ~300 m of the terminus. No up-glacier motion component was measured.

INTRODUCTION

Recent climatic change has driven a strong reduction in the mass balance of most of the Earth's ice masses, resulting in marked retreat and thinning. While large-scale geometrical changes in mid- and high-latitude ice masses are well documented, and have stimulated widespread measurement programmes and process investigations, far less research has been carried out on low-latitude glaciers. Although repeated photographic-, satellite- and ground-based mapping reveals a general recent retreat in the extent of tropical glaciers (e.g. Kaser and others, 1996; Kaser, 1999; Georges, 2004), detailed investigations of the nature of this response are hampered by such glaciers commonly being relatively high, small, steep and debris-covered (e.g. Paul and others, 2004). Despite these difficulties, it is recognized that the insulating effect of supraglacial debris affects the way debris-covered glaciers respond to climate forcing. For example, Kick (1962) recognized that thick supraglacial debris has a buffering effect on a glacier's geometric response to short-term climatic fluctuations. A supraglacial debris cover that thickens towards a glacier's terminus can also result in a reversed mass-balance gradient, where greater ablation occurs some distance up-glacier rather than near the terminus. Consequently, warming or drying can lead to the tongue thinning and decreasing in gradient while the terminus position remains stationary (e.g. Nakawo and others, 1999). Terminus position may also be relatively insensitive to periods of positive mass balance, despite the ablation zone thickening and steepening. Where spatially distributed surface change has been investigated, researchers have generally reported widespread change at decadal timescales (e.g. Mark and Seltzer, 2005) or local change in terms of specific processes such as the development of supraglacial ponds (Benn and others, 2001). Studying change over a 37 year period (1962–99) at three glaciers in the Cordillera Blanca, Peru, Mark and Seltzer (2005) measured surface lowering of 0.14–0.59 m a^{-1}, explaining this range of values in terms of glacier aspect.

Surface velocities are also difficult to measure at high-resolution on high-altitude, debris-covered glaciers. Although satellite-based velocity mapping has seen some success (e.g. Kääb, 2005), steep debris-covered surfaces make high-resolution velocity mapping from satellite images difficult. Detailed velocity investigations have therefore focused on field-based mapping of surface boulders. For example, Lliboutry (1977) surveyed marked boulders on the surface of debris-covered Glaciar Hatunraju, Peru. Here, measured velocities ranged from 0.4 to 10 m a^{-1}, with velocities decreasing near the terminus, although considerable systematic errors were present as a consequence of the measurement technique. Shroder and others (2000) also surveyed marked boulders located 2.5 km up-glacier from the terminus of Raikot glacier, Nepal, calculating velocities of 12 cm d^{-1} over a 4–6 day surveying period. In parallel measurements at Shaigiri glacier, Pakistan, boulder velocities averaged 11.7 cm d^{-1} some kilometres from the terminus and dropped to less than a few centimetres per day near the terminus (Shroder and others, 2000). A similar pattern was reported by Kirkbride (1995) on the basis of long-term boulder velocity measurements (by repeat photogrammetry and surface surveying) on the surface of Tasman Glacier, New Zealand. Although not a high-altitude glacier, velocities at Tasman Glacier also decreased towards the terminus, falling to below detection levels within 350 m of the terminus. Kirkbride (1995) also found that boulder movement directions became more variable and sensitive to local topography towards the terminus, in extreme cases resulting in apparent up-glacier surface motion.

Taken together, these studies on debris-covered glacier tongues point to (1) surface geometrical change that is slow and locally variable, often being driven by melting of ice exposed at the edges of supraglacial ponds, and (2) surface velocities that decrease sharply down-glacier, with a zone approaching the terminus where net down-glacier velocity may be approaching zero and of inconsistent direction.

The aim of this study is to complement and extend our current understanding of surface processes at debris-covered

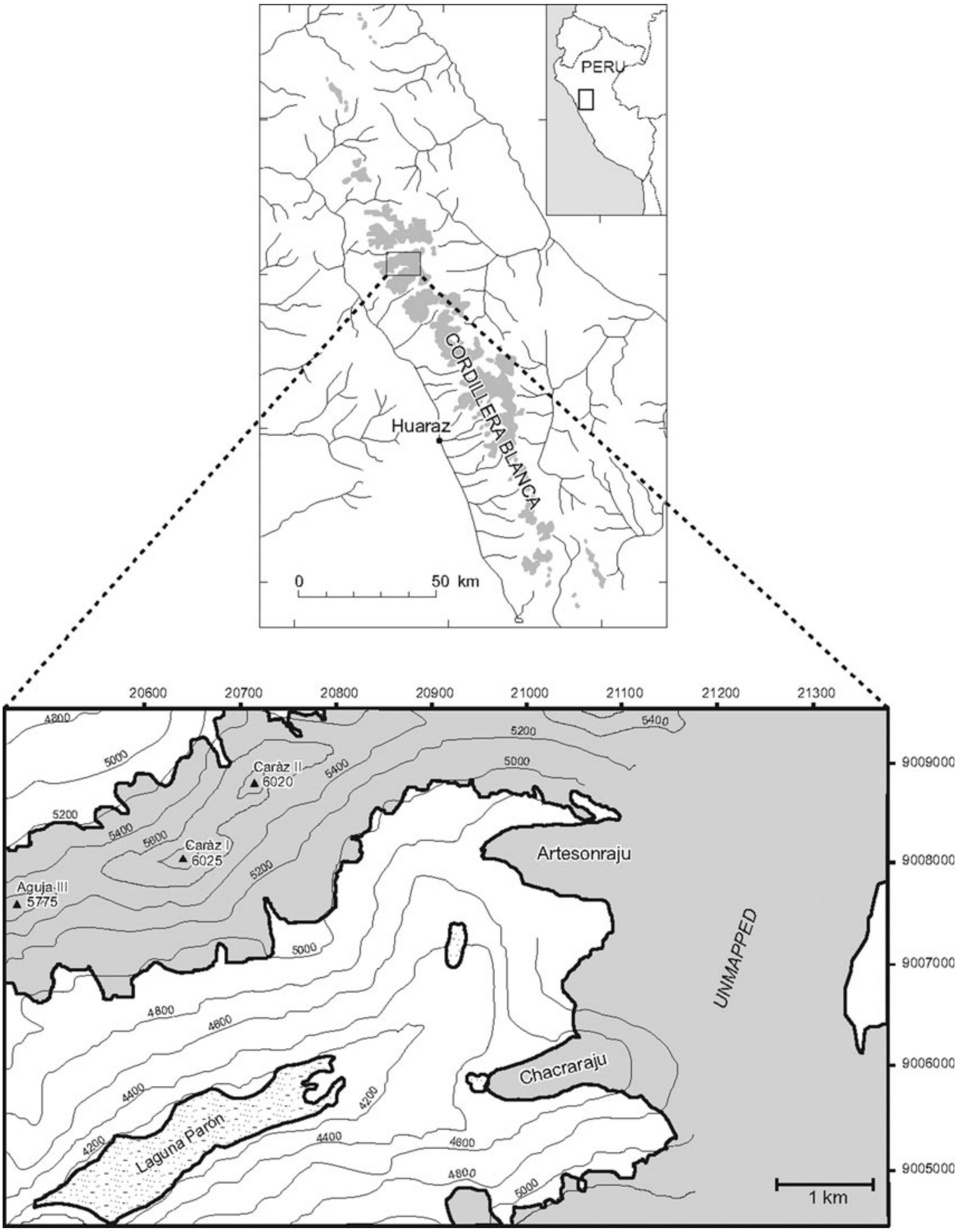

Fig. 1. Location map of Chacraraju, Peru. Ice-covered area is shaded.

glaciers by investigating the high-resolution spatial variability in surface velocity and mass balance over the debris-covered tongue of Chacraraju (Glaciar Chacra), Peru. First, we report the results of two automatic, reflectorless surveys of the surface elevation of three areas of the glacier tongue carried out in the dry seasons of 2004 and 2005. The resulting digital elevation models (DEMs) are then differenced and the resulting DEMs of difference (DoDs, representing the spatial field of elevation difference between two temporally separated DEMs) are analyzed and interpreted in terms of the nature and causes of surface change. Second, we report the results of an optical survey of the velocities of 12 stakes inserted directly into the glacier surface over a period of 7 days during the dry season, 2005.

FIELD SITE AND METHODS

Field site

Fieldwork was undertaken on the debris-covered tongue of Chacraraju, which terminates at ~4450 m a.s.l. at the head of the Paron Valley, Cordillera Blanca, Peru (Fig. 1). The glacier tongue is almost completely debris-covered and flows at a low angle in a generally east-to-west direction. Much of the glacier's supraglacial debris is dominated by boulder-sized material (Fig. 2). The glacier terminates within an arcuate latero-terminal moraine complex which contains an ephemeral, shallow proglacial lake. While the glacier's frontal moraine rises only a few metres above the level of its terminus, the glacier's lateral moraines rise steeply for

Fig. 2. Photograph of the debris-covered surface and bounding lateral moraines of Chacraraju, looking east to west from the base of the icefall towards the glacier's terminus. The supraglacial pond in the foreground is ~10 m across. The lake in the centre distance is Laguna Parón.

several tens of metres above the current debris-covered ice surface (Fig. 2).

Methods

Surveying was undertaken using a total station (Trimble 5600) from three survey base stations located off the margins of the glacier: station 1 located on crest of the northern lateral moraine and stations 2 and 3 located on the dry margins of the frontal proglacial lake (Fig. 3). A fixed back-site reference was surveyed at the beginning and end of each survey, and was also re-surveyed every ten readings during each optical survey. The station was re-zeroed and readings repeated if the reference altered by more than 5″s. The tripod remained assembled in situ for the entire period of research each year in order to minimize set-up and re-levelling variability. All positional coordinates are reported relative to a local coordinate base, which was set to (0,0) at the location of station 1. The orientation of this local grid was set to that of the Peruvian map datum (PSAD56). Three forms of survey were undertaken:

1. Optical survey of roving retro-prisms, used to define the glacier's margins and large-scale, low-resolution surface. A pole-mounted prism was carried across the glacier surface, and readings were sighted manually at a variety of locations, including equally spaced points along transects, locations of notable breaks-of-slope and sampling sites.

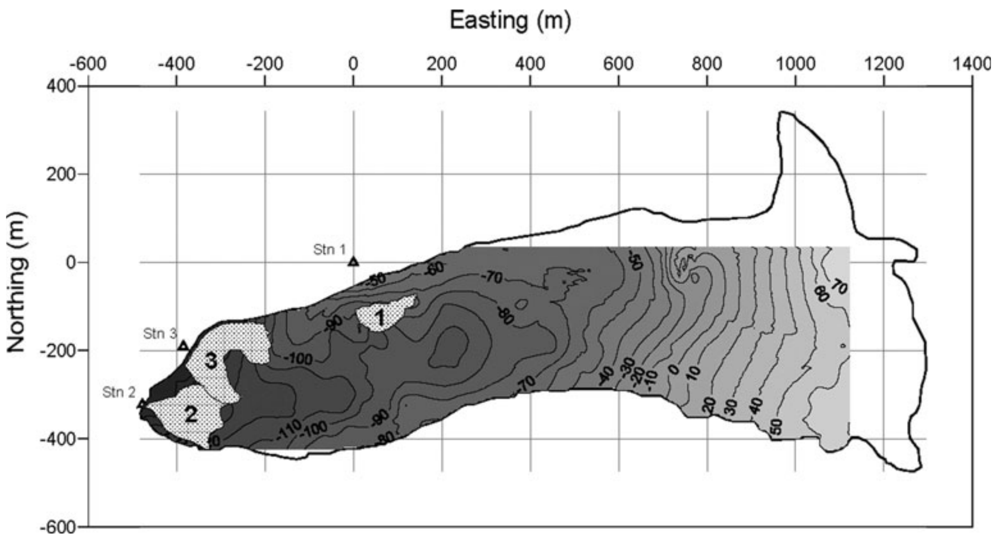

Fig. 3. Elevation map of the surface of Chacraraju, with elevations and coordinates expressed in metres relative to the location of station 1. The three survey stations are located just off the glacier margins, and the automatically surveyed areas are indicated by numbers 1–3.

Table 1. Summary data for the manual survey error analysis based on 30 repeat surveys from station 1 to each of four fixed prisms located on the glacier surface (FP) and the reference prism

Object	Distance	Standard deviation		
		Easting	Northing	Elevation
	m	mm	mm	mm
Reference	164	4	2	3
FP2	1138	8	35	15
FP4	581	20	40	10
FP10	364	12	8	19
FP11	288	8	7	5
Mean		10	19	10

2. Optical survey of fixed retro-prisms, used to measure ice surface velocity. Twelve prisms were welded to extended ice screws and manually inserted into the glacier surface at locations where the surface debris was thin enough and fine enough to be cleared away or penetrated. Where debris was cleared away to allow insertion, the debris was replaced around the screw to return the surface as closely as possible to its original condition.

3. Automatic survey in reflectorless mode, used to measure high-resolution surface change over 1 year. The Trimble 5600 uses laser time-of-flight analysis to detect surface reflections directly at ranges of up to ~400 m. Retro-prisms are therefore not needed when the instrument is used in this reflectorless mode. In this study, the instrument's servomotor was used in reflectorless mode to scan three prescribed surface areas of the glacier (one from each survey station) at a horizontal resolution of 1.0 m (Fig. 3). The overlapping areas surveyed in both June 2004 and June 2005 were then interpolated onto a common 1 m × 1 m grid, and the 2004 interpolated grid was subtracted from the 2005 interpolated grid. The resulting DoD has positive values where the surface increased in elevation over the year, and negative values where elevation decreased.

Error approximation

Specified distance-measurement accuracy of the Trimble 5600 is ±(3 mm + 3 ppm) in single-prism mode and ±(3 mm + 2 ppm) in reflectorless mode (Höglund and Large, 2003). Since the instrument is set up only once for each automatic survey and the error is randomly distributed during such a survey, we take ±(3 mm + 2 ppm) to be the error for automatic surveys. Consideration of the distances involved in these automatic surveys yields an error of <4.0 mm in all cases. However, repeated field-based optical surveys include operator- and instrumentation-based angular errors that depend on specific field procedures and conditions. In this study, optical survey accuracy was therefore assessed empirically through surveying, from station 1, the reference prism and three fixed surface prisms 30 times each. The surface prisms were located at distances and angles to include all variability in the full 12-prism array. Each repeated survey involved all set-up stages undertaken during separate field surveys, i.e. mounting, levelling and focusing the instrument, and targeting and recording the distance and angle to each prism. The analysis therefore incorporated both operator- and instrument-based survey errors.

Results of repeated manual surveys indicate approximately normal distributions of measured distance around a mean value for each prism, with the total spread of measured distances being typically <40 mm in easting, northing and elevation (Fig. 4). Results for all four prisms are summarized in Table 1, yielding mean standard deviations of 10 mm in easting, 19 mm in northing and 10 mm in elevation. Although there is some evidence of error increasing with distance, the relationship is not statistically significant. This is partly because greater error is apparent in the angular measurements than in the distance measurements while the geometrical relationships between the prisms and the survey station are different. For example, if a prism is travelling east-to-west parallel to the survey line-of-sight, a greater error will be apparent in that prism's northing than in its easting. If, on the other hand, a prism is travelling east-to-west orthogonal to the survey line-of-sight, a greater error will be apparent in that prism's easting than in its northing. Thus, in the absence of a distance-related error we consider our error in the following analysis to be one standard deviation of the 30 positions recorded for each prism, i.e. 10 mm in easting, 19 mm in northing and 10 mm in elevation. These positional errors are translated into velocity errors by dividing the positional error of the stake concerned by the time separating the two positional measurements.

Station-to-station surveying yielded identical positions in both years, indicating that survey stations did not move relative to each other between the two years.

RESULTS

Glacier surface change

The three sites of automatic surface survey, labelled 1–3 (Fig. 3), have respective surface areas of 6067, 16 303 and 20 846 m^2. While site 1 is located towards the northern margin ~500 m up-glacier of the terminus, sites 2 and 3 are

Table 2. Summary data for the DoDs calculated on the basis of the automatic surveys carried out in 2004 and 2005

Site	Surface area	2004	2005	2005–04	Cut (gain)		Fill (loss)	
	m^2	m	m	m	m^2	%	m^2	%
1	6067	–88.4	–89.0	–0.58	1182	19.5	4885	80.5
2	16 303	–152.9	–152.8	0.07	8167	50.1	8136	49.9
3	20 846	–148.1	–148.9	–0.77	3537	17.0	17 309	83.0
All	43 216	–141.5	–142.0	–0.43	12 886	29.8	30 330	70.2

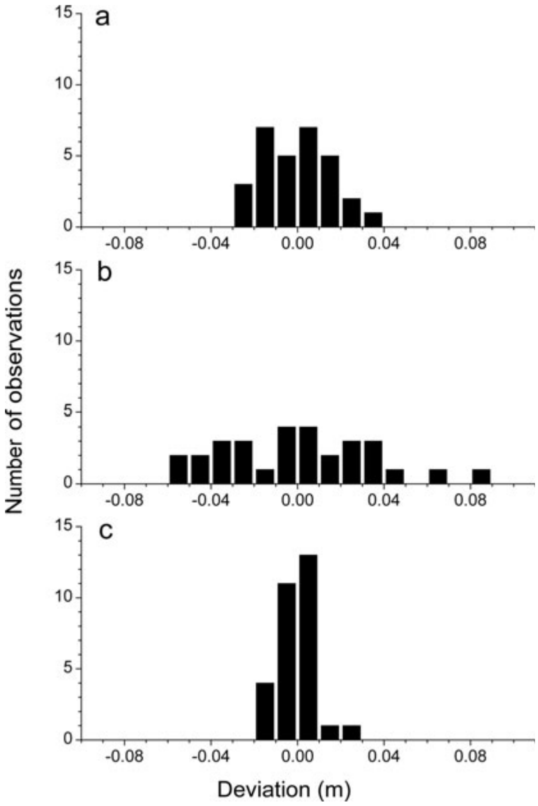

Fig. 4. Histogram of deviations from the mean distances in (a) easting, (b) northing and (c) elevation, measured over 30 repeat surveys to the most distant stake from station 1.

located adjacent to the glacier's terminus, with site 2 being located to the south of site 3. All three sites are characterized by substantial local relief, with their DEMs revealing elevation ranges of –65 to –100 m at site 1, –120 to –170 m at site 2 and –112 to –174 m at site 3 (Fig. 5). The 2005–04 DoDs reveal local variability in the direction and magnitude of surface-elevation change, i.e. some areas of positive surface change and others of negative surface change are measured within all three sites (Fig. 6). Histograms of these elevation changes reveal that all individual nodes fall within the range –4 to +4 m, with virtually all nodes registering elevation-change values greater than the survey error (Fig. 7). Area-averaged change for each site is summarized in Table 2. At site 1, the surface lowered by 0.58 m, on average, with ~80% of the area experiencing surface lowering and the remaining ~20% a surface rise. The pattern is similar at site 3, experiencing an average lowering of 0.77 m, with ~83% of the survey area lowering in elevation over the year. Site 2 experienced almost equal elevation rise and lowering (each accounting for 50% of the surveyed area), resulting in a net average elevation gain of 0.07 m. Combining the three sites yields an average surface lowering of 0.43 m over the year 2004/05.

Glacier surface velocity

Ice surface velocities at 12 fixed stakes, measured over a 7 day period in 2005, are illustrated in Figure 8. Here, a clear pattern of increasing velocity with distance from the glacier terminus is seen for all stakes. Thus, velocities range from a maximum of 62 mm d^{-1} at the base of the icefall, located ~1700 m from the glacier terminus, to only ~10 mm d^{-1} approaching the glacier terminus. These velocities are also

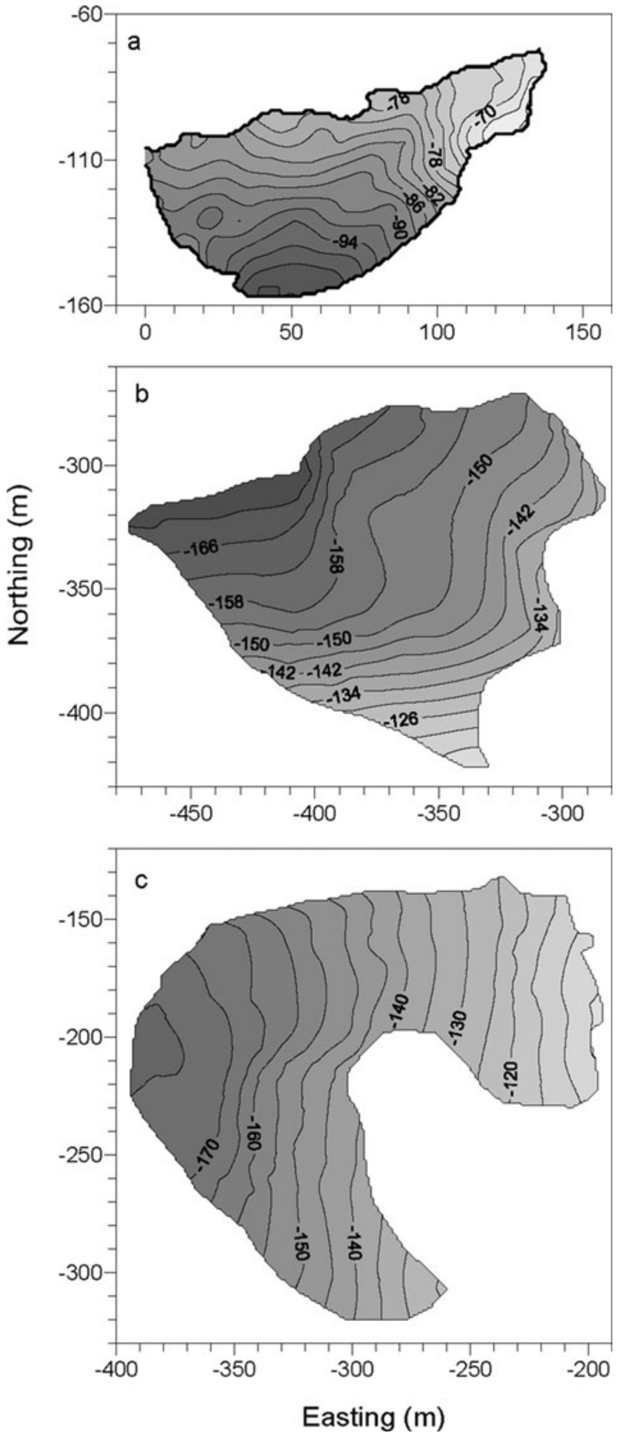

Fig. 5. Surface-elevation contour plots of the interpolated automatic survey sites measured in 2004: (a) site 1, (b) site 2 and (c) site 3. Elevations and coordinates are expressed relative to the location of station 1.

laterally consistent with stakes located at similar longitudes yielding similar velocities. Plotting the down-glacier (east–west) component of velocity against easting reveals a consistent pattern of change (Fig. 9). The increase in velocity with distance from the terminus appears to be non-linear, and is best approximated by a power function with an exponent of ~2 ($v = 3.3 + 0.000\,000\,72 d^{2.1}$, where v is surface velocity (m d^{-1}) and d is the distance from the glacier's terminus (m)). It is also noticeable that down-glacier velocity appears not to decrease to zero over the surveyed section, instead

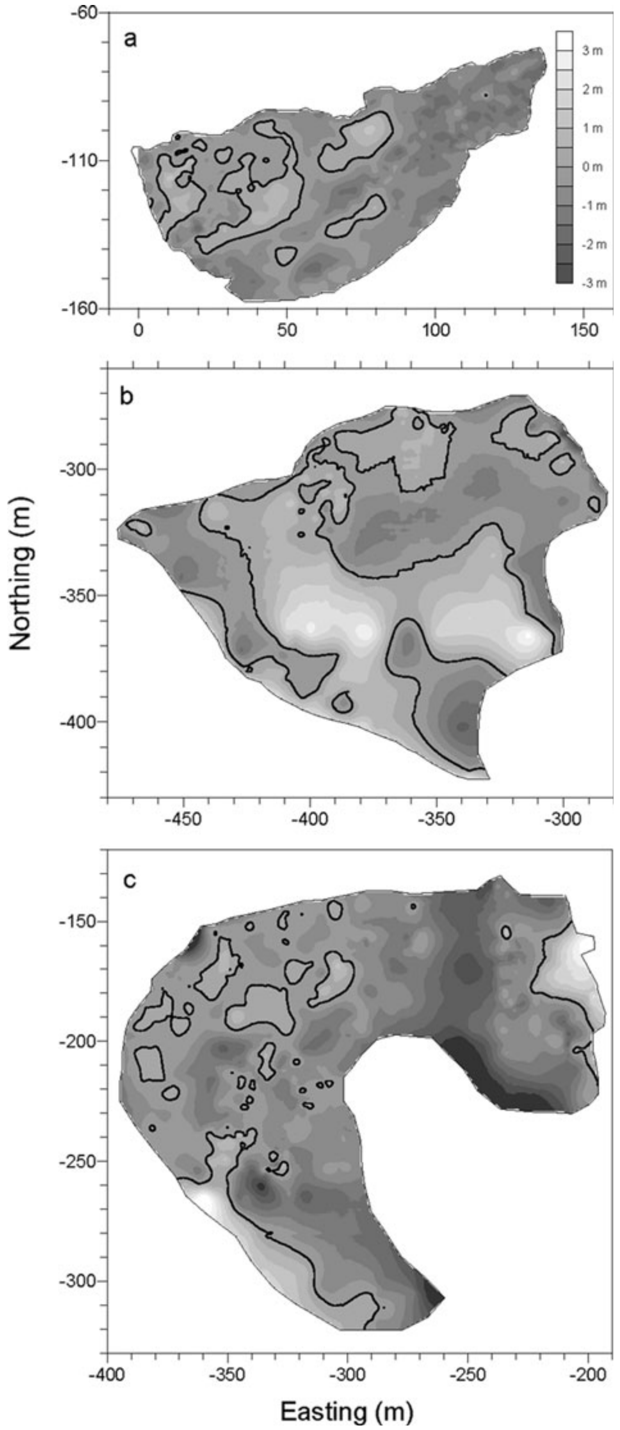

Fig. 6. Shaded relief plots of surface-elevation DoDs calculated by subtracting the elevation field of the 2004 DEMs from that of the 2005 DEMs for (a) site 1, (b) site 2 and (c) site 3. Positive values equate to a surface-elevation gain, and negative values to a surface lowering. The zero-change contour is marked as a solid line. Coordinates are expressed relative to the location of station 1.

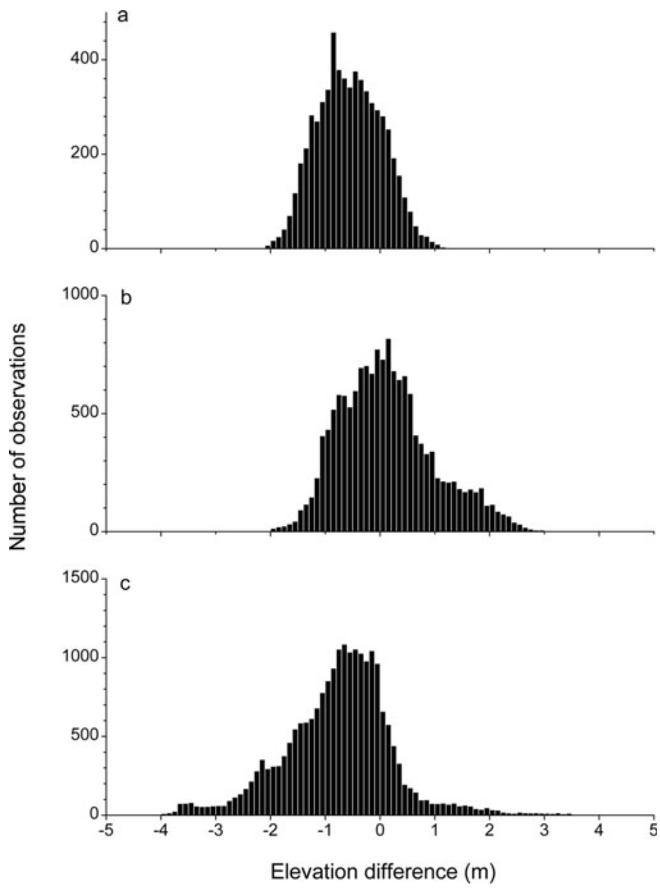

Fig. 7. Histogram of the individual node values of the DoDs illustrated in Figure 6 for (a) site 1, (b) site 2 and (c) site 3. With an approximate maximum survey error of ~4 mm, yielding a total maximum error of ~8 mm, nearly all node changes exceed their likely error.

falling to <10 mm d^{-1} at 300 m from the terminus (the most westerly fixed prism location). However, the low velocities measured near the glacier terminus do mean that survey error becomes significant in this zone; in one case the error exceeds the measured velocity.

The directional consistency of the measured velocity vectors also changes systematically along-glacier. The furthest up-glacier prisms are characterized by consistently down-glacier directions, while prisms located closer to the glacier terminus (those characterized by the lowest velocities) show greater variability in their directions. Despite this increasing variability, all 12 prisms have a down-glacier component to their motion, with none indicating up-glacier motion (Fig. 9). However, it must be borne in mind that the measured near-terminus velocities are of the same order as their errors, and these reconstructed directions may also be in error for the smallest measured velocities.

SUMMARY AND DISCUSSION

Highly spatially variable surface change was measured over the year 2004/05 at all three automatic survey sites on Chacraraju. Individual nodes changed in elevation by up to 4 m, either rising or falling. According to the conservation of mass, local surface-elevation change may be comprised of individual components of (1) mass balance, (2) the advection of thicker or thinner ice, (3) ice thickening or thinning due to compressive or extending flow and (4) ice loss or gain at the glacier base (e.g. Paterson, 1994, p. 256–7). While the unavailability of a full velocity field and a DEM of the glacier bed precludes a formal analysis of these terms, our measured local variability is most probably dominated by the first two: surface ablation or accumulation and the advection of thicker or thinner ice. Accordingly, some of the measured change most probably reflects the passing of individual large

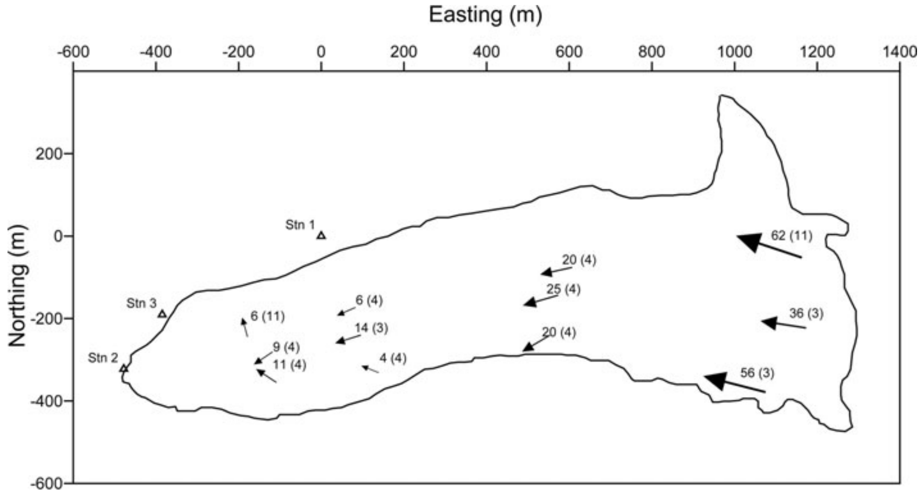

Fig. 8. Vector plots of ice-surface velocities measured in 2005. Arrow positions give the locations of the survey stakes; arrow length scales with the measured velocity; and arrow direction indicates the direction of the measured velocity. Actual measured velocities are given (mm d^{-1}) next to each arrow, with the calculated error (explained in the text) in parentheses. Coordinates are expressed relative to the position of station 1.

boulders through the survey grid, possibly supplemented by movement of such boulders relative to the underlying ice surface. The debris-covered surface of such glaciers is well known to be perennially unstable, particularly in the vicinity of migrating supraglacial melt ponds. However, the effects of boulder movement (both with the underlying ice surface and relative to it) would be approximately averaged out over the total survey areas concerned. The areally averaged surface change measured at Chacraraju is therefore considered to be a close approximation of true surface mass balance over the glacier tongue. Here, three separate areas over the debris-covered tongue revealed net change over the year of –0.58, +0.07 and –0.77 m, yielding an overall average for the combined surveyed area (43 216 m^2) of –0.43 m. We consider this to be an accurate reflection of the lowering rate of this glacier under the influence of continuing climatic warming. This rate of 0.43 m a^{-1} is consistent with, though at the higher end of, decadal-scale measurements taken on

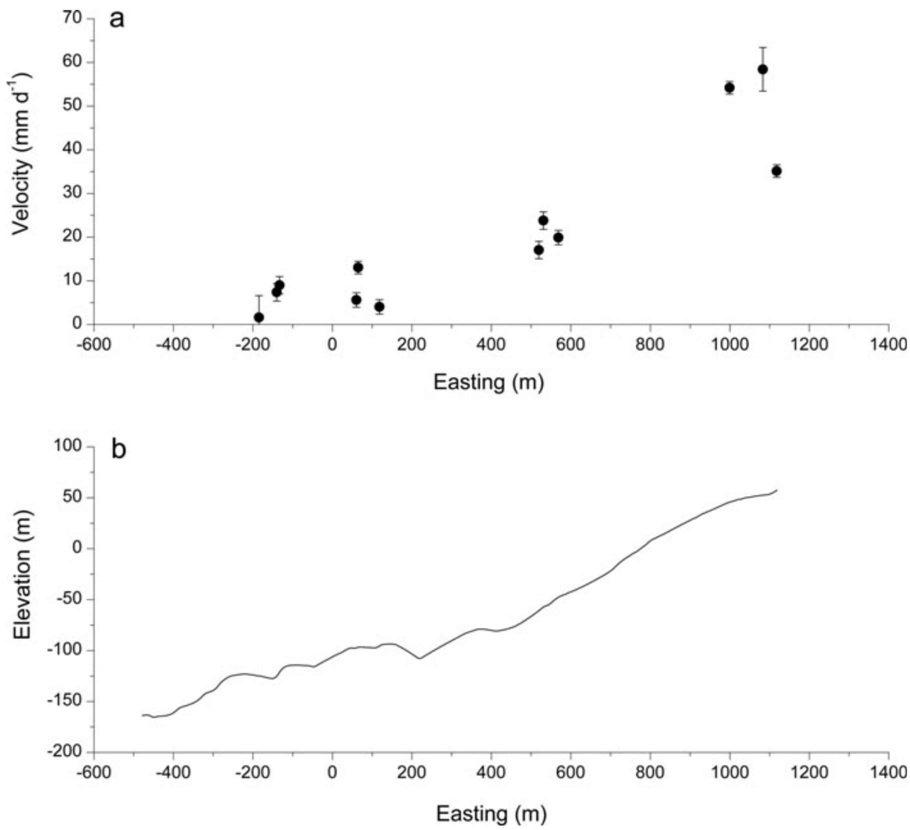

Fig. 9. (a) Bivariate plot of east-to-west velocity measured at each survey stake against distance from the glacier terminus, with error bars shown as vertical whiskers. (b) Longitudinal surface profile along the centre line of the glacier.

similar glaciers in the area (Mark and Seltzer, 2005). This suggests relatively effective lowering at Chacraraju, despite the buffering capacity of its thick debris mantle. Finally, it is worth noting that these measurements were made away from supraglacial ponds, where far more rapid local rates of rising and lowering are to be expected as those ponds migrate laterally over the glacier surface (Reynolds, 2000; Benn and others, 2001).

Ice-surface velocities increased as an approximate power function away from a value of <10 mm d^{-1} near the terminus to approaching 0.1 m d^{-1} in largely debris-free ice at the base of the glacier's icefall. While velocity vectors were consistently orientated in a down-glacier direction further from the terminus, directions became more variable closer to the terminus. Since all stakes were emplaced into ice, this variability does not reflect the movement of surface boulders relative to the underlying ice surface, but the ice surface itself. Integration of the continuity equation for ice indicates that (neglecting non-local stress propagation) surface velocity broadly scales with ice thickness raised to the power of four and ice surface slope raised to the power of three. While the effect of ice thickness cannot be evaluated meaningfully without a DEM of the glacier bed, our measurements of the forward surface motion of Chacraraju continuing right to, or at least very close to, the terminus may be largely explained by the presence of a positive surface slope right to the terminus (Fig. 9b).

This investigation reveals that even thickly debris-covered, low-angle glacier tongues, such as that at Chacraraju, are dynamic glacier components beneath which glacier ice melts and moves. Future investigations should focus on the glaciological processes controlling these dynamic phenomena. Such investigations could usefully quantify the contributions of all individual components of the continuity equation to measured surface change. There is a similar and associated need to identify the contributions of individual motion components (and their, presumably, mainly hydrological controls) to the measured surface motion field. To such an end, recent studies of supraglacial (e.g. Benn and others, 2001) and englacial (e.g. Gulley and Benn, 2007) drainage at high-altitude, debris-covered glaciers could be integrated with surface energy-balance investigations (e.g. Kaser and Georges, 1999) and with new investigations of the nature of subglacial drainage, about which virtually nothing is known. Eventually, this information could be integrated into numerical models of the mass-balance-driven motion of such glaciers, bringing our predictive ability of their response to continued climate change up to the same level as that currently available for high- and mid-latitude ice masses.

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