

TOURISM, SUMMER SKI-ING, HYDROELECTRICITY AND PROTECTION OF THE PUBLIC IN THE FRENCH ALPINE GLACIAL AREA: THE DEVELOPMENT OF AN APPLIED GLACIOLOGY

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ABSTRACT. The first part of the paper is devoted to a historical review of applied glaciology problems in the French Alps since the last century (cog railway to the top of Mont Blanc, construction of mountain huts, preventive emptying of subglacial water pockets under Tête Rousse glacier, etc.). The second part is devoted to the study of modern projects concerned with construction of cableway stations or cableway pylons on or near the glaciers, with the preparation of ski runs on glaciers during summer, with the different problems met during works to capture subglacial torrents for the needs of hydroelectric companies.

RÉSUMÉ. *Tourisme, ski d'été, hydro-électricité et protection du public dans les zones englacées des Alpes françaises: l'élaboration d'une glaciologie appliquée.* La première partie de la communication est consacrée à un rappel historique des principaux problèmes de glaciologie appliquée qui se sont posés depuis le siècle dernier dans les Alpes Françaises (chemin de fer à crémaillère jusqu'au sommet du Mont Blanc, construction de refuges, vidanges préventives de poches d'eau sous-glaciaires à Tête-Rousse, etc.). La deuxième partie concerne les problèmes actuels rencontrés lors des constructions dans la glace ou en bordure immédiate des glaciers soit de gares de téléphérique, soit de pylones de remontées mécaniques; lors de l'aménagement de pistes pour le ski d'été sur glacier; lors de travaux entrepris sous les glaciers pour le captage à des fins hydro-électriques, des torrents sous glaciaires.

ZUSAMMENFASSUNG. *Tourismus, Sommer-Skifahren, Wasserkraftwerke und Schutz der Öffentlichkeit in den vergletscherten Alpengebieten Frankreichs: eine Darstellung der angewandten Glaziologie.* Der erste Teil dieser Arbeit gilt der historischen Übersicht über die Probleme der angewandten Glaziologie in den französischen Alpen seit Beginn dieses Jahrhunderts (Zahnradbahn zum Gipfel des Mt Blanc, Bau von Berggütern, Verhinderung des Auslaufens von subglazialen Wasserbecken unter dem Tête Rousse-Gletscher, etc.). Der zweite Teil behandelt moderne Projekte im Zusammenhang mit dem Bau von Liftstationen oder -pfeilern auf oder nahe an den Gletschern, mit der Präparation von Skiabfahrten auf Gletschern im Sommer sowie mit verschiedenen Problemen, die sich bei der Fassung subglazialer Ströme für die Gewinnung elektrischer Energie ergeben.

IN Moliere's comedy *Le Bourgeois Gentilhomme*, the hero M. Jourdain spoke in prose without knowing it. In the nineteenth century the inhabitants of high mountains of the French Alps were engaged in "applied glaciology" also without knowing it. Allow me to recall as introduction to my paper a few instances concerning some of the main problems which have been reported during the last century.

In the second part of the nineteenth century during the great adventure of building railways, one of the most impressive projects was the construction of a cog-railway all the way to the top of Mont Blanc. This project involved a study by Vallot which was the first systematic study of thickness of the ice cap on the top of Mt Blanc. The picture shows that the railway followed the areas where the ice was absent or of minimum thickness. It was in fact very important to make the tunnels so that they did not come into contact with the ice, but stayed in the rock all the time. The project was not completed except for one part between 1 000 and 3 000 m; but the glaciological research was done!

In 1892 a subglacial water pocket of more than 100 000 m³ broke out from the small glacier of Tête Rousse killing 175 people in the valley below and destroying the thermal establishment of St Gervais. Therefore the Administration des Eaux et Forêts took preventive action and constructed a tunnel through the rock in order to empty other possible water pockets so that they should not cause any further destruction. This was one of the first projects in subglacial hydrology.

In this period one could use ice from glaciers to fill up ice boxes in restaurants and in butcher's shops. The main problem was how to preserve the ice. This was done by means of sawdust, straw, and also snow.

Another problem that was present for mountaineers was how to build and protect mountain huts near or on the glaciers. The problem still exists: the refuge du Goûter would not survive if great volumes of ice were not dug out every year at the cost of some \$2 000 per year. The observatory built by Vallot was subject to great ice pressures and had to be taken down and rebuilt on an isolated rock knob. It has remained there since the beginning of the century. Janssen built his observatory on the very top of Mt Blanc. Because of the annual snow accumulation of 1 m per year the seven-metres-high building constructed in 1893 had completely disappeared in 1908.

Today the need for applied glaciology in the Alps is of course much greater and there can be a mutual exchange of information: The glaciologist should really take an active part in the exploitation of the mountains particularly for the sake of safety, forecasting work and hydro-electric plans. On the other hand the planners of mountain resorts will be able to let the glaciologists collect information from places not normally available.

I would like to give a few examples of projects that we have carried out in connection with recent developments during the last few years.

At the *Glacier de la Grande Motte* a cableway station was built on rock below the summit at an altitude of 3 453 m. One part of the station had to be cut into the ice and this has caused certain problems because of the ice pressure. We have found that the stagnant ice around the station has a diverging flow with a speed of 4 to 10 m per year. The next step will be to measure pressures on the station walls and to propose what action will be taken in the future. One could think of a concrete wall splitting the ice flow or perhaps putting up large mirrors along the walls in order to melt the ice and snow around the station.

The problem is quite different at the *Glacier d'Argentière*. The glacier is growing in thickness and sometimes the cable car passing over it hits the ice and a trench has to be dug out with a pick to permit the passage. Here some work has been done to study the lateral advance of the glacier. Another problem is that the glacier, advancing laterally (3 cm per day) is now threatening one of the pylons. The ice is about 30 m high and the pylon is 17 m: that prevents the construction of any protection walls. The solution has been to melt the ice with a system of hot water.

To melt basal ice, Electricité de France have developed equipment with which they can spray warm water at a temperature of 35°C and can make under the glacier a tunnel 2 m high and 1.5 m wide at a rate of 8 to 9 m per day which corresponds to the melting of 1.1 m³ of ice per hour.

On the *Glacier de Chavière* the preparation of ski runs and the construction of ski-lifts for summer ski-ing has caused certain problems. We had to know the movement conditions of the glacier, particularly the monthly variations, in order to adjust the constructions on the ice surface. One also has to know where the crevasses are, to be able to limit the safe areas for ski-ing. For the study of the movement we survey a system of stakes. We also use a Flotron camera system which gives us the daily movement.

In order to detect the different snow structures and the crevasses we have experimented with several different films, filters, and false colour; we worked in the visible part of the spectrum and in the near infra-red. On the pictures of the studied area taken with the normal Ektachrome 64 film with an ultra-violet filter it is difficult to see anything except the white snow surface. On the picture taken with infra-red film and a Wratten 12 filter one can distinguish more snow features which allow us to map the surface of the glacier. The same can be said about the picture with infra-red film and an ultra-violet filter. The best results are obtained with infra-red film and a Wratten 87 filter, which eliminates the visible radiations. One can then see crevasses which are still hidden under snow: they appear as black lines.

The second kind of applied glaciology concerns situations where new opportunities created by human activity near, on, or in the glaciers help glaciologists to make observations of features which have never before been available for study.

The best-known examples are connected with construction works for the hydroelectric companies. They want to catch the subglacial waters and in the tunnels constructed for this purpose in the last 10 years glaciologists have had wonderful opportunities to study plasticity of ice, subglacial cavitation characteristics of the basal ice, and the associated subglacial drainage.

(a) *Plasticity of ice*

We have observed that under the Mer de Glace about 500 m from the front and under ice 100 m thick, the bottom movement amounts to between 3 and 8 cm per day. An ice tunnel 1.5 m wide is usually closed in about 3 weeks. The basal ice observed after melting shows a stratification with pure ice and silty ice which indicates bottom freezing.

Under the Glacier d'Argentière ice pillars are squeezed out of tunnel openings about 4 m² in cross-section and they can be several metres long and they preserve a cross-section corresponding to that of the orifice.

In areas with high pressures it is possible to find ice shavings several metres long or with very original shapes. We have also found that where holes of a diameter of 5 cm have been drilled from tunnel ceilings up through 10 m of rock (or even more), ice from the glacier above has been squeezed down these narrow holes. The ice comes out like toothpaste and makes very nice cores.

(b) *Subglacial cavitation*

Under the Glacier d'Argentière we have found subglacial cavities of many different sizes and communicating over long distances from one side of the glacier to the other. There are cavities which may be 5 to 10 m high and 30 to 40 m long. There is always a remarkable contrast between the glacier upper surface, which is badly crevassed, and its bottom surface which is very smooth.

(c) *Subglacial drainage*

The subglacial drainage has been shown to be very unstable. The subglacial hydrology is characterized by a continuous variation both because of water changing its course over the bedrock and also because water very often finds its way through englacial tunnels. This means that it is very difficult to capture the water under a temperate glacier.

The problems in capturing torrents for the needs of hydroelectric companies are:

- (1) A good knowledge of the subglacial topography.
- (2) An access to the base of the glacier by tunnels in the rock.
- (3) The risks of obstruction of these tunnels by ice or by subglacial deposits.
- (4) The instability of the subglacial drainage
 - (a) on the bedrock: necessity of several points of capture,
 - (b) in the ice mass: possibility of absence of water on the bedrock, all the discharge being intra-glacial.
- (5) The highly erosive power of subglacial waters. The silt content in the subglacial waters is often of the order of 25 to 100 g per litre and can reach values over 200 g per litre after heavy rainfalls. So the erosion is very high and the engineers have developed special techniques for the construction of pipes and turbines. As an example I can mention that after 6 000 hours under the Mer de Glace a turbine wheel had lost 700 kg which is 23% of its original weight. For civil engineering work the best materials have proved to be: "Linatex" for sluice sills, synthetic rubbers or cast-iron linings for the penstocks, granites (with large differences according to their origin) for the reception channels beneath the trash racks. All concretes have been reinforced

with "Achromine" or corundum; quartzites give a less satisfactory result. The steels used to construct turbine blades are steels with 13 or 17% chrome alloyed with nickel, this giving the best guarantee of resistance. The most commonly used steels are 17 : 4, 13 : 3 and 13 : 4 (percentage Cr and Ni).

These are some of the problems which have been reported in the last few years in the French Alps.

I have reported some observations and measurements concerning them. These have not always been solutions. The capture of the subglacial torrent at Argentière has shown us how necessary it is in these kinds of problems to be prudent and wise. It is the same today as in the past when Vallot rebuilt his laboratory; we are often obliged to proceed by trial and error. This is also "applied glaciology"!

DISCUSSION

G. NOLL: Have you tried to use polarizing filters for the photographic survey of crevasses?

Ř. VIVIAN: No, we have not. Our best results were using infra-red 2236 film in conjunction with a Wratten 87 filter.

G. ØSTREM: After having demonstrated all the difficulties experienced under the glacier, do you conclude that it will be impossible to collect water subglacially?

VIVIAN: The difficulties are high nonetheless. Each glacier may have a different set of problems, and the behaviour of the Argentière may not necessarily be mirrored in Norwegian glaciers.

T. CARSTENS: You mentioned the high concentration of sediments in the ice near the under-side of the glacier. Have you observed ice from these layers, that is too heavy to float, sinking to the bottom when the glacier ends up in a lake?

VIVIAN: No.

CARSTENS: There are some interesting examples of large chunks of sediment-laden ice embedded in the bottom in Anchorage harbour, Alaska. This heavy ice happened to be deposited in the navigation channel and was recovered during maintenance dredging.