Proceedings of the 4th Meeting on Italian Antarctic Glaciology

Editors
Massimo Frezzotti & Valter Maggi

TERRA ANTARTICA REPORTS NO. 8

4th Meeting on Italian Antarctic Glaciology (4th CONGA)

held in
Milan, 25 – 26 June 2002
Dipartimento di Scienze Ambiente e Territorio (DISAT), Università di Milano Bicocca, P.zza della Scienza 1, 20126 Milano

convened by
Giuseppe Orombelli, Massimo Frezzotti & Valter Maggi

organized by
Project on Glaciology of the Italian *Programma Nazionale di Ricerche in Antartide* (PNRA)

TERRA ANTARTICA REPORTS, NO. 8
Editors Massimo Frezzotti & Valter Maggi

ISBN 88-88395-02-4

Contents

Preface
G. Orombelli VII

Introduction
M. Frezzotti & V. Maggi IX

List of referees X

MASS BALANCE, DETECTION AND MONITORING OF CHANGE IN GLACIERS

Local Glacier Snout Monitoring in Northern Victoria Land, Antarctica
A. Bondesan, M. Meneghel & M.C. Salvatore 1

Snowcover in Antarctica: Physical and Morphological Features of Surface Layers
A. Cagnati, M. Valt, R. Casacchia & R. Salvatori 5

Mass Balance of Campbell Glacier (Northern Victoria Land, Antarctica): Preliminary Analysis
M. Mancini, M. Frezzotti, C. Smiraglia, R. Gragnani, A. Zirizzotti, M. Motta & M. Pavan 11

Penetration of Radiation in Antarctic Snow and Ice
L. Motta & M. Motta 15

Mass Balance and Energy Balance at Strandline Glacier (Terra Nova Bay, Antarctica):
Methods and Preliminary Results
M. Motta, G. Diolaiuti, G. Vassena & C. Smiraglia 21

PALAEOCLIMATE AND PALAEOENVIROMENTAL INFORMATION FROM SNOW AND ICE

Snow-atmosphere interaction

A Record of Heavy Metals Concentration in Antarctic Snow since the mid-19th Century
G. Cozzi, C. Barbante, F. Planchon, C. Boutron, V. Gaspari, E. Wolff, C. Ferrari, P. Cescon 29

Temporal Variability of Iron and Other Bioactive Trace Elements in Antarctic Continental Ice
V. Gaspari, C. Barbante, G. Cozzi & P. Cescon 33

Identification of Sources of Antarctic Aerosol in Victoria Land by Means of
Principal Component Analysis of Chemical Data
C. Truzzi, L. Lambertucci, A. Annibaldi, G. Gambini, S. Becagli,
R. Traversi, R. Udisti & G. Scarponi 37

Natural climate variability in Antarctica over the last millenium "ITASE"

Variability of Snow Depositions along the 1998/99 ITASE Traverse
S. Becagli, M. Frezzotti, R. Gragnani, A. Migliori, M. Proposito, R. Traversi & R. Udisti 43

Terra Antartica Reports
2003, **8**, 21-28

Mass Balance and Energy Balance at Strandline Glacier (Terra Nova Bay, Antarctica): Methods and Preliminary Results

M. Motta[1], G. Diolaiuti[2], G. Vassena[3] & C. Smiraglia[2*]

[1]Dipartimento di Scienze della Terra, Università di Torino, Via Valperga Caluso 35, 10125 Torino - Italy
[2]Dipartimento di Scienze della Terra " Ardito Desio", Università di Milano,
Via Mangiagalli 34, 20133 Milano - Italy
[3]Dipartimento di Ingegneria civile, Università di Brescia, Via Branze 38, 25123 Brescia – Italy

**Corresponding author* (claudio.smiraglia@unimi.it)

INTRODUCTION

Intensive fieldwork was carried out during the 16th Italian Campaign in Antarctica (2000-2001) with the intention of completing the groundwork required for calculating the mass balance and energy balance of several local glaciers in northern Victoria Land. The studied glaciers are of limited size and have well-defined profiles, with elongated, convex terminal tongues. The glacier tongues form a clearly delimited frontal scarp, although the exact position of the front is generally concealed by a mantle of snow and ice (*i.e. apron*).

Data-collection methods and preliminary results for Strandline Glacier, located in the vicinity of the Italian station at Terra Nova Bay, are discussed in this report. Strandline Glacier is characterized by distinct areas of accumulation and ablation: substantial snow accumulation occurs along its borders, deflation in the middle sector. The lower portion of the latter area forms a prominent tongue which terminates in a cliff, where ablation mainly consists of *dry calving*, as shown by the blocks of ice lying at the base of the cliff which feed an *apron* (Baroni & Orombelli, 1987; Chinn et al., 1989).

METHODS AND RESULTS

The study on the evolution of local Antarctic glaciers aims to define the response of such glaciers to climatic variations. Although the response is expected to be sensitive even to small environmental changes, it is usually of limited magnitude, thereby difficult to quantify (Chinn, 1980; Chinn et al., 1989; Baroni et al., 1995), and with a reaction time probably in the order of decades (Schneider, 1999). Various methods were used to measure seasonal or annual changes in local glaciers. Surveying techniques such as real-time kinematic (RTK) GPS (Gandolfi et al., 1994), quantum-photo-radiometry (for evaluating energy exchanges at the snow-atmosphere interface) and experimental parcels were thus adopted alongside traditional topographic surveying (theodolites) and methods for measuring ice-snow accumulation (stakes and trenches for measuring ablation and accumulation) (Meneghel & Smiraglia, 1991).

Mass balance data collection

In order to calculate the seasonal and annual mass balance of Strandline Glacier, it was necessary to quantify the material lost at the cliffed front and to estimate surface ablation and accumulation. Topographic profiles of the glacier terminus cliff were surveyed with a theodolite fixed station located beyond the boundaries of the glacier; RTK GPS measurements (Langley, 1998) were used to evaluate surface variations. When used with short bases (< 1 km), the positioning precision of this method is of 1-2 cm (Cina & Manzino, 2000). This is thus an ideal method for accurately estimating planoaltimetric variations (Vassena et al., 2001), not only where the stakes for measuring ablation are originally positioned but also at a large number of measurement points.

The RTK GPS survey aimed to determine the surface of the glacier twice in the same Antarctic expedition (at the beginning and end of the campaign) in order to evaluate changes and, at the same time, to lay the foundations for future surveys (Rentsch et al., 1990); research also aimed to compare new data with the results of a previous topographic study (Gandolfi et al., 1994).

As a starting point for these procedures, several vertices with known coordinates had to be positioned near the glacier, and the *base* GPS receiver was positioned on these vertices. These vertices were assigned codes of 100 and 200, and positioned with respect to the permanent GPS station of the Italian *Programma Nazionale di Ricerche in Antartide* (PNRA) operating at the Italian station in Terra Nova Bay (BTN), slightly less than two kilometres from Strandline Glacier.

The first survey of Strandline Glacier was carried out on 5, 6 and 11 December 2000. At the time, the survey covered a total of 1020 points used for the planoaltimetric survey of the glacier surface and definition of the glacier boundary. An identification code was adopted for the points surveyed, and a brief description was drawn up for some of these points. The RTK technique was used for measuring. The base reference station was located in vertex 100, at the bottom of the cliff.

The definition of 1020 planoaltimetric points along the entire surface of the glacier allowed an accurate planoaltimetric description of the glacier (Vassena et al., 2001). Most importantly, it was possible to make an updated survey of surface morphology, and to measure a large number of points with a planoaltimetric accuracy of 1-2 cm. Figure 1 displays the first of the two DEMs for Strandline Glacier, obtained on the basis of a regular 10-meter grid and calculated by applying a kriging method to survey data.

The representation clearly indicates the position of the dome of exposed ice in the lower, central part of the glacier, just above the cliff. At the end of the season, the second survey enabled the collection of 1000 planoaltimetric points to process the second DEM. The two DEMs were compared to detect surface and altitude changes. During the considered period, the Strandline Glacier surface showed very limited altitudinal variations (± 5 cm), in good agreement with the results of the traditional stake method (mean value – 4 cm w.e.) Surface variation measurements using stakes and pits took place at the same time as the topographic survey. The objective was to determine surface variations in accumulation and ablation, and to compare topographic survey data with traditionally collected data.

The conducted surveys confirmed that Strandline Glacier is characterized by accumulation zones where wind-borne snow accumulates and summer melting gives rise to very limited

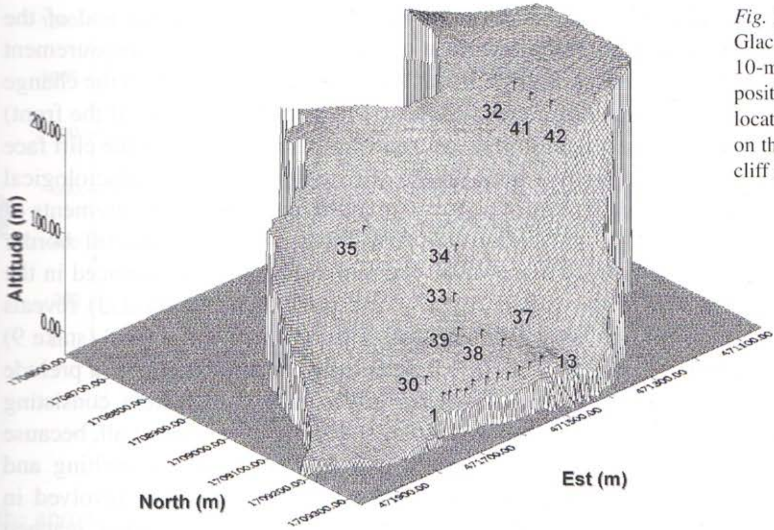

Fig. 1 - Display of the Strandline Glacier DEM obtained from a 10-m regular grid with the position of the ablation stakes located on the glacier surface and on the upper boundary of the ice cliff (1-13 points).

seepage (Baroni & Orombelli, 1987). Some observations on the density and crystallographic characteristics of several kinds of ice were also carried out during field measurements. Water accumulation in crevasses of the upper part of the glacier and refreezing, with the formation of veins of *congelation ice* ($\rho \approx 910$ kg/m^3), were observed. The ice enclosing the veins is *granoblastic ice* ($\rho \approx 893$ kg/m^3) and was formed by a metamorphic process involving visco-plastic flow, according to rheological zones of dry-based local Antarctic glaciers (Chinn, 1985). The *granoblastic ice* deteriorates when exposed to sunlight, particularly on the frontal cliff, and becomes destruction ice with albedo and density ($\rho \approx 706$ kg/m^3) similar to those of *firn* (Zanon, 1988). The ice in the gully on the orographic left-hand slope and in the apron is *exudation ice* ($\rho \approx 909$ kg/m^3) and *infiltration ice* ($\rho \approx 833$ kg/m^3) (Shumskhy, 1964) formed by a melting-refreezing process in the snow mantle. Blue ice, formed through sintering of wind-borne snow, outcrops at the top of the central deflation area.

Ablation on the glacier surface was measured with ablation stakes; data are reported in table 1 and were converted into mm of water equivalent. Table 1 reveals that in the upper part of the glacier (stakes 42-41-32) ablation increases with altitude (in the summer season) due to wind erosion.

The front cliff underwent calving and melting ablation processes. Two different methods were used to evaluate ablation processes at the Strandline ice cliff. Topographical surveys were

Tab. 1 – Stake measurements from 11 November 2000 to 9 January 2001 (mm w.e).

N° stake	*37*	*38*	*39*	*35*	*34*	*33*	*40*	*42*	*41*	*32*	*Mean value*
Altitude (m a.s.l.)	70	70	70	78	78	78	112	195	211	240	-
Thickness variations (mm we)	-99.9	-159.5	-119.3	42	35,1	62,5	48,4	-14.6	-79	-110.7	-39,5
Daily variations (mm we)	-1.7	-2.7	-2.0	0.7	0.6	1.1	0.8	-0.2	-1.3	-1.9	-

carried out using the total station technique and GPS both at the beginning and end of the campaign. The method allowed us to quantify the retreat of the ice cliff in 13 fixed measurement points by comparing the obtained vertical profiles. It was therefore possible to detect the change in the position of the ice cliff (in 15 days, a retreat of about 2 m in the central part of the front) caused by crack propagation from the glacier surface and calving of ice flakes from the cliff face (Smiraglia et al., 2003). The second method entailed the positioning of thirteen glaciological stakes (Fig. 1) on top of the cliff, 3 m from the border, in order to make daily measurements of ablation. From 22 December 2000 to 9 January 2001, the mean retreat of the cliff border (caused only by melting and sublimation) was 28 cm. The retreat was very pronounced in the right portion of the terminus where the gentler slope (corresponding to stakes 1-3) reveals surficial streaming by melting, but not calving. In the central sector there was a local (stake 9) advance, which can be attributed to the progressive enlargement of tension fractures, a prelude to calving, measured through the topographic method. The left sector (10-12 stakes), consisting of a 45°-80° slope instead of a vertical scarp, showed a moderate retreat, or none at all, because vertical reductions prevailed. Taking this into account, cliff ablation (through melting and sublimation only) should be calculated by averaging stakes 1-8 (the stakes not involved in calving phenomena during the considered time period). The calculated ablation reached 20.9 mm/day, amounting to 18.7 mm of w.e./day.

Collected data suggest that the dynamics of the Strandline Glacier ice cliff are similar to those of the Dry Valleys local glaciers, where the terminus cliffs represent only a very limited portion of the total ablation zone, but account for a large part of total ablation (Chinn, 1987; Lewis et al., 1998).

ENERGY AND MASS BALANCES IN EXPERIMENTAL PARCELS

The relationships between mass balance and energy fluxes on Strandline Glacier were evaluated through experimental parcels. These are glacier areas with boundaries marked by expressly dug channels that intercept and deviate meltwaters originating upglacier, and by other channels that collect meltwater accumulated within the parcel. The parcels were equipped with a hygrometer, a Delta OHM HD 9021 thermometer and an HD9021 RAD/C radiometric probe oriented according to the surface of the parcel, which measures cumulative radiance in the 400 ÷ 900 nm portion of the spectrum. The loss in mass by evaporation was measured by removing a block of ice on the side of the parcel, weighing it and replacing it in its original position on the glacier in a container of the same shape. The first parcel (S1; Fig. 2) was set up on 10 December 2000 at the far end of the orographic left of

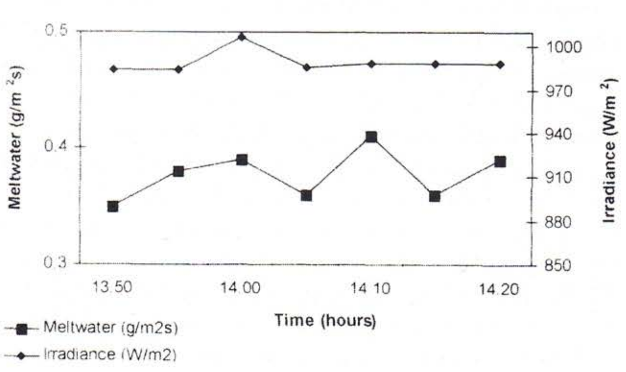

Fig. 2 – Thermal balance of the S1 parcel: the measurement time is reported on the X axis (from 1:50 p.m to 2:20 p.m on 10 December 2000), the quantity of meltwater (g/m^{2}s) collected at the same time is reported on the Y axis, and the measured irradiance (values expressed in W/m^2) is reported on the second Y axis.

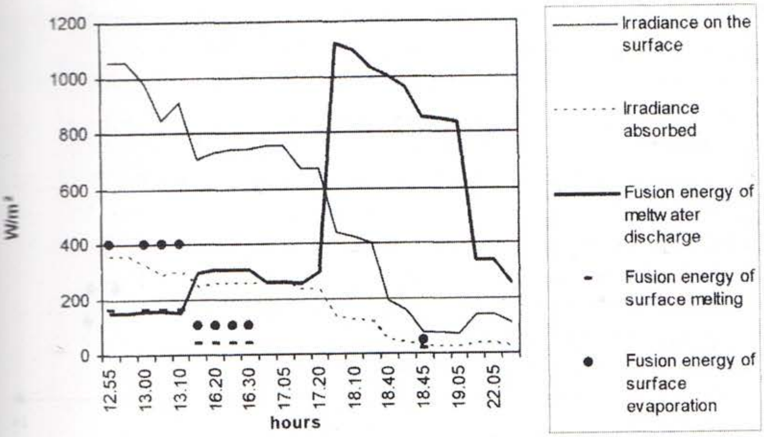

Fig. 3 – Energy balance of the S2 parcel: Air temperature remained slightly below 0° for the entire measurement period (from 12:55 p.m to 22:05 p.m. from 21 to 23 December 2000). This made it possible to discard sensible heat flows.

the apron. The S1 parcel measured 9 m², had a N 21°E exposure, a gradient of 22.5° and was built-up on exposed ice. The latter consisted of *superimposed ice* (Lliboutry, 1964;1965) on the surface and of *exudation* and *infiltration ice* deeper down. Water flowed along the lower limit of the *superimposed ice* (0.1-0.2 m in depth) in anastomosed channels 1 – 10 cm in diameter.

Probably owing to the lack of wind, the loss in mass through evaporation proved to be lower than the detection limit (0.0025 g/sm²). During the operative period, the *coalbedo* (1-α) reached 32 ± 1 %, and S1 absorbed 113 ±1 kJ/m². The fusion energy of the collected water reached 45 ± 1 kJ/m². By subtracting this amount from the absorbed energy, 68 kJ/m² were theoretically lost through evaporation and sensible heat flow. The sensible heat flow was negligible: the ice was at the melting point, there was little difference between its temperature and that of the air (Δt = +4,5°C, measured with a whip Hg thermometer at a height of 1,5 m), and there was no wind. It can be concluded that 0.076 g/sm² evaporated. This is not a negligible amount, and the detached block should have yielded a similar result. This demonstrates that the calculation is not realistic, and that meltwater takes a certain amount of time to reach the collector. This hypothesis was verified from 21 to 23 December 2000 on the S2 parcel (Fig. 3), a parcel of 3,4 m² with a N 6° E exposure and a slope angle of 25°, situated 15 m upstream of the S1 parcel. It was shaded from the sun at 6:40 p.m. and remained unexposed to the sun until the early hours of the morning. Trials were conducted on this parcel at various times of the day in order to evaluate changes in the rate of melt flow.

Until 1:00 – 2:00 p.m., the energy balance (Fig. 3) showed a higher absorbed radiance than the fusion energy associated with the meltwaters flowing out of the parcel. In the early afternoon, the meltwater did not all stream out but finished filling the effective porosity (intergranular interstices). After 1:00 – 2:00 p.m., the outflowing water exceeded the amount that could form in that same period due to the absorption of all penetrating solar radiation. After 5:30 p.m., the outflowing water out actually exceeded the amount that could form if all the incident radiation were used for melting. This undoubtedly demonstrates that the water formed during the previous hours, and that it had taken a fair amount of time to flow out. The highest flow rates were registered slightly before sundown; at 10:05 p.m., more than three hours after sundown, the flow rate became comparable to the afternoon rate. On the contrary, the parcel showed no runoff during the morning hours (Fig. 4), in spite of the fact that radiance peaked at that time of day (Fig. 5).

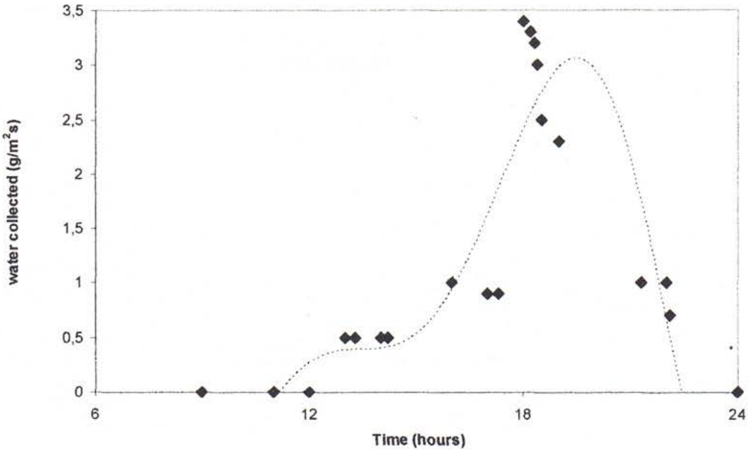

Fig. 4 – Water collected by the S2 parcel from 21 to 23 December 2000; measurement times (daily hours) are reported on the X axis, the quantity of water (g/sm^2) collected from the S2 parcel is reported on the Y axis; the dashed line helps highlight the data trend. Water runoff was absent in the parcel during the morning hours and peaked at about 6 p.m.

Radiance variability and albedo were measured in the ablation area on 22 December, from 6:15 to 6:35 p.m. in order to check the representativeness of the parcel in terms of the entire glacier. Results show that radiance was constant throughout the ablation area, except in the frontal cliff, where it was higher.

Results also demonstrate that at the beginning of summer, when ice ablation has just begun and in the absence of wind, melting leads to a loss in glacier mass that is at least five times greater than that caused by evaporation (Fig. 6).

CONCLUSIONS

Topographic and more traditional glaciological field surveys of Strandline Glacier both revealed that surface ablation was very small; in contrast, ablation was strong on the terminus cliff due to calving and melt processes.

Topographic data was also used to create two DEMs of the glacier; thickness and surface variations were determined by comparing the two models. GPS measurements of stake

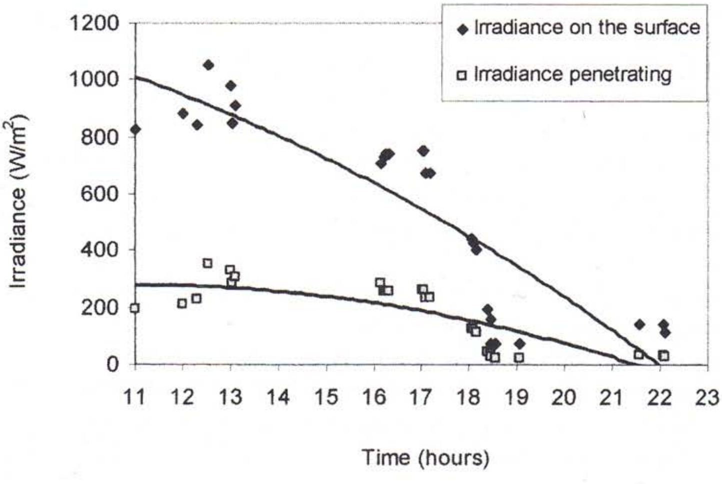

Fig. 5 – Mean variation in radiation during the hours of insulation, the measurements were collected from 11 a.m. to 10 p.m. from 21 to 23 December 2000; x-axis: measurement times (daily hours); y-axis: measured radiance values (W/m^2).

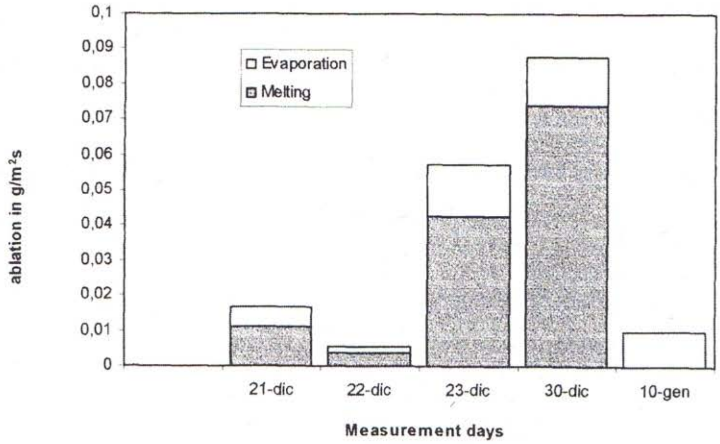

Fig. 6 – Ablation (melting and /or evaporation) measured at the selected block, expressed in g/sm^2. Measurements were collected from 21 December 2000 to 10 January 2001. On 10 January 2001, the sky was overcast and there were snowfalls. On the other days, under clear skies, melting clearly prevailed.

positions at the beginning and end of the campaign were used to determine glacier surface velocities, (a few centimetres in the considered period); this information is indispensable for the planned modelling of glacier dynamics.

The acquired data allowed the compilation of pertinent monographs on the fixed reference vertices, which will allow future operators to repeat the surveys with the same degree of accuracy. The definition of an absolute reference system on-site will also allow the use of other methods of measurement, *e.g.* airborne laser altimetry or satellite image analysis, while continuing to survey using the RTK GPS approach.

As for the energy balance, preliminary results show that the parcels were representative of incident radiance on the entire Strandline surface except the ice cliff, where radiance is stronger because of the different aspect and albedo. Data show that during the daily melting hours, the energy used to melt the collected water was always greater than the absorbed radiance and usually greater than the incident radiance.

The experiment also showed that water reaches the channels quite some time (about 2 hours) after the daily maximum radiance value (1100 W/m^2). This demonstrates that the collected water did not form at the time of maximum measured radiance and that it flows out only when its quantity exceeds the effective porosity.

Acknowledgements - Research was carried out in the framework of the Italian *Programma Nazionale di Ricerche in Antartide* (PNRA) 1999-2001, project *Glaciologia e Paleoclima* (national leader G. Orombelli; operative units directed by C. Smiraglia and A. Biancotti) and was financially supported by ENEA through a collaboration with the *Università degli Studi of Milano Bicocca.*

REFERENCES

Baroni C.& Orombelli G.,1987. Il Ghiacciaio Strandline (Baia Terra Nova, Antartide). *Geografia Fisica e Dinamica Quaternaria*, **10**, 337-350.

Baroni C., Frezzotti M., Meneghel M., Orombelli G., Smiraglia C. & Vittuari L., 1995. Results of monitoring of local glaciers at Terra Nova Bay (Victoria Land, Antarctica). *Terra Antartica*, **2**, 41-47.

Chinn T. J. H., 1987. Accelerate ablation at a glacier ice-cliff margin, Dry Valleys, Antarctica. *Arctic and Alpine Research*, **19**, 71-80.

Chinn T. J. H., 1980. Glacier balances in the Dry Valleys area, Victoria Land, Antarctica. World Glacier Inventory-Proceedings of the Riederealp Workshop. IAHS Publication **126**, 237-246.

Chinn T. J. H., Whitehouse I. E. & Hoefle H. C., 1989. Report on a reconnaissance of the glaciers of Terra Nova Bay area. *Geologisches Jahrbuch*, **E38**, 299-319.

Chinn T. J. H.,1985. Structure and equilibrium of the Dry Valleys glaciers. *New Zealand Antarctic Record*, **6**, Special Supplement, 73-88.

Cina A. & Manzino A. , 2000. Misure GPS in tempo reale: applicabilità e precisioni. *Bollettino SIFET*, **4**.

Gandolfi S., Meneghel M., Salvatore M.C. & Vittuari L., 1994. Kinematic global positioning system to monitor small Antarctic glaciers. *Annals of Glaciology*, **24**, 326-330.

Langley R. B., 1998. *RTK GPS*. Issue of GPS World 1998 Advanstar Communications Inc.

Leick A., 1995. *GPS Satellite Surveying*. 2nd Edition, John Wiley & Sons.

Lewis K. J., Fountain A.G. & Dana G. L., 1998. Surface energy balance and meltwater production for a Dry Valley glacier, Taylor Valley, Antarctica. *Annals of Glaciology*, **27**, 603-609.

Lliboutry L., 1964, 1965. *Traité de glaciologie*. Paris, Masson, 2 vol.

Meneghel M., 1999. I ghiacciai locali di Baia Terra Nova. Dodici anni di osservazioni. In: *Convegno Nazionale di Glaciologia Antartica e paleoclima, Padova, 6-7 Luglio 1999- Riassunti*, Materiali Dipartimento di Geografia Università di Padova, 4-6

Meneghel M. & Smiraglia C., 1991. Preliminary data on the mass balance of the Strandline Glacier (Terra Nova Bay, Antarctica). *Memorie della Società Geologica Italiana*, **46,** 39-67.

Rentsch H., Welsch W., Heipke C. & Miller M., 1990. Digital terrain models as a tools for glacier studies. *Journal of Glaciology*, 36, 124, 273-278.

Schneider C., 1999. Energy balance estimates during the summer season of glaciers of the Antarctic Peninsula. *Global and Planetary Change*, **22**, 117-130.

Shumskhy P. A., 1964. *Principles of structural glaciology*. New York, Dover Publications.

Smiraglia C., Motta M., Vassena G. & Diolaiuti G., 2003. Dry calving processes at the ice cliff of an Antarctic local glacier: the study case of Strandline Glacier (Northern Victoria Land, Antarctica). In: *Proceedings of 2003 EGS Meeting, Cryospheric Sciences Session, Abstract EAE03-A-10580,* Nice, 6-11 April 2003.

Vassena G., Diolaiuti G., Motta M. & Smiraglia C., 2001. *Rilievi GPS in modalità RTK per lo studio dei ghiacciai antartici locali*. In: "Conferenza Nazionale ASITA, La qualità dell'informazione Geografica", 9-12 ottobre 2001, Rimini, Atti, Vol II, 1427-1432.

Zanon G., 1988. Ricerche preliminari sul bilancio glaciale nell'area della Baia Terra Nova (Antartide). *Geografia Fisica e Dinamica Quaternaria*, **11**, 56-58.