Ice Caves of Terra Nova Bay (Victoria Land, Antarctica)

Mirco Meneghel - *Dipartimento di Geografia, University of Padova, Italy*
Giovanni Badino - *Dipartimento di Fisica Generale, University of Torino, Italy*
Associazione La Venta

Abstract
In the 2000/2001 expedition of the Italian Programme of Research in Antarctica (PNRA) an investigation on the presence of caves in ice has been carried out near the Italian Station of Terra Nova Bay, on the western coast of the Ross Sea (Northern Victoria Land). Three caves have been explored at the snout of glaciers reaching the sea and an other one on the summit of Mt Melbourne, a volcanic cone 2700 m high. The caves on the coast are crevasses moulded and enlarged by the sublimation of ice due to the temperature difference between the glacier ice and the warmer sea water. The Mt Melbourne subglacial cave is generated by the heat of the volcanic rocks; here the water is carried out from the cave as water vapour along chimneys that cross from bottom to top the layer of ice covering the summit of the volcano.

Riassunto
Durante la spedizione 2000/2001 del Programma Italiano di Ricerche in Antartide (PNRA) è stata condotta una ricerca sulla presenza di grotte nel ghiaccio vicino alla stazione italiana della Baia Terra Nova, sulla costa occidentale del Mare di Ross. Sono state esplorate tre grotte nella fronte dei ghiacciai al contatto col mare e un'altra sulla sommità del monte Melbourne, un cono vulcanico di 2700 metri di altezza. Le grotte sulla costa sono crepacci ampliati dalla sublimazione del ghiaccio a causa della differenza di temperatura fra il ghiaccio e l'acqua marina. La grotta subglaciale sul monte Melbourne è generata dal calore delle rocce vulcaniche; l'acqua è estratta dalla grotta in forma di vapore lungo strutture a camino che attraversano completamente il ghiaccio che copre la sommità del vulcano.

Geographic overview
The Italian Base of Terra Nova is placed on a granitic peninsula bordering Gerlache Inlet, in the wider Terra Nova Bay, on the western coast of the Ross Sea, at 74° 41' 42" S lat. and 164° 07' 23" E long. The Transantarctic Mts, whose relief is often higher than 3000 m, fringe the coast. South of the Base the mountain chaine is crossed by outlet glaciers that drain the ice of the inlandsis. On the north huge valley glaciers flow from the mountains to the sea. The Italian Base is placed between the region of the Dry Valleys to the south, where broad deglaciated areas are present and a northern region with a more extended ice cover.
The mean annual temperature is -14 °C, the warmest month is January (mean temperature -2 °C), the coldest ones are May and August (-23 °C). The vertical rate of the air temperature is 0.52 °C/100 m; in summer it rises to

1 - Below - Animals near the Terra Nova base.

2 - Right, above - A general view of the Italian base region. It is possible to see the Mt Melbourne and, on its right, the floating tongue of Campbell Glacier.

3 - Right, below - The entrance of a large cave in the Campbell Glacier front.

4 - The glacier front at Baker Rocks.

5 - Above, right: The Campbell Glacier front, floating on the ice-covered sea. The contact between the ice (around -20 °C) and the sea (-2 °C) allows ice sublimations that create large caves.

0.7 °C/100 m. The permafrost is everywhere, few centimetres or decimetres under the ground surface. Water (in the liquid state) is present only occasionally. In the warmest month some rivulets have been observed, where rocks warmed up by the sun melt ice or firn. Small lakes are present in the deglaciated zones of Tarn Flat and on the Northern Foothills; on the Hell's Gate Ice Shelf a meandering stream (with a discharge of few dozens litres/second) drains the water due to melting on the surface of the blue ice. Some other small creeks flow on the eastern side of Mt Melbourne, at Edmonson Point and Baker Rocks where dark volcanic rocks outcropping from the ice are easily warmed up by the sun.

Karst in the Antarctica ice

On the base of our preliminary observation in the area of the Northern Victoria Land, three kinds of ice caves have been found:

- covered crevasses (tectonic, syngenetic caves);
- covered crevasses moulded by dry speleogenetic processes due to sea water heath;
- volcanic caves (caves in ice covering a volcano and related to its activity).

The first group of caves is the most numerous, but the less interesting for the ice caver (almost for the involved speleogenetic processes). These caves are formed by crevasses sealed at the top by new deposition of snow. So if the walls of the cave have a tectonic origin, the roof is formed by the deposition of new layers of snow whilst the glacier flows downward from the line where the crevasse have formed. For that aspect the cave can be considered as a syngenetic one. It is necessary to note nevertheless that are probably interesting to give a direct access to the most internal parts of glacier. In the temperate glacier the ice plastic behaviour in general prevents the existence of very deep crevasses: it is possible to show that their scale depth is less than 30 m, because deeper the ice flows to fill the cavity. Nevertheless the ice mechanics strongly depends on temperature and, in particular, low temperatures limit the possibility of plastic ice flowing. The average ice temperature of upper parts of the glaciers near the Terra Nova base are around -40°C and this gives a crevasses depth scale of many hundredths meters. It is possible that so deep and large structures behave like cold air traps, becoming "cold points" for the glacier. If this stratification mechanism is really effective their temperature may be well below the mean yearly temperature and their depth much larger than the former estimation.

Their climate and morphology may be very particular, and can influence the glacier behaviour, but no studies have been devoted to these structures until now.

Caves of sea-glacier interface

The caves of the second group are more interesting; we found many examples near the terminus of glaciers reaching the sea. We explored two caves on the ice tongue of the Campbell Glacier (Fig. 5) and an other one at the front of an unnamed glacier near Baker Rocks (Fig. 4). The initial stage of these caves is tectonic: actually they are crevasses closed in the upper part. Inside the cave two opposite facts are present: temperature is 15-20°C below 0°C and the ice walls show evident solution forms. On the walls there are scallops and rills elongated along the dip (Fig. 13). From the ceiling stalactites hang, sometimes covered by sublimation crystals. All this morphology denotes both sublimation and melting/freezing processes. The floor is flat and smooth, and is a little bit lower than the fast ice outside the cave (Fig. 6).

The main process that governs the genesis of that peculiar morphology is the thermal exchange: the caves are exactly at the contact between the glacier ice coming from the Transantarctic Mts, that has a temperature approaching the mean annual temperature of the air, about -18°C, and the sea that under the fast ice has a temperature of -1,9°C. In the perspective of Thermodynamics the caves are in the zone of thermal contact between two "heat sources", able to yield heat and maintain the same temperature, because of their heat capacity that can be considered infinite. An other element of contrast between the continental glacier ice, the fast ice and the sea water is the content of salts, that in an unknown manner influences the process of freezing, melting and sublimation.

As a first approach to analyse the process we decided to measure the temperatures inside the ice to understand if, how much and in which direction the heat flows. We found that the floors are quite warmer than the walls and that is the key to understand the process of that dry speleogenesis. The water vapour pressure of the floor ice is higher than that of the ice of the ceiling. So the floor

6 - Drilling holes inside the Campbell 2 cave, to measure the thermal transfers from the walls and the floor. The air temperature is -19 °C.

7 - Campbell Glacier, front. This entrance is so large and unstable that the cave roof has acquired a parabolic equilibrium shape.

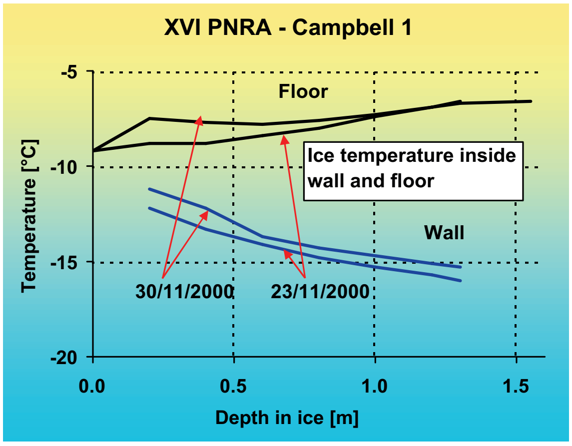
8 - Above, right: A large conduit below the glacier on the Mt Melbourne top, due to fumarolic energy release. The temperature is 0 °C.

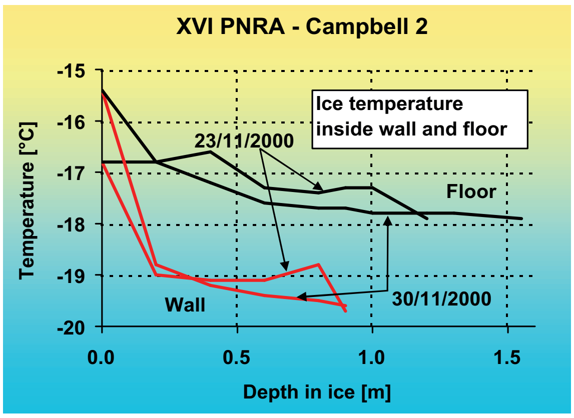
9 - Temperature gradients inside walls and floors af Campbell 1 and 2 caves

warms up and moistens the air in contact; the air rises and, if it is not driven outside the cave, reaches the dew point and forms sublimation crystals releasing the latent heat at the same time. Probably it is this latent heat of sublimation that warms up some air whose flow besides the ice crystals moulds the rills. The process is quite fast: repeated visits allowed us to estimate a digging rate of 0.5-3 cm per day. These caves probably can play a role in the breakdown of floating ice tongues (Fig. 7).

Fumarolic caves

Volcanic caves are created by sublimation (and some melting too) of ice at the contact with the warm rocks of active volcanoes, or by the emission of warm gases due to fumarolic activity. The presence of volcanic ice caves has been reported for the summit of Mt Erebus and Mt Melbourne volcanoes. We visited one of that





caves in the Terra Nova Bay zone, at the contact of ice with the warm surface of the Mt Melbourne volcano. The heat from the rocks surface flows into the ice, here at a temperature around -30°C, and affects it by melting, sublimation and air circulation, developing broad caves. The entrance of the cave is visible from far because the air rich in humidity coming from the cave flows outside and at the contact with the cold atmosphere deposits by sublimation a vertical "pipe" around the entrance, that stands up like a chimney (Fig. 10 and 14). Ice thickness here is just few dozens metres; the cave is developed for more than a hundred metres in a broad warm tunnel at the contact between ice and volcanic rocks (Fig. 8). We did not smell any volcanic gas. The process is analogous to the one of other sub-glacial caves found in far regions, mainly in Iceland, but here is dominated much more by the water vapour state, than the liquid one, like the caves observed in the coast. Really we did not find water in liquid state inside the cave. Only the water vapour leaves the cave, carrying 4.8 g of water every cubic metre. The cave is eventually a structure that represents the equilibrium between erosion, related to the air flux and the volcano's heat, and the collapse of the vault, due to the ice plasticity and flow. At the entrance of the cave we observed an air flux of about two cubic metres per second, with a related transport of 10 g/s of water vapour, equivalent to an erosion of about a ton of ice every day.

Analysis of the measurements carried out in the field

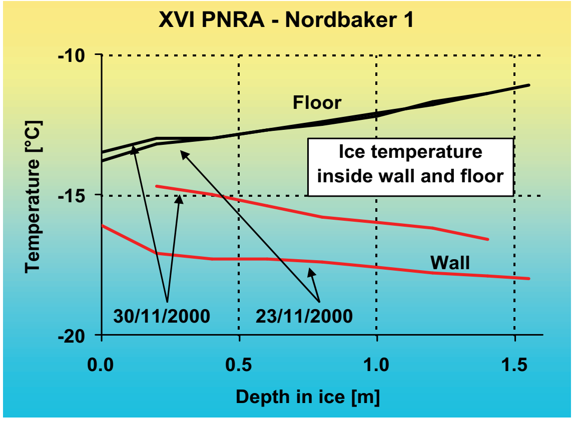
Inside the three explored caves of the Campbell Glacier and Baker Rocks we measured the vertical temperature rate of the floor and the horizontal temperature rate of the walls at about one metre from the floor. We repeated the measurements after ten days. In that time interval the thermal wave had a displacement of 0.75 cm.

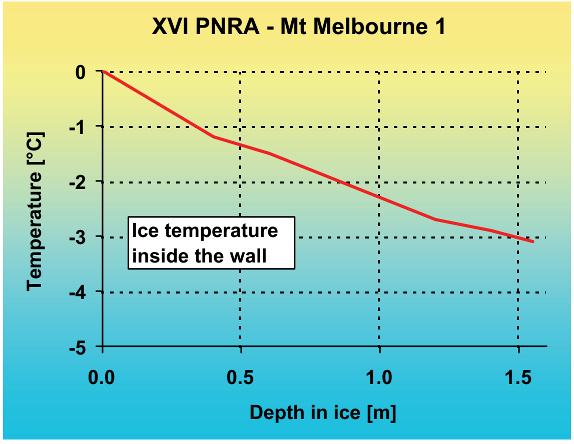
Campbell 1. Small cave (10 m) with no air flux. The thermal energy flow to the wall is 8 W/m^2, that from the floor is 4 W/m^2. The temperature changes are probably due to air fluxes coming from the large entrance (Fig. 9).

Campbell 2. Large cave (80 m) with a strong air flow coming from the glacier. Air and ice seem too cold in comparison with the average yearly temperature (-14ºC). The floor is warmer than the walls but it absorbs energy (1.8 W/m^2 and 2.2 W/m^2 from wall) probably because we made the measure quite far (60-70 m) from the glacier front, a region that is probably too far from the sea.

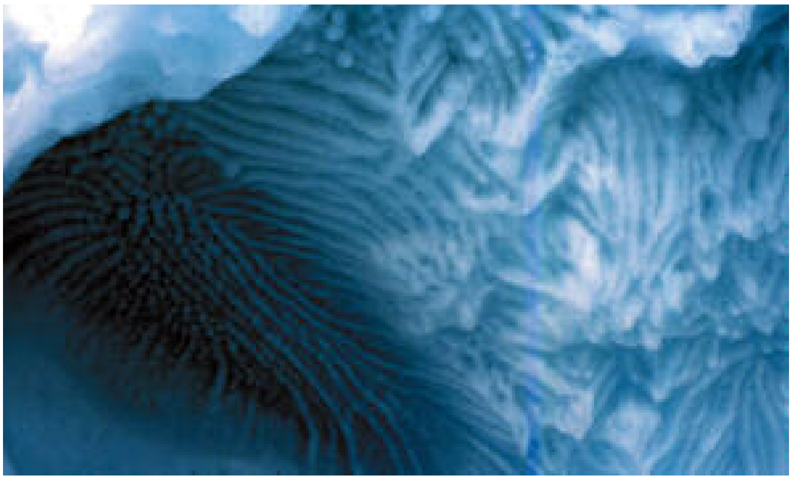
Baker Rocks 1. This cave is slightly different from the previous, quite narrow (1-2 m), and very high, with an entrance on the top that allows the snow deposition inside. Thermal fluxes are 3.7 W/m^2 from the floor (the measure was at 10 m from the sea), 1.7 W/m^2 to the wall in the first measure and 4 W/m^2 in the second. The wall heating is very strong and difficult to explain. The

10 - At the bottom of first shaft (15 m) of the Mt Melbourne fumarolic cave.





11 and 12 - Temperature gradients inside walls and floors at Baker Rocks and Mt Melbourne caves.



13 - Sublimation microforms (image total width 0.5 m) on the Campbell 2 cave roof. These are the "digging" forms of this dry speleogenesis, that seems to proceed unsuspectably fast at these temperature, with a speed of some centimetres per day.

strong air flow and the thermal insulation due to the snow probably play a fundamental role (Fig. 11)

Melbourne 1. It is a huge cave at the contact between ice and rock, near the Mt Melbourne top.The conduits are 5-8 m large and 2-3 m high, and have been explored (not completely) for 200 m. The graphic (Fig.12) show that the wall absorbs 4.5 W/m² and that the heating process is regular.

Conclusions

We have now a general idea of karst phenomena in Antarctica. Due to the cold climate there are only minor examples of typical glacial karst phenomena formed by runoff. The streams on explored glaciers (Collins, South Shetland) are very small. In some regions of the main continent, yet to be explored, the seasonal runoff may be stronger and the interaction of meltwater streams with very cold ice may create morphologies different from the typical temperate glacier karst. However, our observations near the Terra Nova base show that there are other types of glacial karst formed by volcanic heat, tectonics and local thermal imbalances. These volcanic fumaroles can create caves carved on the contact of ice with rock. This cave type is well known in Iceland, where "warm" (0°C) ice tolerates the presence of meltwater. On the reverse, the caves seen in Antarctica, on Mt Erebus and Mt Melbourne, formed in ice at -30°C, and so water refroze immediately. However, strong airflow permits active sublimation, resulting in vapourization of ice in warmer areas and crystallization on cooler zones near the cave entrances. Crevasses in ice are largely tectonic in origin and are not normally classed as glacier caves. Crevasse depth depends upon temperature. For soft, temperate ice (0°C), the ice plasticity is high and the crevasse depths range from 25 to 30 m. However, when ice temperature is lower, crevasses may be much deeper: at -50°C (ice temperature of the Antarctic Plateau) the crevasses reach 3-400 m. If these crevasses act as cold traps and are filled with the coldest winter air the depth may increase up to 700-1000 m: we suppose that the internal microclimate could influence the glacier behaviour. However, to date this has not been confirmed by exploration and research.

The caves discovered during the XVI PNRA expedition, due to thermal unbalance at the contact between cold glaciers flowing from the Plateau and warmer sea ice, were completely unexpected and appear to be, by far, the most interesting. The contrast in ice temperature results in strong differences in equilibrium vapour pressure in the adjacent atmosphere, which results in significant sublimation and redistribution of ice. Marine salt probably plays a role, but further studies are necessary to understand these caves .

14 - The entrance of a fumarolic cave on the Mt Melbourne. (2700 m asl) The well-curb is due to sublimation of outflowing vapour.

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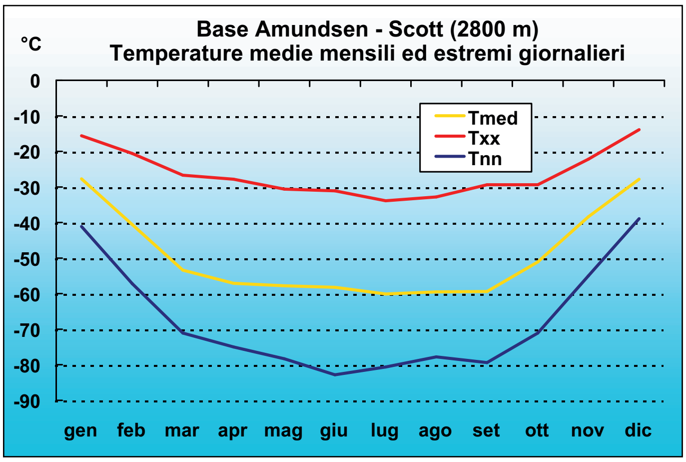
Annotazioni di meteorologia antartica

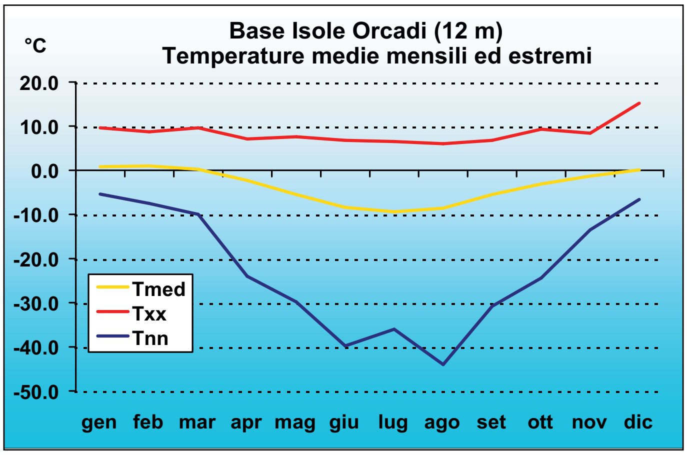
In alto a sinistra: il vento spazza le rocce di Frontier Mountain, ai margini dell'altopiano antartico a 2000 m slm, circa 250 km da Base Terra Nova.
A destra: a Frontier Mountain l'ablazione porta allo scoperto i sassi presenti nella massa di ghiaccio e fra essi eventuali meteoriti, di cui la zona è considerata una delle maggiori "trappole" dell'Antartide.
Sopra: il vento catabatico in caduta dalle montagne sopra il Ghiacciaio Reeves, poco a sud di base Terra Nova.

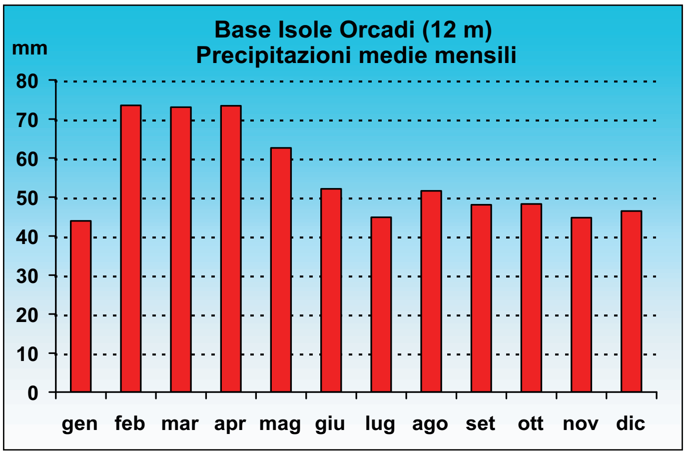
Gelo intenso e costante, venti violenti, precipitazioni scarse all'interno, più abbondanti in prossimità dell'oceano. Le stazioni meteo in servizio presso le basi scientifiche consentono di tratteggiare i caratteri del clima antartico, il più estremo della Terra. Le temperature più basse si registrano sui rilievi dell'interno, dove la notevole continentalità si traduce in elevate escursioni termiche tra l'estate e l'inverno: alla Base Amundsen - Scott la temperatura media mensile passa dai -60.1 °C di agosto ai -27.7 di gennaio. Ma la palma del freddo più intenso spetta alla base russa di Vostok (3500 m): i -89.2 °C misurati il 21 luglio 1983 rappresentano la temperatura più bassa fin'ora registrata sulla Terra da una stazione di superficie. Il clima delle coste è meno gelido e più umido: alla Base Mc Murdo in un anno cadono in media 213 mm di precipitazioni. L'elemento più severo del clima antartico è rappresentato dai *venti catabatici*, impetuose correnti d'aria più densa e pesante per l'estremo raffreddamento del cuore del continente, che spirano verso le coste con raffiche superiori ai 150 - 200 km/h. Sulla Penisola Antartica e sulle isole circostanti l'influenza oceanica determina una modesta escursione termica annuale (alle Isole Orcadi si passa da -9.4 °C in luglio a 1.0 in febbraio) e precipitazioni più abbondanti e distribuite lungo tutto l'anno.

Base Amundsen - Scott (2800 m) periodo 1961-88

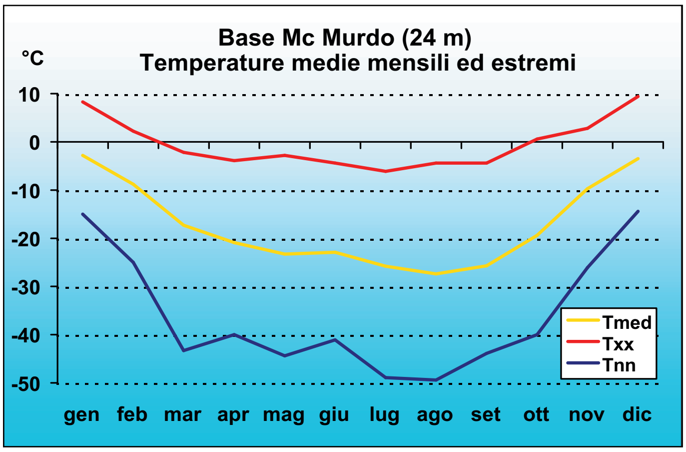
	Tmed	Tnn	data (gg.aaaa)	Txx	data (gg.aaaa)
gen	-27.7	-41.1	31.1965	-15.6	10.1985
feb	-40.6	-57.2	28.1978	-20.6	3.1984
mar	-53.4	-71.1	25.1983	-26.7	25.1975
apr	-57.1	-75.0	8.1982	-27.8	13.1968
mag	-57.8	-78.3	26.1982	-30.6	3.1981
giu	-58.2	-82.8	23.1982	-31.1	14.1963
lug	-60.1	-80.6	25.1965	-33.9	16.1986
ago	-59.5	-77.8	4.1978	-32.8	3.1963
set	-59.4	-79.4	25.1986	-29.4	13.1983
ott	-51.1	-71.1	1.1983	-29.4	31.1961
nov	-38.4	-55.0	1.1983	-22.2	29.1980
dic	-27.8	-38.9	1.1983	-13.9	14.1984
anno	**-49.3**	**-82.8**	**23.1982**	**-13.9**	**14.1984**

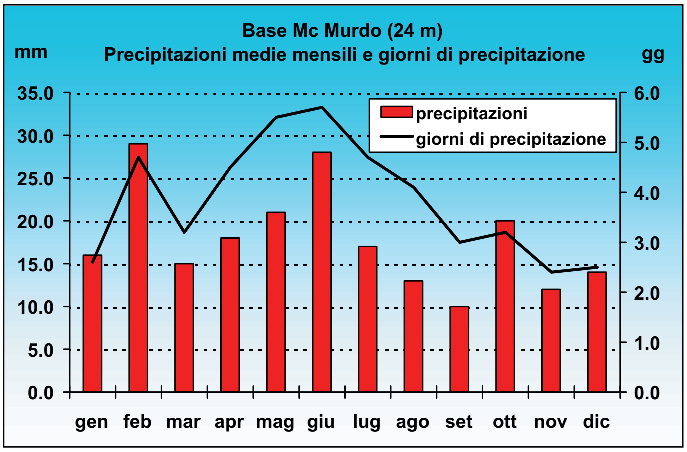


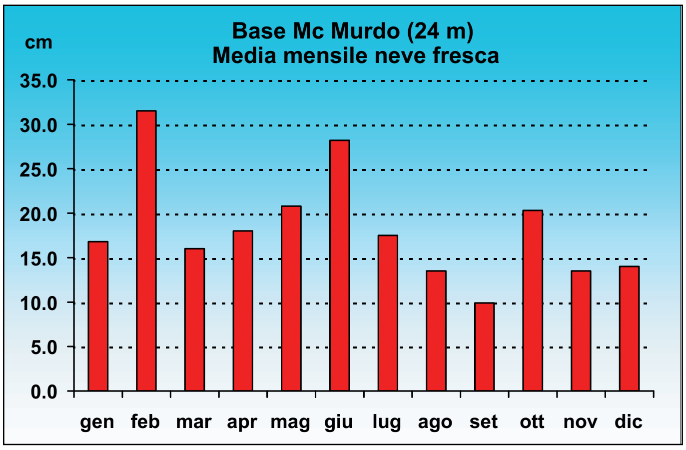




Base Isole Orcadi (12 m) periodo 1961-90								
	Tmed	Tmn	Tmx	Tnn	data (gg.aaaa)	Txx	data (gg.aaaa)	Pmm med
gen	0.8	-0.9	2.7	-5.4	13.1972	9.6	7.1979	43.9
feb	1.0	-0.7	2.9	-7.5	19.1972	8.7	8.1980	73.5
mar	0.2	-1.8	2.0	-10.0	26.1972	9.6	25.1974	73.0
apr	-2.3	-4.6	-0.1	-24.0	30.1989	7.1	2.1980	73.4
mag	-5.5	-8.5	-2.5	-29.8	15.1973	7.6	6.1974	62.6
giu	-8.4	-12.3	-4.6	-39.8	27.1972	6.8	18.1981	52.1
lug	-9.4	-13.9	-5.3	-36.0	29.1980	6.5	25.1985	44.8
ago	-8.6	-13.0	-4.8	-44.0	9.1972	6.0	21.1987	51.6
set	-5.5	-9.4	-2.0	-30.8	13.1972	6.8	23.1985	48.0
ott	-3.1	-6.0	0.1	-24.4	1.1977	9.3	26.1989	48.2
nov	-1.3	-3.4	1.5	-13.5	17.1979	8.4	3.1983	44.7
dic	0.1	-1.6	2.4	-6.6	10.1978	15.2	23.1987	46.4
anno	**-3.8**	**-6.8**	**-0.8**	**-44.0**	**9.1972**	**15.2**	**23.1987**	**662.8**







Base Mc Murdo (24 m) periodo 1961 - 86								
	Tmed	Tnn	data (gg.aaaa)	Txx	data (gg.aaaa)	Pmm med	N. gg Pmm	HN med
gen	-2.8	-15.0	15.1978	8.3	2.1974	16.0	2.6	16.8
feb	-8.8	-25.0	28.1984	2.2	3.1985	29.0	4.7	31.5
mar	-17.3	-43.3	30.1965	-2.2	16.1984	15.0	3.2	16.0
apr	-20.9	-40.0	15.1986	-3.9	16.1968	18.0	4.5	18.0
mag	-23.3	-44.4	24.1965	-2.8	9.1971	21.0	5.5	20.8
giu	-22.9	-41.1	3.1976	-4.4	28.1972	28.0	5.7	28.2
lug	-25.8	-48.9	26.1985	-6.1	5.1965	17.0	4.7	17.5
ago	-27.4	-49.4	3.1975	-4.4	13.1972	13.0	4.1	13.5
set	-25.7	-43.9	23.1986	-4.4	3.1972	10.0	3.0	9.9
ott	-19.4	-40.0	14.1976	0.6	30.1977	20.0	3.2	20.3
nov	-9.7	-26.1	1.1986	2.8	26.1971	12.0	2.4	13.5
dic	-3.5	-14.4	5.1978	9.4	29.1978	14.0	2.5	14.0
anno	**-17.3**	**-49.4**	**3.1975**	**9.4**	**29.1978**	**213.0**	**46.1**	**220.0**

***Legenda tabelle**: Tmed = temperatura media mensile (o annuale); Tmin = media mensile (o annuale) delle temperature minime; Tmax = media mensile delle temperature massime; Tnn = temperatura estrema minima; Txx = temperatura estrema massima; Pmm = media delle precipitazioni mensili (o annuali); N. gg Pmm = numero di giorni con precipitazioni; HN med = quantità media di neve fresca.*
Sopra a destra: un piccolo ghiacciaio isolato sulla destra idrografica del Ghiacciaio Collins. Ghiacciai simili, che non finiscono né in mare né in un altro ghiacciaio, sono piuttosto rari in Antartide ed oggetto di ricerche specifiche perché si possono monitorare le variazioni della fronte.

The glacio-speleological activity of La Venta Exploring Team

The geographical association **La Venta**, founded in 1990, organizes and carries out exploration and research projects in several areas of the planet, paying particular attention to underground world phenomena. Besides researching on limestone, gypsum and quartzite, La Venta has developed a long-term project on glacier caves, operating in several glaciers at different latitudes.

The first explorations date back to 1991: a short survey expedition to **Marconi Glacier** (Argentinian Patagonia) allows to evaluate the great potential of the patagonian ice masses, even though, once compared to its southern brothers flowing down the Hielo Sur, the Marconi appears relatively small.

In 1993 survey expeditions are carried out to **Svalbard Islands** and **Pakistan,** whereas in 1994 a similar reconnaissance is headed to **Kirgizistan**

After a survey in 1994, in 1995 La Venta organizes a full-scale expedition to **Perito Moreno** glacier (Argentina). During the mission the cavers explore and map Perito Meccanico, more than 1,000 m long and yet the longest endoglacial cave in the world. Furthermore, the first cave diving explorations in endoglacial submerged galleries are attempted.

In 1997 the association moves to glacier **Viedma** (Argentina), aiming at evaluating the logistical problems of an expedition in the area, to be carried out the following year. Notwithstanding the great interest of this glacier, the expedition never takes place due to the huge logistical difficulties and the lack of helicopters to transport the equipment to the base camp.

During the same year La Venta takes part to an expedition to **Vatnajökull** glacier (Iceland), the largest in Europe, organized by Etsim Politecnico of Madrid and sponsored by the Explorers' Club.

During the Autumn months of 1997, 1998, 1999 and 2000, theatre of the explorations is **Gorner glacier** (Switzerland), where members of the association descend several moulins and realize difficult cave dives, thanks to the technical experience of Hielo Patagonico 95 (**Perito Moreno**, Argentina).

Between January and March 2000 La Venta organizes another two expeditions: a former one to **King George Island** (Austral Shetlands, Antarctica), in collaboration with the Russian Academy of Sciences, having as main object the determination of the southernmost limit of the glaciokarst phenomenon. During such expedition the first glacier caves of Antarctica are discovered and explored. The latter takes place in **Tyndall glacier** (Chilean Patagonia), in the Torres del Paine National Park.

From above to below:
The first explored cave in King George, the moulin Brunello AN-1.
An extremely strong southern wind destroyed the Base Camp and forced to dig a hole to survive during the night.
The Base Camp situation after 12 hours of wind.

At the end of the same year a member of La Venta takes part to the XVI Expedition of the **Antarctic Research National Project** of ENEA, in the area of the **Italian base Terra Nova**. There, the first studies on the formation of caves at extreme low temperatures are carried out.

During its research activity La Venta has produced three documentaries: *Vortice Blu* (Hielo Patagonico 95, Argentina), *Nel cuore del Tyndall* (Tyndall 2000, Chile), and *Glacier Caves*, realized for National Geographic in Gorner glacier (Switzerland).
More information is available at **www.laventa.it**

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