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Radio echo-sounding through supraglacial debris on Lirung and Khumbu Glaciers, Nepal Himalayas

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Abstract We have used ground-based radio echo-sounding (RES) to measure the ice thickness of debris-covered Lirung and Khumbu glaciers in the Nepal Himalayas in pre-monsoon season, 1999. Successful ice thickness measurements of ice up to 450 m on Khumbu and 160 m on Lirung Glacier were made using a portable lightweight (<5 kg) RES system at elevations up to 5400 m a.s.l., through supraglacial debris up to 3 m thick. These measurements provide valuable data for glacier climate response modelling and demonstrate the suitability of RES for making ice thickness measurements on a wide variety of debris-covered glaciers.

INTRODUCTION

Glaciers in the Himalayas are very sensitive to summer warming because both accumulation and ablation occur primarily during the summer monsoon season (e.g. Ageta *et al.*, 1980). Small increases in summer temperature increase the rain/snow fraction of precipitation, as well as increasing the ablation. The ablation regions of most of the large Himalayan glaciers are covered with rock debris. Understanding the response of glaciers to climate change requires knowledge of the ice volume. Here we report measurements of ice thickness made on two debris-covered glaciers in Nepal Himalayas. We have chosen radio echo-sounding (RES) over alternative methods for measuring ice thickness distribution (e.g. seismic reflection, gravity measurements) because it is faster, provides better resolution, uses easily portable instrumentation, and does not require explosives.

The use of RES for determining ice thickness has long been common in polar and temperate regions, but few successful thickness measurements have been made on debris-covered glaciers. Three main obstacles hamper the use of RES on temperate debris-covered glaciers. First, the supraglacial debris attenuates the amount of energy transmitted into and out of the underlying ice. Second, englacial rock and water inclusions cause much of the transmitted energy to be lost to scattering. Third, the rugged surface terrain on many of these glaciers reflects some energy, which complicates the interpretation of the bed reflection.

STUDY SITE

Field measurements were made during May and June 1999 at two locations (Fig. 1):

- The ablation region of Lirung Glacier in the Langtang Valley is separated from the accumulation area by a steep ice-free rock wall. The ablation area is 4 km long, 0.4–0.6 km wide, and ranges in elevation from 4000–4400 m a.s.l. The ablation area of Lirung Glacier is covered by rock debris that increases in thickness from about 0.5 m immediately below the rock wall to about 3 m near the terminus.
- The ablation region of Khumbu Glacier ranges in elevation from 5400 m a.s.l. immediately below the icefall to 4900 m a.s.l. at the terminus. This section of the glacier is about 9 km long and 0.7–1 km wide. The debris cover on Khumbu Glacier varies from generally less than 0.10 m below the icefall to more than 2 m near the terminus (Nakawo *et al.*, 1986). Both Lirung and Khumbu Glaciers have significant surface undulations that we estimate to have wavelengths of 10–100 m and amplitudes up to 10 m.

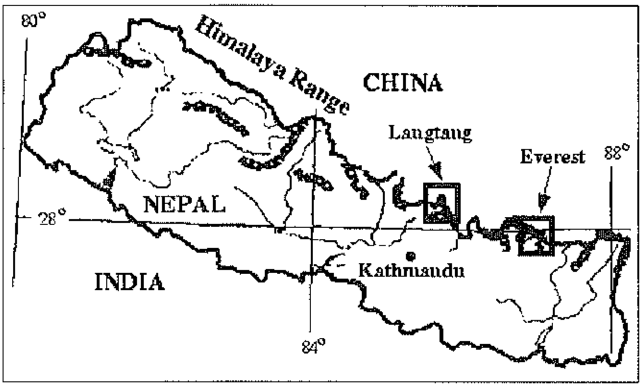

Fig. 1 Location of the two study sites in the Nepal Himalayas: Lirung Glacier in the Langtang region and Khumbu Glacier in the Everest region.

INSTRUMENTS AND METHODS

We assembled a RES system with the specific goal of making it lightweight and constructing it with the best available portable instrumentation technology. The transmitter used for these measurements was a lightweight (<0.25 kg) mono-pulse unit described by Jones *et al.* (1989). A Tektronix THS 720A (100 MHz, 500×10^6 samples s^{-1}, 12-V input digital oscilloscope (1.5 kg) was used to receive and stack 256 measurements (at 10 Hz) at each location. A Hewlett Packard 200 LX palmtop computer (3 V, 0.25 kg) was used to control the oscilloscope and to store the stacked records. Power for the transmitter and the oscilloscope was supplied by separate 12-V, 2 Ampere-hour batteries that last for about 100 records. Batteries were recharged using two 10-W flexible solar panels (United Solar Systems: USF-11). Weighted dipole antennae (ϕ = 300 Ω) (Watts & Wright, 1981), threaded inside climbing webbing for protection, with centre frequencies of 5, 7, 10 or 20 MHz, were used depending on the ice thickness and debris cover. Thicker ice and/or debris cover required the use of lower frequencies. One and a half full dipole antennae lengths separated the transmitter and receiver. Because of rough surface topography, a geodetic survey measurement was made at the centre of the transmitter–receiver pair at each of the RES measurement points to record the horizontal and vertical location.

Because of the difficulty in unambiguously interpreting individual isolated spot RES measurements, ice thickness was determined from a series of contiguous measurements that were typically spaced 10 m apart. Such a profile is necessary in order to interpret individual measurements of ice thickness in context with the adjacent measurements. Over short distances, the bed reflection is spatially consistent and appears in each record, but interfering reflections (from rock or water inclusions) generally appear at different depths in each record. An example of a single measurement and then that measurement with the surrounding measurements is shown in Fig. 2. It is not possible to identify the bed reflection of the single measurement (Fig. 2, *left* panel) but it can be determined when considered in context with the surrounding measurements (Fig. 2, *right* panel).

Ice thickness measurements were made by first determining the highest frequency that allowed us to detect a bed reflection. When a bed reflection was not observed, we used a lower frequency; the lowest used was 5 MHz. Longer wavelength (lower frequency) increases the amount of energy that passes through the surface debris layer and decreases the amount of energy scattered from within the ice. However, longer wavelengths also decrease the resolution and the longer antennae associated with lower frequencies are more difficult to move in rough terrain.

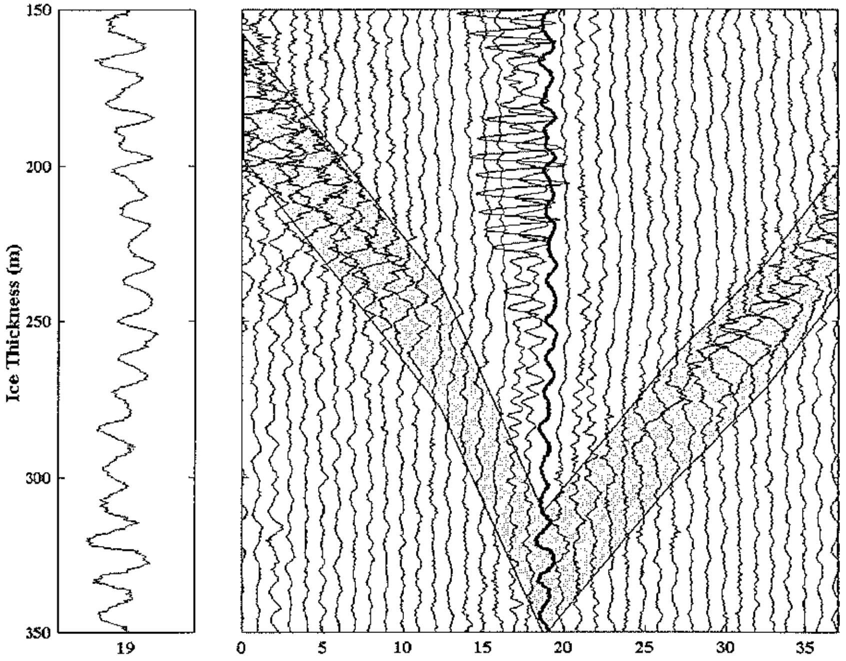

Fig. 2 *Left* panel: Example single record from Khumbu Glacier. *Right* panel: The record on the left (#19) is now drawn as a heavy black line, and is shown with the adjacent records of the profile that span the glacier. The grey band shows the region of the bed reflection.

Once the optimal frequency was determined, a profile of measurements was recorded by laying out the antennae, connecting the transmitter and receiver, making the measurement, surveying the centre point, turning off (to conserve power) and disconnecting the instruments and moving the RES system to the next location (generally 10 m between records). Having four people made moving the system over the rough surface terrain efficient (Fig. 3). Two additional people surveyed the location of each measurement—one person surveyed from a known benchmark and the other travelled with the RES system with a corner reflector; that person also assisted in moving the system. Care was necessary to ensure RES measurements were not made at the same time as hand-held radio communication between the two surveyors because the hand-held radio transmissions interfered with the RES record. In addition, we found that RES profiles along the flattest surface path (avoiding paths along ridges) and profiles that avoided large supraglacial lakes gave the best results.

When all the equipment was working properly and the surface terrain was not very difficult, we were able to complete a measurement cycle every 10–15 min, of which approximately 2 min were required for the receiver to stack and save the record. Most complete profiles done on Lirung and Khumbu Glaciers consisted of between 20 and 50 records.

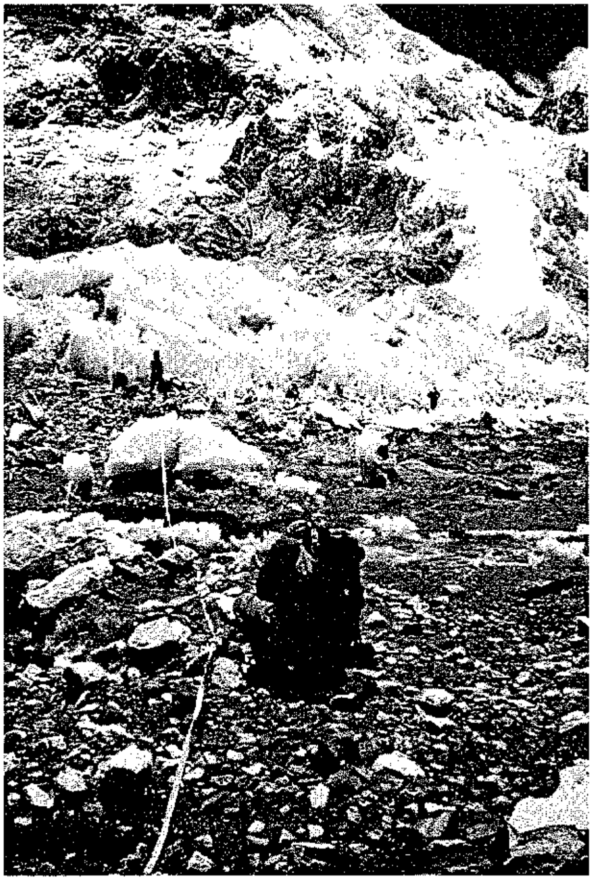

Fig. 3 Radio echo-sounding the BC line on debris-covered Khumbu Glacier.

DATA AND ERROR ANALYSIS

For each profile, all records were first bandpass filtered. The records were then adjusted vertically relative to one another using the surveyed surface elevation. These data were then migrated using the maximum convexity technique outlined in Robinson & Treitel (1980). Where the amplitude of the surface topography is of the order of the ice thickness, it is necessary to adjust the records for surface elevation before migrating to accurately determine the ice thickness.

Errors in our RES measurements arise from three main sources:
- from the migration,
- from our inability to select the precise bed reflection location from the migrated records and
- from uncertainty in the radio wave velocity within the glacier.

Errors in migrating the data could result from incorrectly using the input parameters but it is quite stable for reasonable estimates. Errors in selecting the bed location from the migrated record depends on signal frequency and strength of the bed reflection and generally results in constant uncertainty for all measurements in a profile. Errors in wave velocity results in uncertainty that increases with ice thickness. For these measurements, the uncertainty in selecting the bed reflection was between 5 and 20 m. Wave propagation speed was assumed to be 167 ± 4 m μs^{-1}. Additional uncertainty that is related to the maximum potential resolution for a given transmitted wavelength is small compared to the other uncertainties in these data.

SUMMARY OF RESULTS

The profile (G2 line) shown in Fig. 4 was measured 3 km downglacier from the icefall, and is typical of the results from Khumbu Glacier. The results of profiles that could be interpreted from Khumbu and Lirung Glaciers are summarized separately.

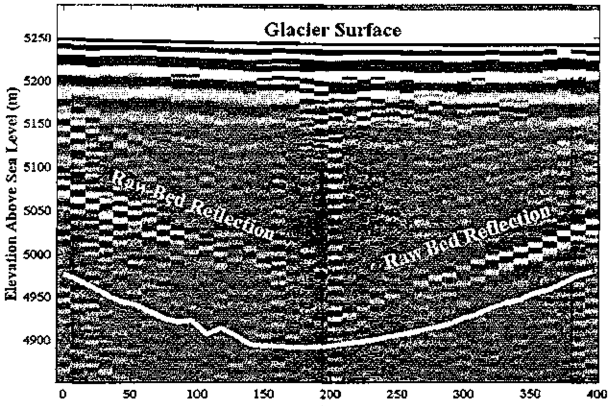

Fig. 4 Figure 2 RES profile (G2 line) from Khumbu Glacier 3 km downglacier from the icefall. The heavy white line shows the bed after migration. Accounting for the geometry of the transmitter–receiver pair results in a greater ice thickness as is seen at the centre of the subglacial trough. The glacier surface and unmigrated bed reflection is shown with text.

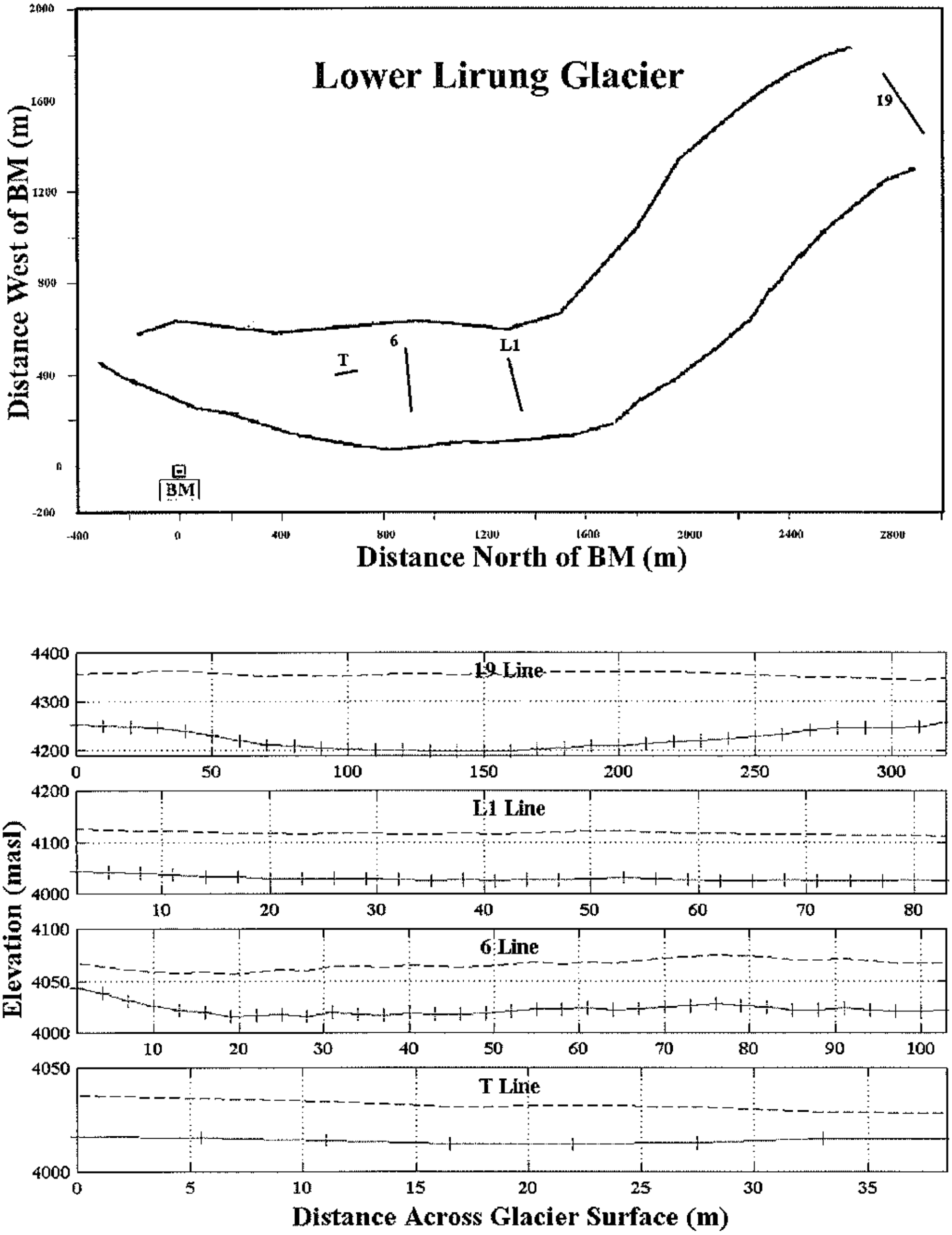

Fig. 5 *Upper* panel: Location map of Lirung Glacier, Nepal Himalaya, showing successful RES profiles using the coordinate system in Aoki & Asahi (1998). *Lower* panel: Summary of surface (dashed lines) and bed topography measurements (solid line with + at each measurement) on Lirung Glacier, May 1999. Note that the vertical and horizontal axes are different in each panel. Uncertainty in the surface elevation is less than 0.5 m and in the bed elevation it is less than 15 m. We list the start and end points (*x*, *y*, *z*) of each profile rounded to the nearest metre. 19 line: (2929, 1465, 4357), (2795, 1683, 4347); L1 line: (1345, 240, 4125), (1293, 462, 4111); 6 line: (912, 241, 4067), (888, 519, 4067); T line: (666, 415, 4037), (632, 409, 4028).

Lirung Glacier

Eight profiles were recorded on Lirung Glacier but only five produced interpretable bed reflections. Uninterpretable profiles resulted from either profiling near supraglacial lakes, which produced interference; profiling along supraglacial ridges, which produced multiple reflectors; or from using a frequency that was too high to detect the bed. The locations of the four longest, successful profiles are shown in Fig. 5 (*upper* panel) and the analysed results are summarized in the *lower* panel. Ice thickness varied from 157 ± 10 m about 1 km below the icefall (Fig. 5, 19 line) to 20 ± 5 m near the terminus (Fig. 5, T line).

These measurement are comparable to the estimates of Naito *et al.* (1998) who used measurements of surface velocities and laminar flow theory for ice to estimate ice thickness of 100 m or more in the upper section of the ablation region of Lirung Glacier and about 50 m on the L1 line.

Khumbu Glacier

Over a 12-day period, we measured eight transverse profiles on Khumbu Glacier with 10 m spacing between measurements and 1–2 km between profiles (Fig. 6). Ice thickness varied from 440 ± 20 m about 0.5 km below the icefall (Fig. 7, BC line) to less than 20 m about 2 km up from the terminus (Fig. 7, L3 line). Only the final profile

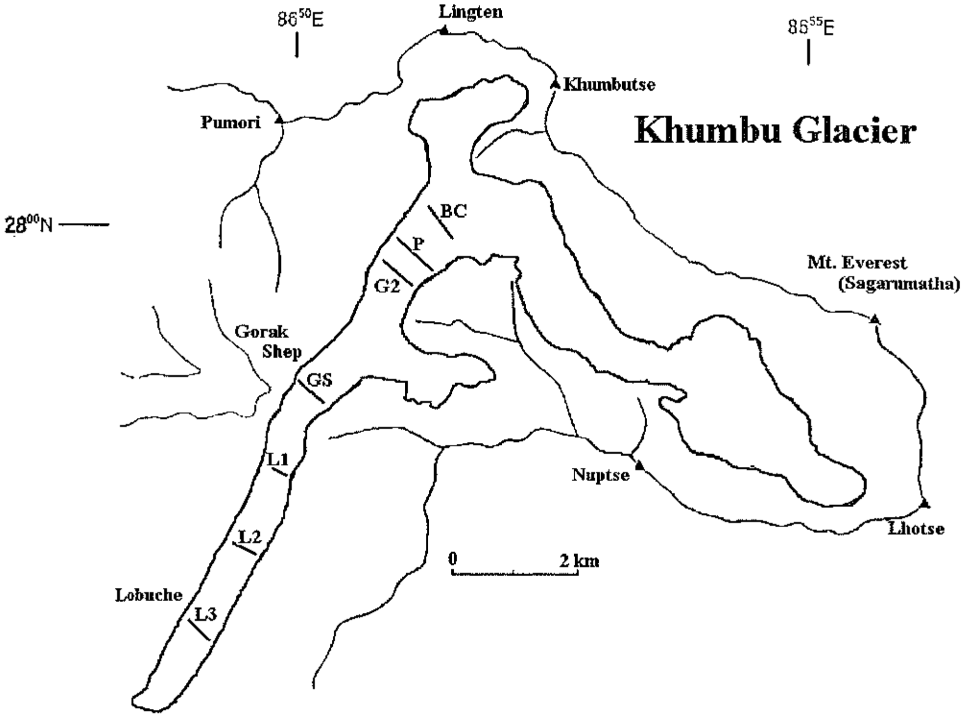

Fig. 6 Approximate location map of successful profiles on Khumbu Glacier.

near the glacier terminus did not produce interpretable results because either the ice thickness was less than 20 m or because the thick surface debris (>3 m) prevented sufficient energy transmission into the underlying ice. Previous measurements of Khumbu ice thickness include those by Moribayashi (1978) who estimated thickness based on gravity measurements. These estimates were somewhat thinner on BC line, but thicker on P line than the present measurements but the reason for this discrepancy is unknown. Kodama & Mae (1976) estimated the thickness of Khumbu from surface flow speed through laminar flow theory, similar to methods Naito *et al.* (1998) used for Lirung, and calculated ice thickness to be thinner than the present direct

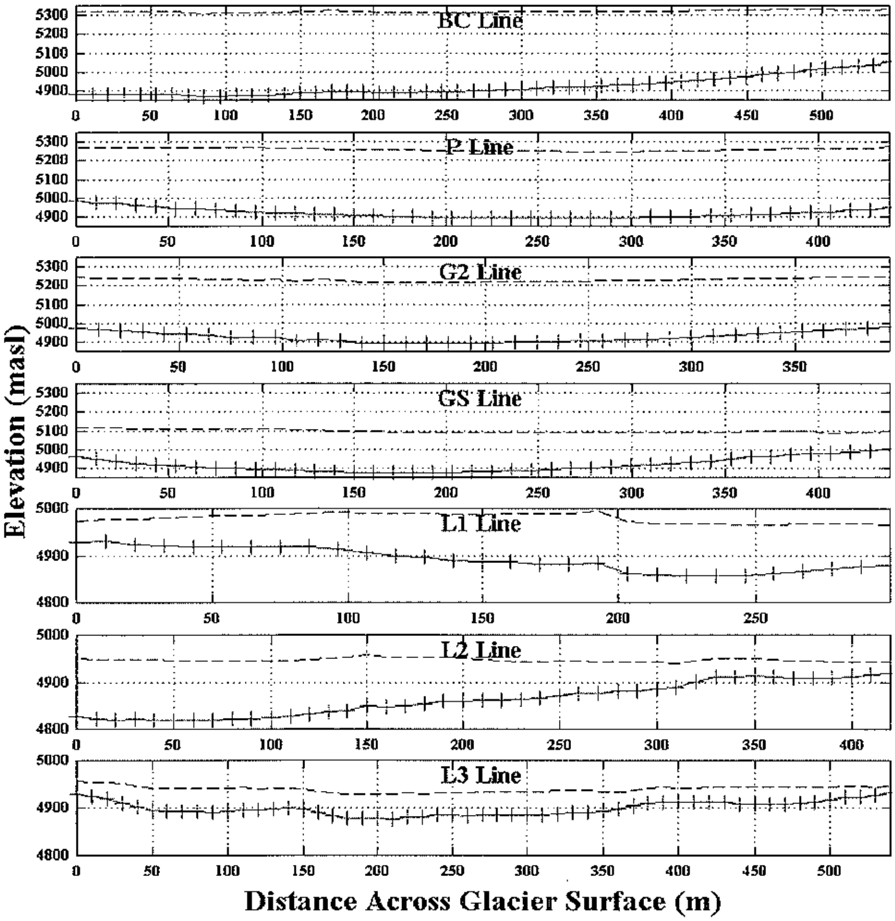

Fig. 7 Summary of surface (dashed lines) and bed topography measurements (solid line with + at each measurement) on Khumbu Glacier May–June 1999. Note that the vertical and horizontal axes are different in each panel. Uncertainty in the surface elevation is less than 0.5 m and in bed elevation is less than 20 m. We list the start and end points (*x*, *y*, *z*) of each profile rounded to the nearest metre using the coordinate system in Watanabe *et al.* (1980). BC line: (2866, 12 120, 5319), (2821, 12 624, 5332); P line: (2288, 11 300, 5270), (2037, 11 643, 5276); G2 line: (2866, 12 120, 5319), (2821, 12 624, 5332); GS line: (571, 9304, 5117), (275, 9518, 5097); L1 line: (–229, 7645, 4972), (–302, 7623, 4966); L2 line: (–815, 6607, 4951), (–453, 6492, 4943); L3 line: (–176, –1002, 4957), (–369, –583, 4946).

measurements. This is likely due to the assumption of laminar flow and if the calculations of Naito *et al.* (1998) and Kodama & Mae (1976) had accounted for lateral drag, the estimates should have been thicker. Higuchi *et al.* (1977) estimated the thickness based on the relation between surface slope, flow speed and the thickness, given in Budd & Allison (1975). These estimates appear to give ice thicknesses closest to our direct measurements, though direct comparison is not possible due to the difficulties of co-registration.

CONCLUSIONS

Successful ice thickness measurements were obtained using a combination of relatively low frequencies and by measuring a series of records that helped locate ambiguous bed reflectors. In addition, though none of the commercial instrumentation used was rated for use above 3000 m a.s.l., all of the equipment performed well at elevations up to 5400 m a.s.l. The success of these ice thickness measurements at relatively extreme conditions of high elevation and thick supraglacial debris cover demonstrates the potential of such a RES system for measuring ice thickness in a wide variety of conditions.

The direct measurements of ice thickness on Lirung and Khumbu Glaciers generally resulted in greater ice thicknesses than previous studies that have used surface velocity measurements together with laminar flow theory to estimate ice thickness. As a result, we feel that ice thickness estimates using laminar flow theory can be concluded to be underestimated for both Lirung and Khumbu due in part to neglecting the effects of lateral drag.

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