Airborne laser altimetry survey of Glaciar Tyndall, Patagonia

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Abstract

The first airborne laser altimetry measurements of a glacier in South America are presented. Data were collected in November of 2001 over Glaciar Tyndall, Torres del Paine National Park, Chilean Patagonia, onboard a Twin Otter airplane of the Chilean Air Force. A laser scanner with a rotating polygon-mirror system together with an Inertial Navigation System (INS) were fixed to the floor of the aircraft, and used in combination with two dual-frequency GPS receivers. Together, the laser–INS–GPS system had a nominal accuracy of 30 cm after data processing. On November 23rd, a total of 235 km were flown over the ablation area of Glaciar Tyndall, with 5 longitudinal tracks with a mean swath width of 300 m, which results in a point spacing of approximately 2 m both along and across track. A digital elevation model (DEM) generated using the laser altimetry data was compared with a DEM produced from a 1975 map (1:50,000 scale — Instituto Geográfico Militar (IGM), Chile). A mean thinning of -3.1 ± 1.0 m a^{-1} was calculated for the ablation area of Glaciar Tyndall, with a maximum value of -7.7 ± 1.0 m a^{-1} at the calving front at 50 m a.s.l. and minimum values of between -1.0 and -2.0 ± 1.0 m a^{-1} at altitudes close to the equilibrium line altitude (900 m a.s.l.). The thinning rates derived from the airborne survey were similar to the results obtained by means of ground survey carried out at ∼600 m of altitude on Glaciar Tyndall between 1975 and 2002, yielding a mean thinning of -3.2 m a^{-1} [Raymond, C., Neumann, T.A., Rignot, E., Echelmeyer, K.A., Rivera, A., Casassa, G., 2005. Retreat of Tyndall Glacier, Patagonia, over the last half century. Journal of Glaciology 173 (51), 239–247.]. A good agreement was also found between ice elevation changes measured with laser data and previous results obtained with Shuttle Radar Topography Mission (SRTM) data. We conclude that airborne laser altimetry is an effective means for accurately detecting glacier elevation changes in Patagonia, where an ice thinning acceleration trend has been observed during recent years, presumably in response to warming and possibly also drier conditions.
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1. Introduction

Understanding the physics of glaciers and their mass balance is a key component for assessing the impact of climate change (Oerlemans, 1994). Southern South America (Fig. 1) provides a unique mid-latitude environment for the study of glaciers, with the Patagonian

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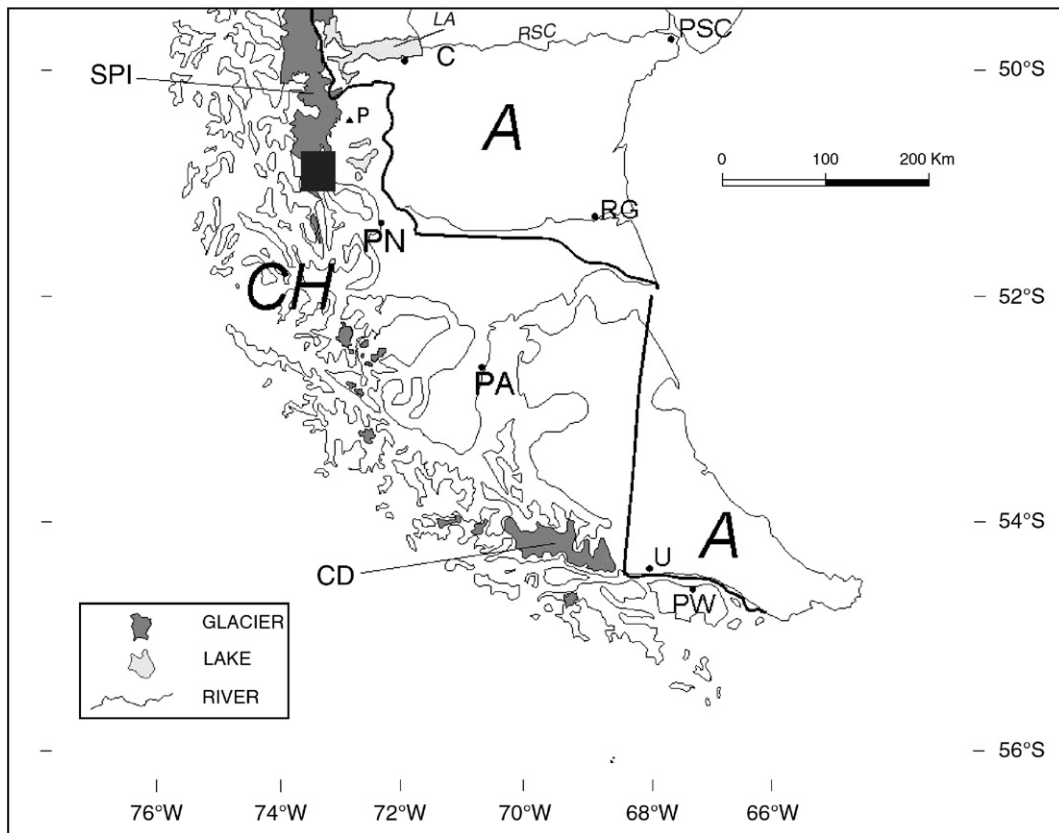*E-mail address:* krk@kms.dk (K. Keller).
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Fig. 1. Location map of the field area. The black box shows the location of Glaciar Tyndall. A, Argentina; C, Calafate; CD, Cordillera Darwin; CH, Chile; LA, Lago Argentino; P, Cordillera del Paine; PA, Punta Arenas; PN, Puerto Natales; PSC, Puerto Santa Cruz; PW, Puerto Williams; RG, Río Grande; RSC, Río Santa Cruz; SPI, Southern Patagonia Icefield; U, Ushuaia. The black thick line is the border between Chile and Argentina.

Ice Fields being one of the largest non-polar ice bodies in the world (Casassa et al., 2002). The temperate nature of the ice in Patagonia (Shiraiwa et al., 2002), together with large accumulation and ablation rates, indicates that they are especially sensitive, with short response times to climate changes.

The traditional stake-method for computing mass balance, also known as "glaciological method", is not an effective means for assessing the state of large (>10 km long) glaciers in Patagonia, because of logistic constraints and difficulties in measuring high accumulation and ablation rates. A more effective means for mass balance measurements is the so-called "geodetic method", in which changes in ice thickness are detected by means of repeated surveys of glacier elevation (Krimmel, 1999).

Airborne laser altimetry provides an accurate and efficient way of producing digital elevation models (DEMs). Comparison with historical DEMs derived from maps or early field surveys results in the assessment of thinning rates with adequate accuracy. Airborne laser

altimetry also provides excellent data for calibration of satellite altimetry and for creating a baseline reference for comparison of future satellite-derived DEMs as more data becomes available from future missions (Bamber and Rivera, 2007-this issue). In this paper we present the first measurements of airborne laser altimetry of a glacier in the Andes, Glaciar Tyndall, Patagonia.

2. Airborne sensors

The Chilean Air Force (FACH) provided the use of a DHC-6 Twin Otter airplane based at the Punta Arenas airport. The aircraft was modified by FACH for the installation of the sensors.

A Riegl LMS-Q140i-60 scanning laser altimeter with a rotating mirror mechanism was used. The scanner was operated at 40 Hz (scan angle±30°) with 208 measurements per scan, resulting in a data acquisition rate of ≈8 kHz. For typical speeds along the ground of 50 m/s and flying height of 250–300 m above ground level (AGL) this results in a mean horizontal ground

resolution close to 1 m. The laser captures the last reflected pulse minimizing disturbances from atmospheric ice crystals and aerosols that might partly reflect the laser beam and cause data errors (Riegl, 2001). Aircraft attitude (pitch, roll and heading) were recorded with a Honeywell H-764G INS with a data capture rate of 50 Hz and a precision of 0.01 to 0.05°.

Two dual-frequency GPS receivers, one Trimble 4000 SSI and one Javad Legacy, both operating at 1 Hz were used onboard for positioning of the aircraft. Two base stations were installed on the ground, which allowed for carrier phase differential GPS corrections during post-processing. The GPS data also provided time synchronization of the different sensors.

The scanning laser–INS–GPS system described above has been previously used with much success in the Arctic and Greenland on both sea ice and ice caps, for a technical description see Forsberg et al. (2003) and Keller et al. (2004). Nominal accuracy of the system used in Greenland was approximately 30 cm, mainly due to errors in the GPS positions generated by the use of long baselines (up to 1000 km). The system used in Denmark resulted in better accuracies (∼15 cm) due to the use of shorter baselines (10–50 km).

In addition to the laser altimeter, a 60 MHz ice-penetrating radar from the Technical University of Denmark, designed originally for sounding glaciers in polar regions (Lintz Christensen et al., 2000) was installed onboard. However, analysis of the radar results showed that bed reflections could not be detected, indicating that the abundant supraglacial and englacial water in Patagonian glaciers effectively prevents the penetration of radar signals (Rivera and Casassa, 2002).

As a complement to the laser system, one nadir-looking digital video camera (Sony DCR-TRV110D) and one nadir-looking 35 mm analogue photographic camera were installed onboard (Canon EOS 3000) for continuously recording the ground track covered by the aircraft (Cárdenas, 2001).
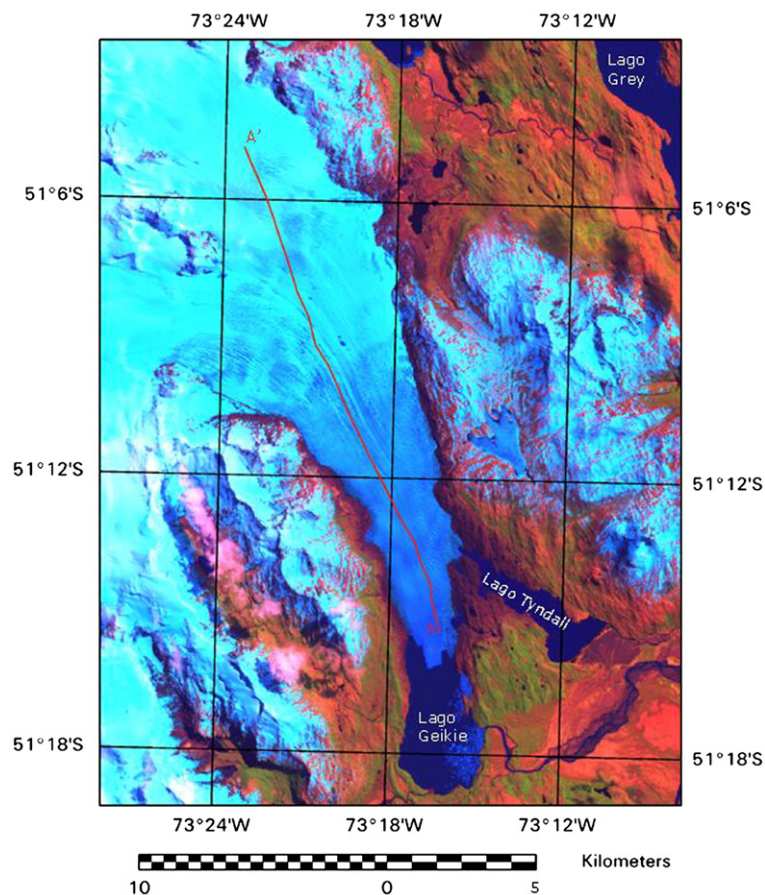

Fig. 2. Landsat ETM+ false colour composite image (bands 1, 4 and 5) of Glaciar Tyndall acquired on October 27, 2000. In red the topographic profile A–A′ of Fig. 5 is shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3. Field survey and precision

A test flight was performed on November 19, 2001 over the campus of Universidad de Magallanes (UMAG) in Punta Arenas for the calibration of the laser altimeter. The main 110 m-long building of the Faculty of Engineering was used as a calibration target, surveying the vertices of the building by GPS to 1 cm accuracy.

During the test flight a four-leaf-clover track was flown over the campus area targeting the surveyed building. During the analysis of data resulting from the test, a calibration of the misalignment angles between the INS and the laser scanner allowed correction of the building position in order that data collected in all four passes co-incided with the coordinates surveyed by traditional static GPS. This process was done manually, yielding an estimated precision of 0.05°. After calibration, the resulting airborne laser data were compared to kinematic GPS data obtained after surveying a field at UMAG campus, yielding a mean elevation difference of 5 cm and a RMS error smaller than 10 cm.

On 23rd November 2001 a flight was performed over Glaciares Grey and Tyndall, Torres del Paine National Park, Southern Patagonia Icefield (SPI). Here we report the elevation results over the ablation area of Glaciar Tyndall, covering an altitude range between 946 and ∼50 m at the calving front of the glacier into Lagos Geikie and Tyndall (Fig. 2). The altitude above ground level (AGL) of the aircraft varied from 150 m to 500 m during the survey, with an average AGL of about 300 m, which results in a mean swath of 300 m.

A GPS receiver was deployed at the base station located at Punta Arenas (PA) airport. Another GPS receiver was installed at Puerto Natales airport, 185 km northeast of PA. Baselines were shorter than 100 km in order to minimize atmospheric errors in the differential GPS positions, allowing an aircraft position determination of 15 cm. Final glacier elevations are referred to mean sea level by subtracting the geoid height (EGM96 global geoid model) from the ellipsoidal heights obtained from the post-processed GPS positions. The Punta Arenas continuous GPS station located at UMAG campus (PARC), where a GPS receiver was set up during the field survey, was used as the fixed benchmark for this survey. Absolute coordinates for PARC are known to an accuracy better than 1 mm (M. Bevis, personal communication).

Because of logistical limitations it was not possible to survey the control site at the UMAG campus at the start and end of each survey to verify the survey system. A surface elevation accuracy of 30 cm has however been verified by a crossover analysis (without any adjustments) of 10,000 pairs of observations which coincide horizontally within 1.0 m at the upper part of Glaciar Tyndall. The uncertainty is mainly caused by inaccurate GPS positions, particularly due to banking of more than 10° during aircraft maneuvers such as turns, causing the GPS receiver to loose track of one or more satellites. The laser contributes about 5 cm in the error estimate and the rest originates from lack of precise alignment and lever arm corrections.
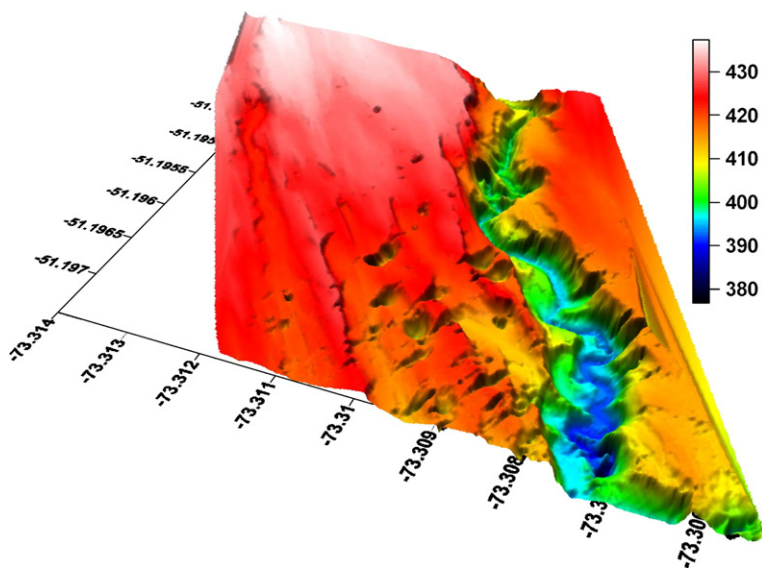

Fig. 3. 3-D view of a reduced section of the ablation area of glaciar Tyndall at a mean elevation of 400 m. A supraglacial stream can be seen at the right hand side. Several individual crevasses and moulins are also seen.

Overall the laser altimetry data of Glaciar Tyndall show very detailed information of the surface topography: surface undulations, morphological features associated with the hydraulic drainage of the glacier, and crevasses can be clearly detected (Fig. 3).

4. Digital elevation models

4.1. Available cartographic data

The ablation area of Glaciar Tyndall was covered by a map generated by Instituto Geográfico Militar (IGM) of Chile, based upon 1975 aerial photographs. The surveyed area is located within Torres del Paine National Park, where IGM had logistic facilities to access the SPI enabling the installation of a few control points on bedrock in the vicinity of Glaciar Tyndall. Poor topographic coverage of the upper section of the glacier resulted from a lack of stereoscopic vision in the aerial photographs over the smooth, featureless and low relief accumulation area of the SPI. As a consequence, the IGM 1:50,000 scale cartography for Glaciar Tyndall has contour lines every 50 m covering only the lower part of the glacier and rock outcrops, but not the accumulation area. Several spot elevations are available from summits and other distinctive features in the accumulation area.

4.2. DEM generation from 1975 cartography

A digital elevation model (DEM) was generated by interpolating contour lines digitized from the available regular 1975 cartography provided by IGM Chile. Three interpolation methods were applied: Inverse Distance Weighing (IDW), Triangulated Irregular Network (TIN), and TOPOGRID (a discretised thin plate spline technique available within commercial software ArcInfo version 8.0.1). To select the best-fit interpolation method two factors were considered; the number of artifacts presented in the resulting DEM and the time and effort of manual interaction needed to produce the DEM. Based upon these criteria, the best method proved to be TOPOGRID. This interpolation procedure did generate some artifacts at the margins of the ice ('sinks'), but they were much smaller and less extensive than the generalized linear and triangular artifacts obtained with the other two interpolation methods. A jack-knifing procedure (Lythe et al., 2001) was employed to account for the error added by the selected interpolation method. For that purpose two DEMs were generated and compared; one with all the available topographic information, whilst for the second DEM only 90% of the contour lines

was used. The TOPOGRID interpolation method was applied to the whole study area with contour lines, spot heights and lakes used as topographic information inputs. A 50 m pixel size was selected, with UTM-18S coordinates, datum WGS-1984 and mean sea level as altitude reference. The horizontal error of the DEM was calculated to be 15 m. This error is related to contour inaccuracy, datum correction, digitization of contour lines and contour line generation.

No vertical error estimations for the regular cartography of IGM were available. However, the regular cartography at 1:50,000 scale is of class 1 accuracy in terms of the American Society for Photogrammetry and Remote Sensing classification. That means that this
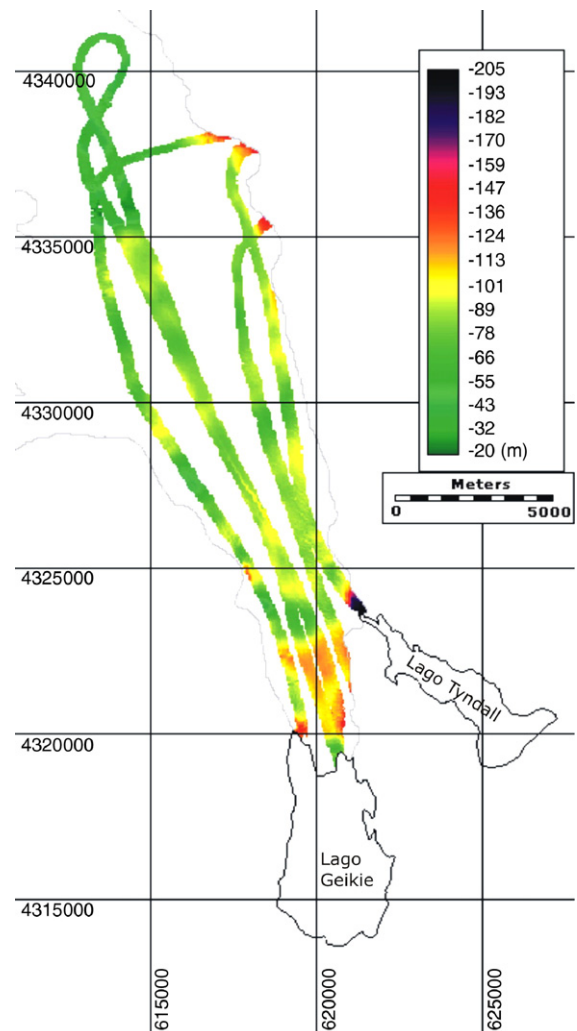

Fig. 4. Ice elevation changes in m between the 1975 DEM and the laser DEM of 2001, in the ablation area of Glaciar Tyndall, Southern Patagonia Icefield. UTM-18S coordinates are expressed in m, WGS 1984.

cartography is the most stringent, with vertical inaccuracies related to the contour interval possessing a vertical error of 17 m. After applying the jack-knifing procedure, it was estimated that the vertical error added by the interpolation procedure yielded 9 m. Therefore, the combined vertical error of the DEM is 19 m.

4.3. DEM from laser altimetry data

By plotting and analyzing the raw laser altimetry data points with ArcView 3.2 commercial software, outliers and spurious data points were filtered. The resulting data were rasterized in a 50 m grid size in order to compare the ice elevation changes with respect to the previous cartography. All data points located within a 50 m pixel size were averaged (equally weighted mean) in order to obtain a single altitude value per pixel. Some pixels contain thousands of laser data, especially at the center of the flight line swaths, whilst at the margins a minimum of about ten points was available for some pixels.

4.4. Elevation control of the DEMs over bedrock

Mean sea level elevations from the laser DEM and the 1975 DEM were compared along two profiles covering only rock areas at the eastern side of Lago Geikie and between the eastern front of Glaciar Tyndall and Lago Grey, resulting in a mean average difference of 1.0 m and a standard deviation of 24.8 m. Considering that the accuracy of the laser DEM is 30 cm, the random error

must be almost completely due to inaccuracies in the 1975 DEM. The ∼ 25 m error for the 1975 DEM is higher than the previous estimation of 19 m (Rignot et al., 2003), but not excessively out of the expected values considering the limited sampled area (4.9 km^2). The spatial distribution of the differences was very biased, with mainly negative values near Lago Geikie and positive differences between Glaciar Tyndall and Lago Grey. This kind of bias is due to the photogrammetric method used to compile the cartography (based upon aerial photographs with restricted number of control points), therefore, the spatial bias of the DEM 1975 is related to slope (higher errors at higher slopes) and distances from the control points (higher errors in remote areas away from the control points). Aspect could also be a factor, which results in some areas in the aerial photographs more illuminated (northern slopes in Chile) and therefore with much better accuracy than other areas with more shadow, such as southern slopes, were the expected accuracy is worst.

5. Results

The ice elevation changes of the glacier are illustrated by comparing IGM and laser DEMs from 1975 to 2001, respectively. A Boolean mask was generated for each dataset in order to differentiate the areas without data and the rock outcrops. Rock outcrops were selected based on the IGM map and a Landsat ETM+ satellite imagery acquired on October 27, 2000.
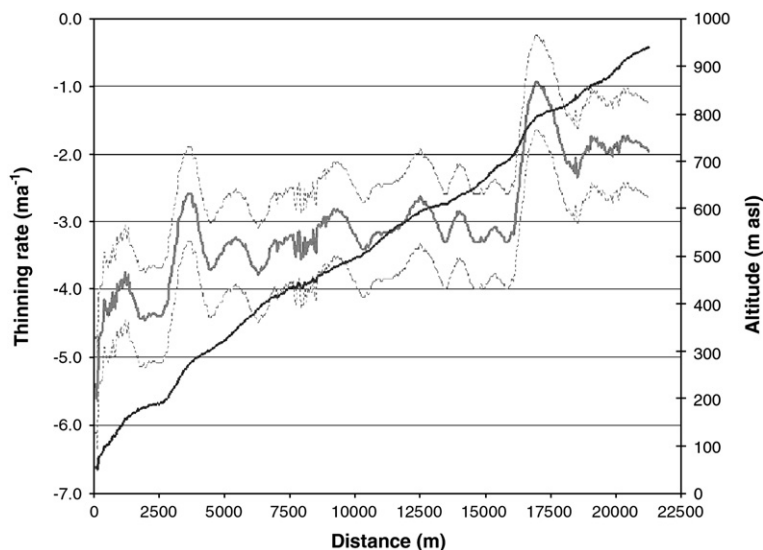

Fig. 5. Ice elevation changes (laser altimetry 2001 DEM – IGM 1975 DEM) (left hand *y*-axis in m a−1) along longitudinal topographic profile A–A′ (see Fig. 2 for location of the profile). The surface topography is shown as a thick line diagonally across the figure (right hand *y*-axis in m). The estimated errors are shown as thin lines.

The laser data were located between the lower end of Glaciar Tyndall (∼ 50 m a.s.l.) and a maximum altitude of 946 m a.s.l., just above the equilibrium line altitude, located approximately at 900 m (Aniya et al., 1996). A generalized thinning trend was observed throughout the glacier. The average ice elevation change rate for all data yielded a thinning of -3.1 ± 1.0 m a^{-1}, with maximum value of -7.7 ± 1.0 m a^{-1} at the freshwater calving front of the glacier into Lago Tyndall. The non-calving eastern tongue (Zapata), also experienced high thinning rates, up to -5.6 ± 1.0 m a^{-1}, whilst the freshwater calving front into Lago Geikie showed values between -3.7 and -5.7 ± 1.0 m a^{-1}. Fig. 4 shows the distribution of ice thinning along the flight tracks.

To analyze in more detail the ice elevation changes versus altitude, a topographic profile was generated. This profile approximately follows the central flow line of the glacier, from the frontal tongue of Lago Geikie up to 938 m a.s.l. (Fig. 2). Fig. 5 shows the resulting ice elevation changes along the profile, with maximum ice elevation change rates in areas close to the calving front, and a reduction of thinning rates at higher altitude, where minimum thinning values between -1.0 and -2.0 ± 1.0 m a^{-1} were observed.

6. Discussion

Glaciar Tyndall has been retreating and shrinking since the end of the Little Ice Age (Rivera and Casassa, 2004), with an acceleration of this trend being observed during recent decades — presumably in response to warming and drier conditions prevailing in Patagonia during the second half of the 20th century (Casassa et al., 2002).

Ice elevation changes of the glacier have been repeatedly measured along a topographic transverse profile first established in 1985 by Naruse et al. (1987) at approximately 700 m of altitude. The same profile was re-surveyed in 1990 by Kadota et al. (1992); in 1993 by Nishida et al. (1995); and in 2001 by Raymond et al. (2005). Based on these values, and considering long-term comparison with previous estimations based upon aerial photographs acquired in 1945 and the IGM regular cartography of 1975, it was possible to confirm an acceleration of the thinning trend at the transverse profile from -2.3 m a^{-1} between 1945 and 2002, to -3.2 m a^{-1} between 1975 and 2002 (Raymond et al., 2005).

The results obtained here are coincident with these estimations, as the mean average ice elevation change along the transverse profile resulted in a thinning rate of -3.1 m a^{-1} between 1975 and 2001. A similar

conclusion was obtained by comparing Shuttle Radar Topography Mission (SRTM) data obtained in 2000 with IGM 1975 data (Rignot et al., 2003), confirming that the glacier is undergoing an accelerated thinning.

Based upon the warming trends recorded in several Patagonian meteorological stations between 1961 and 1990 (Rosenblüth et al., 1997; Carrasco et al., 2002) it was possible to characterize the area as suffering recent rapid regional warming, similar to the observed changes experienced on the Antarctic Peninsula (Vaughan et al., 2003). Villalba et al. (2003) described the surface temperature changes experienced during recent decades by the Patagonian region between 46° and 55°S as "remarkable, more intensive during the summer seasons and affecting predominantly minimum temperatures". In this context, and considering all the dendrochronological evidence obtained in Patagonia by Villalba et al. (2001), it can be concluded that the warming trends observed from instrumental data in Patagonia during recent decades represent an unprecedented warming in the long-term climatic variation since the end of the Little Ice Age (LIA) during the mid-19th century.

This warming trend is presumably the main factor behind Glaciar Tyndall variations, however, a dynamic component could be playing an important role, as the glacier is calving into freshwater lakes where the ice is thinning at high rates which are not completely explained by the warming experienced by the region. Raymond et al. (2005) as well as Rignot et al. (2003) considered that some enhanced basal sliding and creeping due to higher amounts of melt water at progressively higher altitudes, could explain the high thinning at the glacier front, where the glacier could be stretching longitudinally and thinning dynamically. To test this hypothesis, laser data have proved to be reasonably accurate (0.3 m) for mapping the glacier and detect ice elevation changes of relatively small magnitudes, however, new data will be necessary to calculate effects of possible ice flow acceleration and other dynamic components on the glacier variations.

7. Conclusions

We report the first airborne laser altimetry survey for a South American glacier, Glaciar Tyndall of the SPI. Most of the ablation area of the glacier between 50 and 948 m of altitude was surveyed. Results showed extensive thinning throughout the ablation area, with a mean value of -3.1 ± 1.0 m a^{-1}. Thinning increases with decreasing altitude, with a maximum value of -7.7 ± 1.0 m a^{-1} at the freshwater calving front into Lago Tyndall and minimum values of -1.0 to -2.0 ± 1.0 m a^{-1} close to the

equilibrium line altitude at ca. 900 m a.s.l. We see the same trend of increased thinning at lower altitudes as in Greenland (Krabill et al., 2000) and Alaska (Arendt et al., 2002). Ice thinning at Glaciar Tyndall is at least partly driven by enhanced melting due to warmer atmospheric temperatures. In the near future it will be of great importance to continue monitoring changes in glacier thickness in Patagonia by means of airborne laser altimetry, which has proved to be an efficient method for mapping large glaciers which are normally difficult to survey extensively using in-situ field methods. The high accuracy of the airborne laser measurements should provide information, over short survey periods, that would assist in characterizing the mass balance of the upper accumulation area, which is presently unknown.

Acknowledgements

References

Aniya, M., Sato, R., Naruse, R., Skvarca, P., Casassa, G., 1996. The use of satellite and airborne imagery to inventory outlet glaciers of the Southern Patagonia Icefield, South America. Photogrammetric Engineering & Remote Sensing 62 (12), 1361–1369.

Arendt, K.A., Echelmeyer, W.D., Harrison, W.D., Lingle, C., Valentine, V., 2002. Rapid wastage of Alaska glaciers and their contribution to rising sea level. Science 297, 382–386.

Bamber, J., Rivera, A., 2007. A review of remote sensing methods for glacier mass balance determination. Global and Planetary Change 59, 138–148 (this issue). doi:10.1016/j.gloplacha.2006.11.031.

Cárdenas, R., 2001. Sistema digital de adquisición de imágenes: aplicación de sensores aéreos. Unpublished thesis, Faculty of Engineering, University of Magallanes.

Carrasco, J., Casassa, G., Rivera, A., 2002. Meteorological and climatological aspects of the Southern Patagonia ice cap, Patagonia. In: Casassa, G., Sepúlveda, F., Sinclair, R. (Eds.), The Patagonian Icefields: A Unique Natural Laboratory for Environmental and Climate Change Studies. Series of the Centro de Estudios Científicos. Kluwer Academic/Plenum Publishers, New Cork, pp. 29–41.

Casassa, G., Rivera, A., Aniya, M., Naruse, R., 2002. Current knowledge of the Southern Patagonia Icefield. In: Casassa, G., Sepúlveda, F., Sinclair, R. (Eds.), The Patagonian Icefields: A Unique Natural Laboratory for Environmental and Climate Change Studies. Series of the Centro de Estudios Científicos. Kluwer Academic/Plenum Publishers, New York, pp. 67–83.

Forsberg, R., Keller, K., Hvidegaard, S., Olesen, A., 2003. ESAG-2002: European Airborne Gravity and Lidar Survey in the Arctic Ocean. Technical Report No. 21. National Survey and Cadastre, Denmark. ftp://ftp.kms.dk/pub/ESAG.

Keller, K., Hvidegaard, S.M., Forsberg, R., Dalå, N.S., Skourup, H., Stenseng, L., 2004. Airborne lidar and radar measurements over sea ice and inland ice for cryosat validation: CRYOVEX 2003 — final report. Technical Report No. 25. National Survey and Cadastre, Denmark.

Kadota, T., Naruse, R., Skvarca, P., Aniya, M., 1992. Ice flow and surface lowering of Tyndall Glaciar, southern Patagonia. Bulletin of Glacier Research 10, 63–68.

Krabill, W., Abdalati, W., Frederick, E., Manizade, S., Martin, C., Sonntag, J., Swift, R., Thomas, R., Wright, W., Yungel, J., 2000. Greenland ice sheet: high-elevation balance and peripheral thinning. Science 289, 428–430.

Krimmel, R., 1999. Analysis of difference between direct and geodetic mass balance measurements at South Cascade Glacier, Washington. Geografiska Annaler 81A (4), 653–658.

Lintz Christensen, E., Reeh, N., Forsberg, R., Jørgensen, J.H., Skou, N., Woelders, K., 2000. A low-cost glacier-mapping system. Journal of Glaciology 46 (154), 531–537.

Lythe, M., Vaughan, D., BEDMAP consortium, 2001. BEDMAP: a new ice thickness and subglacial topographic model of Antarctica. Journal of Geophysical Research 106 (b6), 11335–11351.

Naruse, R., Peña, H., Aniya, M., Inoue, J., 1987. Flow and surface structure of Tyndall Glacier, Southern Patagonia Icefield. Bulletin of Glacier Research 4, 133–140.

Nishida, K., Satow, K., Aniya, M., Casassa, G., Kadota, T., 1995. Thickness change and flow of Tyndall Glacier, Patagonia. Bulletin of Glacier Research (Data Center for Glacier Research, Japanese Society of Snow and Ice) 13, 29–34.

Oerlemans, J., 1994. Quantifying global warming from the retreat of glaciers. Science 264 (5156), 243–245.

Raymond, C., Neumann, T.A., Rignot, E., Echelmeyer, K.A., Rivera, A., Casassa, G., 2005. Retreat of Tyndall Glacier, Patagonia, over the last half century. Journal of Glaciology 173 (51), 239–247.

Riegl, 2001. Laser mirror scanner, LMS-Q140i-60. Technical Documentation and Users Instructions, Rev. 19–08–2001 (V4.3), Riegl, Laser Measurements Systems GmbH, Horn, Austria. http://www.riegl.co.at/principles/e_gi009.htm.

Rignot, E., Rivera, A., Casassa, G., 2003. Contribution of the Patagonia Icefields of South America to sea level rise. Science 302, 434–437.

Rivera, A., Casassa, G., 2002. Detection of ice thickness using radio-echo sounding on the Southern Patagonia Icefield. In: Casassa, G., Sepúlveda, F., Sinclair, R. (Eds.), The Patagonian Icefields: A

Unique Natural Laboratory for Environmental and Climate Change Studies. Series of the Centro de Estudios Científicos. Kluwer Academic/Plenum Publishers, New York, pp. 101–115.

Rivera, A., Casassa, G., 2004. Ice elevation, areal and frontal changes of glaciers from Torres del Paine National Park, Southern Patagonia Icefield. Arctic, Alpine and Antarctic Research 4 (36), 379–389.

Rosenblüth, B., Fuenzalida, H., Aceituno, P., 1997. Recent temperature variations in southern South America. International Journal of Climatology 17, 67–85.

Shiraiwa, T., Kohshima, S., Uemura, R., Yoshida, N., Matoba, S., Uetake, J., Godoi, M., 2002. High net accumulation rates at Campo de Hielo Patagónico Sur, South America, revealed by analysis of a 45.97 m long ice core. Annals of Glaciology 35, 8490.

Vaughan, D., Marshall, G., Connolley, W., Parkinson, C., Mulvaney, R., Hodgson, D., King, J., Pudsey, C., Turner, J., 2003. Recent rapid regional climate warming on the Antarctic Peninsula. Climatic Change 60 (3), 243–274.

Villalba, V., D'Arrigo, R., Cook, E., Wiles, G., Jacoby, G., 2001. Decadal-scale climatic variability along the extratropical western coast of the Americas: evidences from tree-ring records. In: Markgraf, V. (Ed.), Inter-Hemispheric Climate Linkages. Academic Press, San Diego, California, U.S.A., pp. 155–172.

Villalba, R., Lara, A., Boninsegna, J., Masiokas, M., Delgado, S., Aravena, J., Roig, F., Schmelter, A., Wolodarsky, A., Ripalta, A., 2003. Large-scale temperature changes across the southern Andes: 20th-century variations in the context of the past 400 years. Climatic Change 59 (1–2), 177–232.