Understanding avalanche risk

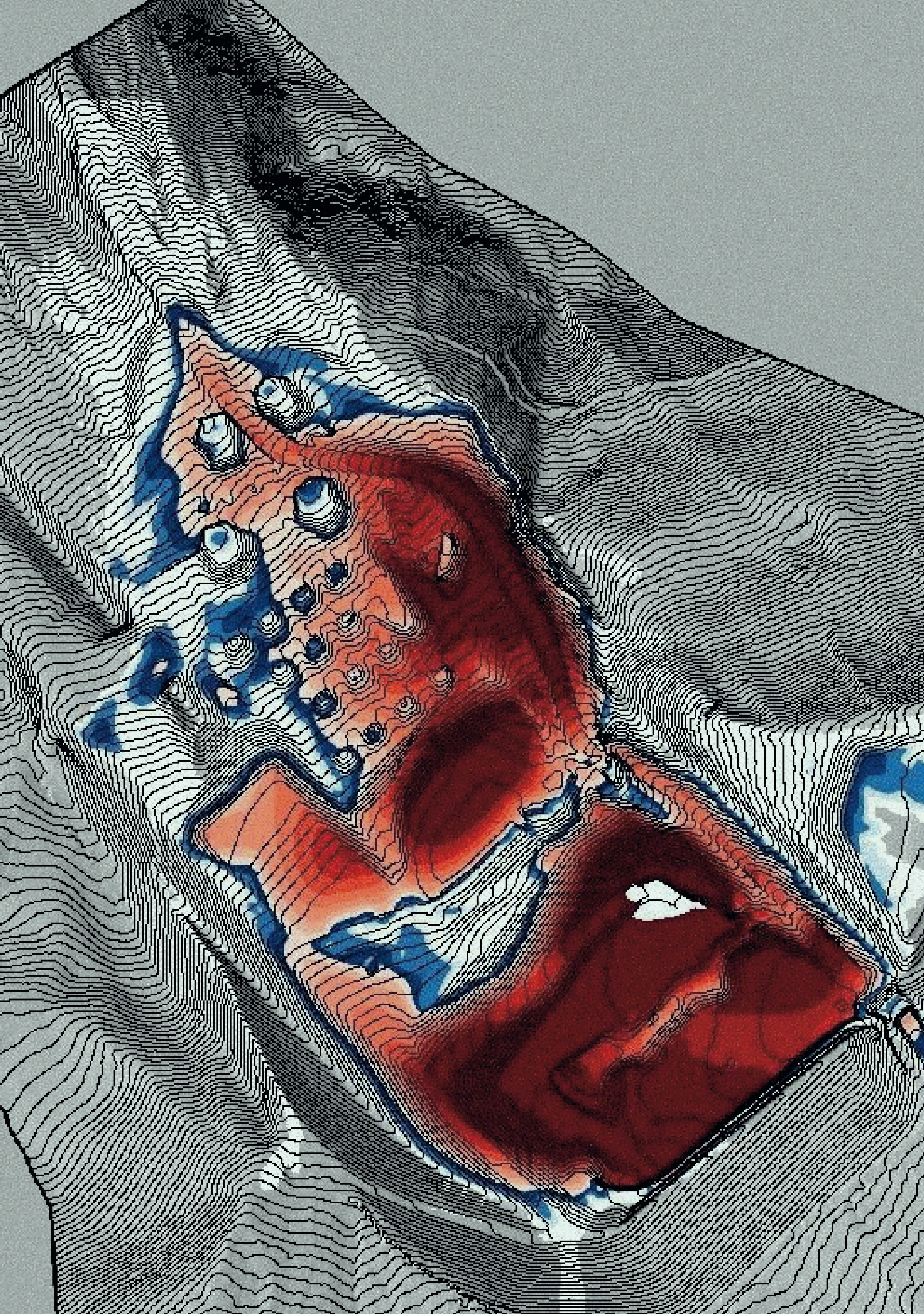
Thierry Caquet, Mohamed Naaim, Patrick Flammarion, Sebastiàn Escalon, Ur Etna, Aliette Maillard, Christine Young, Teresa Bridgeman, Alessandra Riva

UNDER-STANDING AVALANCHE RISK

Harsh mountain environments are host to particularly complex interactions between the three dimensions of disaster risk – hazard, vulnerability and exposure. As global temperatures rise, increasingly sophisticated research tools help our researchers to keep pace with the changing patterns of avalanche risk.

This dossier is dedicated to Xavier Ravanat, a member of the ETNA Unit, killed in a mountain accident in February 2021.

This dossier was first released in French in October 2021.
On the 1st of January 2023, the ETNA research unit joined the Institute of Environmental Geosciences (IGE joint research unit).



The avalanche risk ecosystem

An extensive and detailed understanding of the processes at work combined with continuous dialogue between researchers and a whole network of professionals to ensure that the right protective systems are designed, produced and implemented.

HOW DO AVALANCHES START?

Avalanches with single trigger points
These avalanches are started when the cohesive strength of the snowpack is no longer sufficient to guarantee its stability. This is often how wet avalanches or avalanches formed of fresh snow occur.

Avalanches that start along a fracture line
These avalanches are triggered when a "weak layer" with little cohesive force is located below a more cohesive harder layer. A simple overload, such as a skier crossing the snowpack or a fall from an outcrop, is sufficient to fracture the weak layer, destabilising the upper layer and triggering the avalanche.

AVALANCHE TYPES

1 Wet dense flow avalanches
Wet snow avalanches contain at least 10 kg of water per m³. When the water content rises above 30 kg per m³, friction is greatly reduced and the avalanche can travel longer distances. Despite their generally slower speeds, these avalanches can exert very great pressures, especially where large volumes of snow are involved.

2 Dry dense flow avalanches
The density of these avalanches is between 200 and 400 kg per m³. They are capable of exerting extreme pressure on buildings when they travel quickly (they can reach speeds of up to 150 km per hour).

3 Powder (aerosol) avalanches
Here, powder clouds form from snow suspended in the air above dense snow avalanches. They can reach 50 metres in height and, unlike dense avalanches, can climb the opposite side of a valley.

PREVENTIVE STRUCTURES

4 Active preventive structures
Designed to prevent avalanches from forming, these structures include snow racks, screens or nets, windmill structures, jet roofs or baffles, and snow fences. They are installed in the starting zone to stabilise the snowpack or alter the distribution of the snow, thereby avoiding the overloading that could trigger an avalanche.

5 Passive preventive structures
These structures are intended to slow, divert or stop an avalanche. Examples are braking mounds, diversion berms, retention dams and snow sheds or tunnels.

WHO IS INVOLVED?

The IGE Joint Research Unit ⑥ would not be able to carry out its mission to expand our knowledge of avalanches and develop avalanche control tools without strong synergies with other laboratories. Its closest partner is the French Snow Study Centre (CEN) at the French National Centre for Meteorological Research (CNRM), and its projects are delivered through a collaborative network across France, Europe and beyond. The unit works closely with all those responsible for managing natural hazards in mountain environments, providing a risk prevention service that takes the needs of all stakeholders into account. Managers and operational teams at the Directorate General for Risk Prevention (DGPR) at the Ministry for Ecological Transition (MTE) ⑦, members of the Mountain Landscape Restoration Service (RTM) at the French National Forest Office (ONF) ⑧, professional consultants ⑨, local communities ⑩ groups and associations are all involved.

A WHOLE-SYSTEM APPROACH TO A FAST-CHANGING RISK

Half a century of sustained research has produced an advanced framework and tools for the study of avalanche risk, firmly underpinned by the principles of multi-disciplinarity and inclusiveness. These will prove vital as the changing climate presents us with new challenges. **Overview.**

Should all development be banned in high-risk zones, or should these areas instead be provided with protective infrastructure? The twin demands of development and safety mean that planning decisions are always hard-fought in mountain areas. Decisions concerning avalanche risk can cost millions of euros, but their cost can also be counted in human lives. The evaluation of this risk demands complex research at widely differing scales and in different domains, from the study of the physical processes involved in avalanches to monitoring the ever-changing patterns of hazards, vulnerability and exposure that combine to produce it.

A research unit to investigate all aspects of avalanche risk

1970 was a difficult year for French mountain communities. On 10 February, an avalanche engulfed a UCPA holiday-centre chalet in Val d'Isère, leaving 39 dead. Then, two months later, on the Assy plateau, a landslide formed of a mixture of mud, snow and water buried a sanatorium, causing 72 further deaths. These two tragedies acted as a wake-up call. The French authorities realised that the country had few defences against natural events such as these, events that were both recurrent and hard to predict. They asked the CTGREF[1] to set up a snow study service, which would eventually evolve into the current ETNA Research Unit on Torrential Erosion, Snow and Avalanches at INRAE. The newly fledged service's principal mission was to build a better understanding of avalanche risk. *"In its early days, the unit was chiefly interested in mapping avalanche locations and in developing and improving protective structures"*, Florence Naaim, ETNA's current head tells us as she looks back over the unit's development. *"We then began to study the snow itself, looking more closely at the physics of avalanches. Nowadays we also take account of the potential impacts, the vulnerability of those at risk, and we factor in all the physical and social mechanisms that contribute to the risk. So, we don't just concentrate on the hazard, we look at the risk in the round, adopting a whole-system approach."*

This methodology recognises the systemic nature of risk and the fact that each of its three dimensions – hazards, vulnerability and exposure – evolves differently. It is an approach that the Sendai framework (2015)[2], in particular, has worked hard to promote. Indeed, to be able to predict the harms caused by an event, we must understand how several different factors (such as climate, topography, the spatial practices of societies and their development choices) can combine to produce a disaster, calling for a vision that is both

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Powder (or aerosol) avalanche, recognisable by the formation of a cloud of air and snow above the surface as an avalanche descends the slope.

p. 7
Computer model of the Taconnaz avalanche (15 April 2021) which was brought to a halt by an avalanche protection system.

comprehensive and interdisciplinary. The current profile of the research team reflects this need – the researchers, engineers and technicians who make up its thirty members hail from different disciplines, so that specialists in physics, modelling and measurement work alongside statisticians and historians...

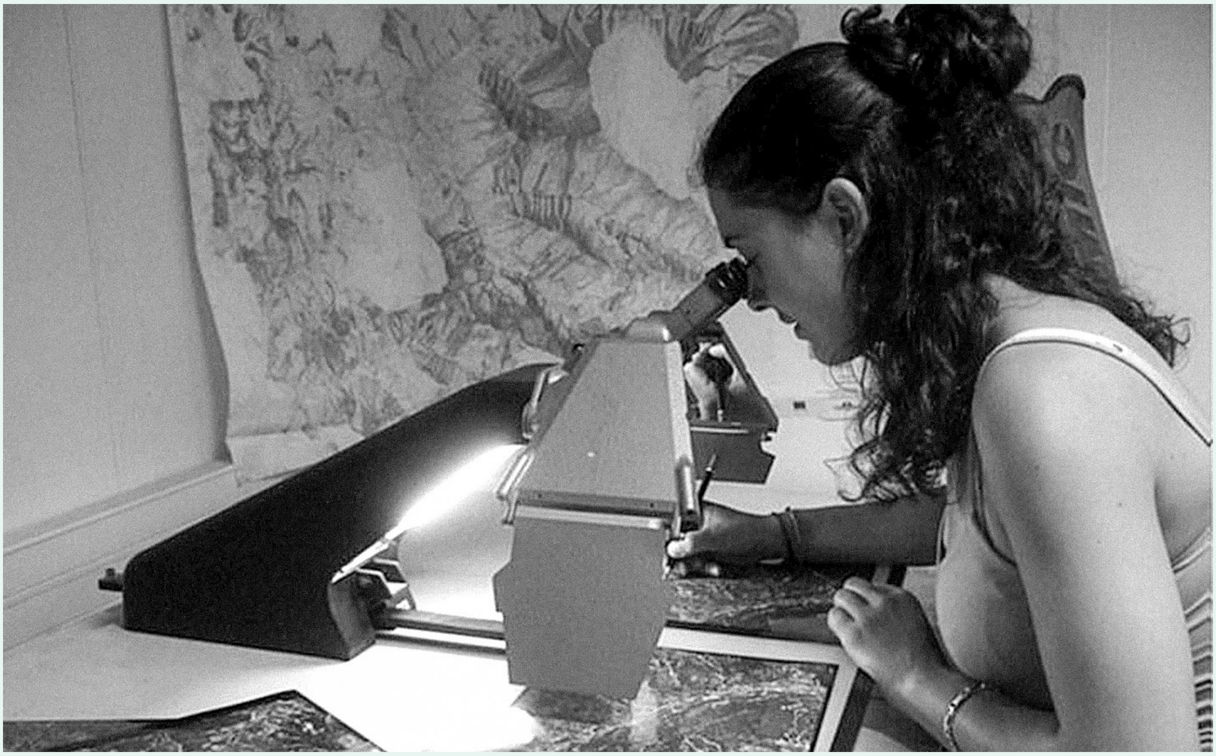
Observe, model, quantify

The tradition of recorded observations in this field goes back to the creation in 1899 of the French Permanent Avalanche Survey (EPA, *see page 59*), still jointly managed with the French National Forest Office and the Ministry for the Ecological Transition. At first, the survey's approach was largely founded on the natural sciences, but it expanded in the 1970s to include research in physics and process modelling. In the early years of the millennium, in order to improve risk quantification, designate zones where risk could be considered acceptable, and optimise mitigation strategies, the Institute's researchers coupled deterministic models of avalanche spread with the statistical data provided by the EPA. This resulted in increasingly accurate probabilistic numerical models designed to evaluate "exceptional avalanches" (with a 100-year return period). Working first at the scale of a single avalanche path, the modelling was then scaled up to take in entire ranges, making it possible to evaluate the hazards for paths that were either poorly documented or unrecorded. This probabilistic hazard analysis, carried out first at local and then at regional scale, has enabled us to characterise the variability of avalanche activity at different spatio-temporal scales. It helps us to understand why certain ranges are more active than others, taking account of their topography and locations, and to use meteorological "forcing" to explore the links between avalanche activity and weather *(see glossary page 54)*.

Meanwhile, methods were also developed to model vulnerability to the impacts of an avalanche, examining how vulnerabilities in both the built environment and those who live in avalanche zones could contribute to the risk. These models →

1. CTGREF: This technical centre for the French National School of Rural Engineering, Water Resources and Forestry was an early predecessor of IRSTEA, which merged with INRA on 1 January 2020 to form INRAE.

2. The Sendai framework for Disaster Risk Reduction 2015-2030, adopted by the third United Nations World Conference, was the most recent in a series of documents ratified since 1994 to improve risk reduction at global level.



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Researchers interpret information taken from aerial photographs to produce the French Avalanche Event Location Map (CLPA).

were then coupled to the quantitative hazard models, enabling individual risk models to be calculated that could be expressed in mortality figures or destruction levels, and protective structures to be optimised. Further parameters drawn from the human and social sciences are now adding to the sophistication of the models.

This fresh input means that expert historians can, for example, help to make better use of archive materials to feed current models. Likewise, historical analysis of development decisions taken by businesses and of their perceptions of risk can be incorporated into our understanding of current vulnerabilities and exposure factors, enabling us to act appropriately.

We might be forgiven for assuming, therefore, that avalanche risk is under control. Sadly, this is far from the case. At present, the socio-environmental systems in our mountains are undergoing a process of very rapid flux brought about by global change (to the climate, society, etc.), meaning that the risks, too, are changing.

The many impacts of a changing climate

To deal with this, we first needed to understand how climate change is affecting the hazards themselves. The research teams began by studying changes in avalanche activity at climate-process scale. This enabled them to show that a series of very harsh winters produced a peak in avalanche activity in France at the beginning of 1980 and that, from the mid-1980s onwards, avalanches at low and mid altitudes then became less frequent and smaller, with a greater proportion of wet snow avalanches. Looking to the future, work conducted jointly with the French meteorological service's Centre for Snow Studies using the IPCC projections *(see page 54)* made it possible to demonstrate that current trends are set to intensify. Thus, for example, a 20 to 30% overall reduction in avalanche activity is projected during the 21st century as the consequence of drastic losses in snow cover. We should nevertheless note that avalanches at high altitudes do not follow this trend.

New patterns of avalanche risk threaten high mountain communities, despite the overall decrease in snow cover.

Indeed, at these altitudes, extreme snowfall may cause the number of avalanches to increase for a time before it falls again, with a continued chance of major dry and cold snow avalanches occurring, such as the 1999 Montroc avalanche in the Chamonix valley. In that event, 14 chalets were swept away and 12 people were killed. The team is currently working to improve the accuracy and detail of future projections of avalanche patterns, incorporating their number, intensity, location and seasonality into the calculations.

The impacts of tourism and buildings

The pace of change for other determinants of avalanche risk is no slower, indeed, it may even be faster. As the climate heats up and agro-pastoral activities are abandoned, we are seeing a rapid reafforestation of the slopes. Meanwhile, the footprint of development continues to expand overall, spurred on, in particular, by the growth in winter tourism. Brand new avalanche protection structures are going up alongside existing structures that may be showing signs of wear, sometimes for lack of maintenance, producing a shifting picture of overall exposure levels. Research is ongoing to reveal the workings of this complex process (which can vary greatly from one local context to another), pulling together qualitative and quantitative analysis at different spatio-temporal scales. It has been possible to show, for example, that in very high alpine valleys, the risk to buildings and their occupants would appear to have risen in the past few decades, as their exposure increases to a continued hazard. By contrast, at lower altitudes, risk levels are falling due to a combination of reduced snow cover and the gradual regeneration of trees along avalanche flow paths, sometimes all the way up to the avalanche starting zones. Quantitative analysis has helped us demonstrate that it may be possible to adapt to these changes by strengthening exposed buildings and managing our forests for protective purposes, gaining greater control of risk levels.
This, then, is the new pattern of avalanche risk that threatens high mountain communities, despite the overall decrease in snow cover. Stakeholders in such areas are being asked to develop an adaptive approach in their long-term investment strategies, but to do this they must have access to detailed and reliable information. The whole-system approach and increasingly detailed studies produced by the research community will help these decision-makers to develop a detailed understanding of the changing nature of the threat they face. ●

RESOURCES

A dataset unlike any other

It is a commonplace that one avalanche will be followed by another. In 1899, when out surveying avalanche damage, Paul Mougin, an engineer working for the French Water and Forests service, decided it was time to try something new – the creation of an inventory of every avalanche that had occurred in Savoie. He intended his records to preserve details of the events along with details on the extent of the forest damaged each year.
Paul Mougin could not know that, 120 years on, his work would be ongoing. Every winter, year after year, 260 ONF staff still collect the avalanche data for 3,600 flow paths in 11 départements across the French Alps and Pyrenees. They scrupulously record dates, starting-point and run-out altitudes and volumes, along with a wealth of other details. These data are recorded in the EPA, the French permanent avalanche survey which, to date, has amassed more than 100,000 observations.
Following the Val d'Isère disaster in 1970, the French government asked for a map to be produced to accompany this catalogue of events. The map would show the maximum extent of the damage caused by the events in the catalogue and is known as the CLPA (French Avalanche Event Location Map). The CLPA provides a record of historic and observed events by mapping the extreme limits of the areas physically impacted by them. It is produced by members of the IGE Joint Research Unit, who first record photographic interpretations and field observations before collating archive documents, interviews and witness statements from local mountain inhabitants and professionals. The EPA and the CLPA, both of which are funded by the DGPR (Directorate General for Risk Prevention) of the French Ministry of Ecological Transition, and are managed by INRAE, allow each event to be tracked through time and space, their complementary visions offering a unique dataset for use by expert advisers and researchers. They are in open access on *www.avalanches.fr*.

CLPA – FRENCH AVALANCHE EVENT LOCATION MAP

850,000	25,000	13,000
hectares mapped	avalanche impact sites catalogued	interviews and witness accounts collated

GLOSSARY

Hazard

A dangerous phenomenon that may occur in a given location, characterised by its situation in time and space, intensity, size, frequency and the level of probability associated with its occurrence.

Vulnerability

The conditions, determined by physical, social, economic and environmental factors or processes, that render individuals, communities, material assets or systems, more susceptible to hazards.

Exposure

The location of individuals, infrastructure, dwellings, production capacity and other tangible assets in risk zones.

Mitigation measures

Measures that reduce or restrict the negative consequences of a dangerous event.

Forcing

The introduction to a model of specific meteorological conditions or events (temperature, precipitation, wind, etc.) that determine the condition and extent of the snowpack and hence local avalanche activity.

(Glossary based on ANR Cahier 10: Risques et catastrophes naturelles, INRAE)

CLIMATE CHANGE

What does the IPCC have to say about avalanches?

Best known for its international advisory reports (see 6th Report, published on 9 August 2021), the Intergovernmental Panel on Climate Change (IPCC) also publishes special reports. The *Special Report on the Ocean and Cryosphere in a Changing Climate* (SROCC), which appeared in 2019, was the first to devote a full chapter to mountain regions.

"While IPCC reports traditionally have plenty to say on glaciers and the polar regions, they had previously contained almost nothing on avalanches and their associated risks, because the issue was so complex that there was a lack of available research results", explains Nicolas Eckert, a researcher from the ETNA unit. Indeed, to be able to track past changes, a long and homogeneous series of observations is needed, and a relatively sophisticated armoury of statistical tools must be assembled to process them. Likewise, the forecasting of future changes in avalanche activity calls for the conversion of general scenarios for climate change into local scenarios that show changes in weather and snow cover. Complex techniques must be employed to manage the change of scale and error corrections, to force regional climate models (RCMs) using conditions from general circulation models (GCMs), to adapt models to mountain topography, and to create snow-cover models where the results from physical models must then be corrected by cross-referencing them with observations. Last, once all these tasks have been completed, data on historically-derived empirical relationships between snow cover and avalanche activity can be fed into the models.

The IPCC report, to which INRAE contributed, concludes with a high level of confidence that future natural hazards in mountain areas, including spontaneous avalanches, will occur in locations and/or seasons where they have not previously occurred. This formulation, the result of a scientific and political compromise, acknowledges the possibility of localised reductions in snow cover that would bring down hazard levels, but also emphasises the problems that could arise from rapid changes in the spatio-temporal distribution of dangerous events. We may thus expect more wet snow avalanches at high altitudes in the middle of winter in locations where there is currently no issue with snow cover. These changes must be taken into account, for example, when calculating the size of ski lifts that could find themselves on new avalanche paths, placing strong pressure at the peak of the tourist season.

MULTI-FACETED RESEARCH

From the scale of a micrometre to that of a mountain range, from observation to modelling, INRAE's researchers draw on the full range of current techniques and technologies, in both snow studies and other disciplines, to understand and predict this complex phenomenon.

Fields of research.

"The physics of avalanches continues to be a key area for investigation ... The scale of our work extends from snow grains to mountain ranges", explains Florence Naaim, who heads up the ETNA research unit. Indeed, where avalanches are concerned, *"you can only make sense of the very large things if you know the tiny things"*, she says. *Observation, experimentation and modelling form the triptych of research activities that generate the necessary knowledge to improve anticipation and preparedness.*

On the mountain: working at landscape scale

The ETNA researchers use a series of local investigation sites to carry out their observations. Of these, one exceptional site, the Lautaret avalanche test site in the Hautes-Alpes, has, since 1973, served as a rich source of data on avalanche dynamics. With the help of a gas explosive device, the team can artificially trigger avalanches on site, analysing their every feature. *"We study their characteristics, for example, their speed or the volume of snow they displace. Our imaging systems allow us to record an avalanche using a rapid camera, or in 3D, so we can gain a better understanding of the interactions between the avalanche and the local terrain. We use sensors fixed to an obstacle along the avalanche's route to measure how much pressure it exerts"*, Emmanuel Thibert, a researcher in the ETNA unit, explains. Setting up this system *"meant that we could demonstrate quite how much snow an avalanche can bring down – up to ten times the volume of the snow in motion in the starting zone. And it allowed us to show that the coefficient that was being used at that time to calculate the pressure exerted on an obstacle based on an avalanche's speed and density had been grossly underestimated (by a factor of 10) in zones with slow speeds (run-out zones)"*, Florence Naaim tells us.

High up on the wind-swept pass known as the Col du Lac-Blanc which sits at 2,700 metres above sea-level near the Alpe d'Huez ski station in the Val d'Isère, INRAE's researchers are also studying the interactions between snow and wind, working with their colleagues from the Snow Study Centre at the CNRM (the French National Centre for Meteorological Research). Indeed, wind is a key factor in the triggering of avalanches. It affects how the snow is deposited and creates cornices or wind loads that can, at any moment, lead to avalanches. *"A natural wind tunnel where we have been recording measurements for 30 years, this site has* →

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Physical model of a dense avalanche. The development of this model allowed the dimensioning of anti-avalanche structures in Taconnaz.

made it possible to test out new measurement techniques and to build a unique climate database which has attracted scientific teams from both Austria and Japan. Our sensors are effectively able to record the movement of hundreds of tons of snow per linear metre of ridge each year", says Florence Naaim.

In the lab: physical models and x-ray machines

But it is not enough to study how avalanches behave out on the mountain. To gain an understanding of the way that each snow grain moves against its fellows, how it speeds up or slows down, other methods are needed. Here, reduced-scale models come into their own, making it possible to set up experiments on the dynamics of snow flows. *"We use two analogous physical processes"*, says Thierry Faug, one of the unit's researchers and an engineer. *"For dense dry flow avalanches, we simulate the behaviour of the dry snow grains in terms of their cohesion and friction using glass beads and PVC powder. For powder avalanches, we release a flow of heavy fluid such as salt water into a lighter fluid, such as clear water. The heavy fluid allows us to simulate the mixture of air and suspended ice particles that make up this sort of avalanche."*

But an even closer examination is required to identify the laws that govern the changes in form and the flows within the snowpack during an avalanche. *"The snow's mechanical properties depend on its microstructure",* Guillaume Chambon, deputy head of ETNA tells us. To access this microstructure, the research team uses x-ray tomography machines. *"These machines allow us to observe details that are just a few micrometres in size. This enables us to study changes in the snow as a function of various parameters such as temperature or pressure and to build three-dimensional models to explore the material's mechanical response using virtual experiments"*, the researcher adds.

Going virtual: digital models to process and exploit the data

Full benefit can only be gained from the practical observations and experiments described above, though, especially in the realm of forecasting, if the unit carries out further work, this time using digital modelling to process the results. What makes digital modelling so necessary? *"We are trying to integrate knowledge on scales ranging from the microscopic to a whole mountainside in a single model",* Guillaume Chambon explains. The models and digital simulations allow the team to set off virtual avalanches, varying the start parameters. By then combining their models with the IPCC's climate predictions, they can build a picture of the future characteristics of avalanches. This combination of methods has already borne fruit. The models for dense and powder avalanches are already very reliable and, for example, allow the team to make detailed recommendations on the anti-avalanche structures that should be installed on the ground.

Now, though, the changing climate calls for further research on wet avalanches, which are formed of a mixture of liquid water and ice and whose dynamics are not yet well understood. Here, observation, experimental work and modelling will doubtlessly once again turn out to be a winning combination as we improve our knowledge of this complex phenomenon, and will help us to optimise our predictive tools. ●

CLIMATE

Wet avalanches as an emerging risk

One of the main developments brought about by climate change is the increase in the frequency of wet avalanches. Faced with this emerging risk, some sites are ill-prepared for the impacts.

The flows generated by wet avalanches, when these occur earlier in the winter season, can set large volumes of snow and water into motion. They also have high pressure loads, of the order of 10 t/m^2, despite their slow-moving character and can cause significant damage. In some extreme cases, when they contain a very high proportion of water, such flows can cover astonishingly long distances, ranging from several hundred metres to a kilometre in length and exceeding their usual boundaries. A further problem lies in the fact that the dynamics of wet avalanches are not yet fully understood: *"We have come up against the limits of our knowledge of these events. We haven't yet managed to create satisfactory models of how they behave"*, Thierry Faug, a researcher in the ETNA unit confesses ruefully. This current limitation has consequences, because the protection provided by anti-avalanche structures installed in many mountain locations is designed for cold and dry snow avalanche scenarios. When a large wet avalanche hits, there is a chance that these protective structures could, in some cases, prove insufficient.

The need to revisit existing protection systems

In such cases, active defence structures, such as racks, nets, screens or windmill structures, designed to prevent avalanches from being triggered at the top of the slopes, could be swept away or could fail to do their job. As the climate continues to heat, the creep[1] behaviour of the snow has changed as a consequence of its increased wetness. *"The higher water content makes the snow heavier and causes more slides in the snowpack, increasing the pressure exerted on structures"*, Thierry Faug explains. The structures must also be designed to resist greater future pressures, so they will be able to cope with the changing nature of the snowpack and starting conditions for avalanches. Equally, care will have to be taken with regard to the siting of new structures in locations where slides at the snowpack base have previously been rare.

Passive defences could also be affected by this change in the snow's water content. Such devices are intended to slow, divert or halt an avalanche and take the form of braking mounds, diversion berms or catching dams. However, in some locations, the margin of protection provided by these structures against hazards is already narrow. To complicate matters, the routes of wet avalanches can sometimes confound expectations by failing to follow the steepest slopes. A high-volume wet avalanche, because its trajectory is difficult to predict, could thus overwhelm passive structures and cause damage. The message is clear: it is not yet time to panic, but preparations should be made. Thierry Faug, provides some reassurance: *"There is no need to reinvent our anti-avalanche strategies. There are some locations, though, where we will need to upgrade the structures to reduce vulnerability and will need to plan in particular for a wet snow scenario that would either supplement or replace the dry snow scenarios"*. Upgrading has already begun, as the Institute's researchers continue to collaborate with the mountain authorities to introduce the appropriate adaptations. ●

1. Slow movement of snow under the force of gravity, combining compaction and shearing with sliding at the base of the snowpack.

RISK PREVENTION IS ALL ABOUT PARTNERSHIP

Global warming is bringing rapid changes to avalanche risk. Research and professional expertise must therefore be combined, as scientists and the many practitioners and stakeholders involved in risk prevention join forces to build the collective knowledge needed to anticipate and prepare for both current and emerging risks. **The case of France.**

As temperatures and precipitation patterns change, French mountain regions must be quick to adapt to protect their inhabitants' future economic activities, not least a sizeable part of the country's tourist industry, all the while remaining vigilant that high standards of safety are in place. They do this by developing local adaptation strategies in line with the national risk prevention policies of the French Ministry for Ecological Transition (MTE) and, in particular, the Directorate General for Risk Prevention (GDPR). The scientific evidence base for these strategies comes, primarily, from the results and outputs of the research activities of INRAE and the French National Centre for Meteorological Research (CNRM).

Collective action for more effective risk prevention

Treated as a major danger in French national risk prevention policy, avalanche risk is managed by many actors. Overall responsibility lies with national government and this is delegated to the French National Forest Office's RTM (Restoration of Mountain Terrain) services. It is the RTM's job to characterise the risks that must be taken into account in local planning strategy and policy. This is mainly achieved through Regional Plans for the Prevention of Predictable Natural Risks (PPRNP) that local planning authorities must follow. Other statutory risk managers for avalanche risk prevention and the protection of buildings and infrastructure are the municipalities, who are responsible for hazard prevention and the organisation of disaster relief, the départements and the regions, who are responsible for highway infrastructure safety, spatial planning and hazard warning information. Local citizens themselves constitute a further group of stakeholders. Most directly affected by the risk, they are served by this emergency planning structure.

Scientific expertise and risk prevention, a fruitful dialogue

While the development of knowledge and acquisition of new data is essential to the creation of emergency plans and the specification of an overall response framework (design of active and passive structures, routes and construction of mountain roads, planting of protective forests, building of shelters, etc.), scientists may also be called upon to advise local communities, consultants and municipalities on anti-avalanche protection measures. *"We only intervene in complex cases, where the outcomes depend on the most recent research and/or where the nature of problem is such that we are assigned sole responsibility for the expertise by the requesting body"*, explains Florence Naaim, head of the ETNA research unit. *"In fact, last January INRAE received its first ISO 9001 certification for the entirety of the quality-assurance system that underpins its delivery of expertise on the prevention of gravity-based risks in mountain areas, including avalanches"*. Here, as in other areas of INRAE's work, there is constant dialogue between researchers and expert practitioners. Research outcomes are used to help public policymakers in their work. In return, dialogue with local officers feeds back into research, allowing fresh directions to emerge and helping to give meaning and purpose to the research.

Data and modelling as a force for prevention

An example of such teamwork can be found in the design and construction of the Taconnaz berm, where the ETNA research team have worked with Ingérop consultants on behalf of the Chamonix-Mont-Blanc Valley inter-community group. This massive structure, 25 metres high, has been built across the foot of the longest avalanche corridor in the Alps, located in the Mont Blanc range. *"Our task was to specify the size, position and form of the berm and the other passive defence structures required"*, explains Thierry Faug, a researcher in the unit. By combining historical data from the EPA (Permanent Avalanche Survey) with digital spread models, it was possible to determine the reference events for the past century (defined by the volume and energy of the avalanches).

A range of protection strategies, devised to halt dense avalanches, was then tested in the lab, beginning with reduced-scale physical modelling (using glass beads and PVC). After estimating the residual risk for the powder element of the flow by measuring salt-water flows in fresh water, the team constructed a digital model fed with real-world topographical information from the site to test their results. *"And since you can't take the research DNA out of the scientist, we took advantage of the construction phase of the project to install automatic sensors for speed and pressure in the anti-avalanche structures, so we could assess their effectiveness and extend our understanding of how they influence the flow"*, continues Thierry Faug. Impact pressures of up to 95 t/m^2 could thus be recorded and compared with the model predictions, confirming the latter in what was effectively a vast quality-control exercise...

Disseminating knowledge

Meanwhile, to help project consultants and contracting authorities to reduce the vulnerability of inhabited zones, a number of technical guides on protection structures were produced. They enabled the publication in 2009 of a European reference guide on the construction of avalanche catching dams and diversion berms, that drew on the work of research teams across Europe, including ETNA. Since the guide's appearance, a regular flow of further knowledge dissemination materials has been produced.

The rapid impact of climate change, in particular, on the incidence and nature of avalanches, makes it imperative to continue research on hazards and risks, and to incorporate the most up-to-date data. However, it is clear that the most important driver in developing a form of risk prevention that is both adapted and effective will be the collaboration between our researchers and national and local authorities and organisations. ●

Dialogue with public policymakers feeds back into research, allowing fresh directions to emerge and helping to give meaning and purpose to the research.

Science-led risk management

An interview with Véronique Lehideux,
Head of Natural Hazards and Water Risks at the French Ministry
of Ecological Transition

Véronique Lehideux runs the French government department responsible for the production and management of national policy on natural risk prevention and the coordination of actions to address major risks. We talked about avalanche risk, the work of her department, and the latter's partnerships with the world of research. **Interview.**

Given climate change and urban expansion, how can we make sure our procedures for the assessment and prevention of avalanche risk are kept up to date?
Natural risk management in France starts with regional plans known as Regional Plans for the Prevention of Natural Risks (PPRN). These are designed to ensure that hazards are taken into account in urban planning, protecting communities from development that would increase the vulnerability of high-risk zones and reducing risk elsewhere by setting out the precautionary measures to be adopted in other zones. They are based on the worst known event or on a reference that is specific to the hazard – an avalanche or flood with a hundred-year return period, for example. For avalanches, a three-hundred-year return reference value has been added to the mapping so we can identify hazard zones for more exceptional events (yellow zones). As we discover more about the effects of climate change on hazards, we may have to adjust our reference thresholds – this has already been done, for instance, for coastal flood risk. For such changes to be approved, the impact must also be very well documented. In the case of avalanches, we have to consider a further parameter that is subject to change – the nature of the snow itself. The water content of snow is rising. To better understand how this affects the behaviour of the snow, the DGPR has been commissioning studies and modelling for wet avalanches from INRAE for some years. For risks in mountain areas, the Ministry established a programme on glacial and periglacial risks with assistance from INRAE. Now run by the ONF, the programme continues to benefit from very substantial input by INRAE.

What is the goal of this work on glacial risks?
In terms of outcomes, we have asked this glacial hazard risk programme to provide foresight on new risks such as the melting of snow cover that was previously permanent and glacier collapse. INRAE supplies scientific support concerning the second of these, working with the French Institute of Geosciences and the Environment (IGE) to monitor and anticipate future developments in the increasingly temperate Taconnaz glacier. Laboratories (ETNA, IGE, Isterre) from the Grenoble Observatoire des Sciences de l'Univers are helping the local Prefecture and the Municipality of Saint-Gervais by studying the water pockets discovered in the Tête-Rousse glacier. Back in 1986, INRAE was also involved in draining the Arsine glacier lake. In both

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cases, we see public research put to practical use, both for diagnostic purposes and to provide solutions that lie beyond the field of operation of private consultants. The DGPR provides support for the scientific investigation of these sorts of hydrological threats and their characterisation.

How do you take local economic and social factors into account in your work on the prevention of natural risks?
The prevention of natural risks takes, as its primary goals, the conservation of human life and the reduction of damage. Priority is given to zones where both hazards and social and economic impacts are strongly indicated, and our response in these zones is proportional to the risk. By introducing a moratorium on development in the zones most exposed to certain natural hazards, we can help to preserve their economic and social fabric, and ensure that the national compensation system, known as "Catnat", remains sustainable. The prevention of natural risks is given its full weight in decisions on sustainable development and adaptation to climate change. The degree of legitimate feeling aroused when disasters are triggered by natural events is a reminder that we are acting responsibly when we take the decision not to build in zones with high exposure to natural hazards.

Internationally, how does France manage its research, expertise and support for public policies on avalanche risk?
France is a member of the Alpine Convention and served as its President in 2019 and 2020. We have also been the Chair of the EU strategy for the Alpine Region (EUSALP) since 2020, agreeing to stay on for a further year in light of the health emergency. These two roles enable us to connect researchers, academics, businesses, managers and policymakers throughout the alpine countries. Our participation in working groups gives us the chance to share and develop knowledge and good practices, while adapting the latter to the individual circumstances of each country in terms of governance and legal frameworks. The European Interreg projects are good examples of this. Cross-border dialogue is very important in maintaining a certain level of harmonisation and in meeting the expectations of local elected representatives.

Can you give an example of work that has been carried out in cooperation with neighbouring countries?
By pooling our methods, models and practices in joint studies involving Italian, Swiss and French experts, we have been able to establish the extent of the PPR Avalanche red and blue zones for the most sensitive avalanche paths in the Chamonix valley. Likewise, in the Pyrenees, the maximum extents of avalanches in Catalonia and Spain have been mapped using the methodology developed in France by INRAE. ●