WHITE OUT

An earthquake in April 2015 shook a glacier near the Mount Everest base camp, dislodging a massive avalanche that killed 21 people. Here, rescuers evacuate injured climbers.

To save lives, researchers explore the physics of avalanches

By Alexandra Witze

Olivia Buchanan loved to ski. She grew up in the high country of Colorado and, at age 23, was studying snow science at Montana State University in Bozeman, hoping to make a career in the mountains she adored. On January 6, 2015, however, the snow turned against her. In the backcountry terrain of Colorado's San Juan Mountains, Buchanan's skis cut through the powder, freeing a slab of hard older snow beneath. An avalanche tumbled 700 feet down the mountain, carrying Buchanan to her death. It was Colorado's second avalanche fatality in a week.

In the United States each year, between two dozen and three dozen people die in avalanche disasters, most of them recreational accidents like Buchanan's. In other parts of the world — such as those picturesque villages nestled at the base of Europe's towering Alps — people's homes and businesses are also at risk.

Scientists are studying the fundamental physics of avalanches in hopes of avoiding tragedies like Buchanan's. A small but dedicated cadre of snow researchers are asking what causes snow particles to clump together and how they interact as they tumble downhill — with the force of up to 100 onrushing cars.

In a steep Swiss valley, scientists have built the world's most advanced avalanche research center. There, they automatically trigger snowdrifts to race downhill, while scrutinizing the avalanche with cameras, radar systems, pressure meters and other high-tech instruments. Among the surprising recent discoveries is how just a slight temperature shift can radically reshape an avalanche, turning it from a slower-moving "wet" avalanche to a faster and more deadly "dry" one.

Other researchers are turning data into models that predict avalanche danger. Recent computer simulations have found that incorporating new types of particle motion — in which snow particles interact much like gas molecules flying through air — improves predictions of how far and how fast a particular avalanche will go. The work helps explain why an avalanche in April 2015 on Mount Everest, triggered by an earthquake in Nepal (*SN: 5/16/15, p. 12*), was so lethal.

"Avalanches can have different flow forms, which is why they can do lots of different things," says Perry Bartelt, an avalanche engineer at the WSL Institute for Snow and Avalanche Research SLF in Davos Dorf, Switzerland. "That makes a big difference when you're talking about how to protect yourself."

Watch and wait

Every avalanche is a battle of snow versus gravity, and gravity always wins. It begins when snow piles up in ridges or drifts and its weight exceeds the load that the underlying snowpack can bear. A block or slab detaches — often along a preexisting weak layer, perhaps an old surface that melted a bit and then froze again — and begins to slide downhill.

The nature of that slipping snow depends on the path that it follows and the properties of the sliding mass. Wet avalanches occur mostly in the springtime, when liquid water percolating among the snow crystals weakens the snowpack. They move at speeds of 15 to 65 kilometers an hour, slumping like liquid concrete down the hillside. Because of their sheer weight, wet avalanches can cause a lot of damage to infrastructure, such as chairlifts and power lines.

Dry avalanches, in contrast, can race along at 130 kilometers an hour or more. They are usually caused when winds pile up more and more fresh snow, then a passing skier accidentally triggers the slope to release. The avalanche barrels downhill at high speeds, with powdery snow billowing out and obscuring the deadly rush. Because of their fast pace, dry avalanches kill far more people than wet ones do.

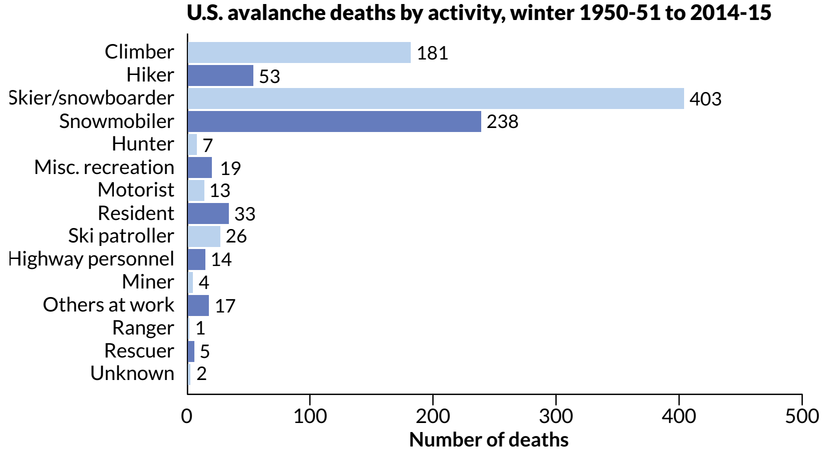
27
Average annual U.S. avalanche deaths since 2005

67
Avalanche deaths in Colorado, the state with the most accidents, since 2005

SOURCE: COLORADO AVALANCHE INFORMATION CENTER

Snow risk In the United States, most avalanche accidents involve recreational users — skiers, snowboarders, snowmobilers, climbers and hikers — on fresh powder.
SOURCE: COLORADO AVALANCHE INFORMATION CENTER

U.S. avalanche deaths by activity, winter 1950-51 to 2014-15



OPPOSITE: ROBERTO SCHMIDT/AFP PHOTO

Two types of flow Avalanches can be categorized in many ways, but one important distinction is between dry flows — where the snow particles move quickly and billow outward — and wet flows, which move in a slower, more dense slide. Air temperature is a key factor in determining the type of flow. SOURCE: NATIONAL AVALANCHE CENTER

	Dry avalanche	Wet avalanche
Cause	Too much stress on the snowpack	Decreasing strength of the snowpack
Are people involved?	In 90 percent of cases, triggered by the victims or someone in the victims' party	Difficult for people to trigger; most occur naturally
Contributing weather factors	Loading of wind-drifted snow or loading of new snow	Rain, prolonged melting by sun or very warm temperatures
Speed and type of flow	Fast (130 km/h or so), usually with an ice dust cloud	Slower (15–65 km/h); moves like wet concrete, usually without an ice dust cloud

To tease out the science between the two, and to understand avalanches more generally, many of the world's leading avalanche researchers flock to the scenic Swiss valley of Sionne. There, the SLF institute oversees an experimental avalanche site, a sophisticated laboratory for understanding snow dynamics. Scientists can scrutinize every detail of natural and artificially triggered avalanches.

The first research instruments arrived in the valley in 1996, although catastrophic snows wiped many of them out three winters later, forcing SLF scientists to rebuild. Today, a 20-meter-high steel pylon rises from the steep hillside, built to withstand avalanches that hurtle at it. It holds instruments that measure air pressure, impact pressure, flow speed, density, temperature and other factors.

Each winter, researchers watch and wait. Every couple of years, they get lucky. When at least 80 centimeters of snow falls in less than three days, and the white stuff builds up in drifts and the skies are clear, Betty Sovilla starts making phone calls. Sovilla, an engineer and avalanche researcher at SLF, is the scientific coordinator for the Sionne site. She mobilizes a team of researchers who travel to the valley and prep the instruments, video and other systems before technicians set off an avalanche to study.

At Sionne, SLF scientists have discovered several fundamental but previously unknown differences between wet and dry avalanches. Small nuances in temperature can have a big impact. For example, avalanches that flow warm and wet smash with an impact pressure that increases with depth, hitting the hardest at the avalanche base. In contrast, avalanches that start at colder temperatures move in a giant shearing sideways collapse, with the densest and fastest-moving parts of the powder cloud smashing the hardest. Whether a person survives a dry powder avalanche could thus depend on whether he or she gets hit with a fast-moving or slow-moving part of the slide.

A shift in temperature is also crucial for the clumpiness of snow. Sovilla and her colleagues recently put fresh snow into a rotating tumbler, the sort used to mix concrete. When the snow was relatively cold, between about −5° and −10° Celsius, it stayed powdery and fine. But just a little bit warmer, about −2°, the snow began to clump together in larger granules.

"This is a fundamental change in the structure of the snow, and it changes completely the movement," Sovilla says. Other properties of the snow, however, such as its density and hardness, did not change nearly as dramatically at −2°.

The experiment may sound like a high-tech version of kids making snowballs, but it is the first time researchers have explored the physical differences underlying the transition between wet and dry snow avalanches, the team reported in June in the *Journal of Geophysical Research: Earth Surface*.

To peer even more closely into avalanches, the SLF team uses a high-resolution radar probe that penetrates the obscuring clouds of a powder avalanche at Sionne. Like a police officer's radar gun, the instrument can map the speed of structures such as the densest concentrations of snow. "If you don't understand the small-scale turbulence, you can't reproduce physically the whole movement of the flow," Sovilla says.

Particle interactions

Making practical use of such real-world data is the job of computer modelers. At SLF, Bartelt and his colleagues develop software that can be used anywhere in the world to reduce avalanche dangers.

Early Swiss models, in the 1950s, treated the physics of avalanches very simply: A block of snow detaches from a slope and slides downhill, slowed only by friction. But avalanches are made not of a single block but of billions of snow crystals, each blown about by various forces acting on it and each interacting with others. Today's models are much more sophisticated and incorporate interactions among particles, such as cohesive effects that help hold back the otherwise expanding cloud of particles. By introducing some of the same equations that govern the expansion of gases, for example, avalanche modelers now better understand how heavy, dense avalanches can transform into fast-moving flows.

Bartelt's main software is called RAMMS, for "rapid mass movements," and it can simulate a wide array of avalanche types. "We simulate the worst case that we can imagine," Bartelt says. Such a simulation might describe how a particular amount of snow falls in a specific area, with winds blowing from a particular direction to build it up unstably and create a hazard.

More than 300 organizations around the world use RAMMS to help evaluate avalanche risk at their particular location. In Juneau, Alaska, city officials have worked with SLF to develop the worst-case scenarios for an avalanche in their city, which rests in a strip of low-lying land between the coast and steeply rising, snow-covered mountains. Having the ocean nearby introduces lots of humidity, and warm moist winds blowing from the south typically collide with dry winds from the north, causing huge amounts of snow to fall in the nearby mountains. In 1962, an avalanche barreled into a city neighborhood, blowing off roofs and chimneys; luckily no one was killed. In 2011, RAMMS modelers ran simulations on where wet and dry avalanches might flow in Juneau, and found dozens of homes in the danger area.

Modeling can also reveal the secrets of other powerful avalanches, like the one that killed 21 people at the Mount Everest base camp last April when a magnitude-7.8 earthquake struck near Kathmandu, Nepal.

The shaking dislodged huge chunks of ice from a mountain glacier, sending air blasting outward and killing people in the camp. Scientists simulated this type of hybrid avalanche, which has a fast-moving core of dense ice and snow particles surrounded by a billowy cloud of lighter dust. By adding equations into the calculations to represent the mean potential energy of particles in the avalanche — that is, the precise location of all the bits of snow and ice dust — the software could accurately describe how the avalanche sucked more air into the core, allowing it to accelerate dramatically, Bartelt and his colleagues write in a paper published online October 21 in *Annals of Glaciology*. "I want the users to begin to appreciate the complexity of avalanches," he says.

All these improved models are helping engineers identify new places that might face danger from avalanches. For instance, Bartelt and his colleagues studied how the icy core and powdery cloud of avalanches can move independently from one another, although how fast and in which direction the core is moving does influence the direction that the powder might travel. Studying a simulation of Switzerland's 1999 All'Acqua avalanche, which damaged a mountain hut as well as an electric power line, the scientists realized that this interaction between the core and the cloud of an avalanche meant the snow can run farther down a hill than previously expected. That suggests more places in steep mountain valleys are at risk than thought.

"We simulate the worst case that we can imagine."
PERRY BARTELT

Saving lives

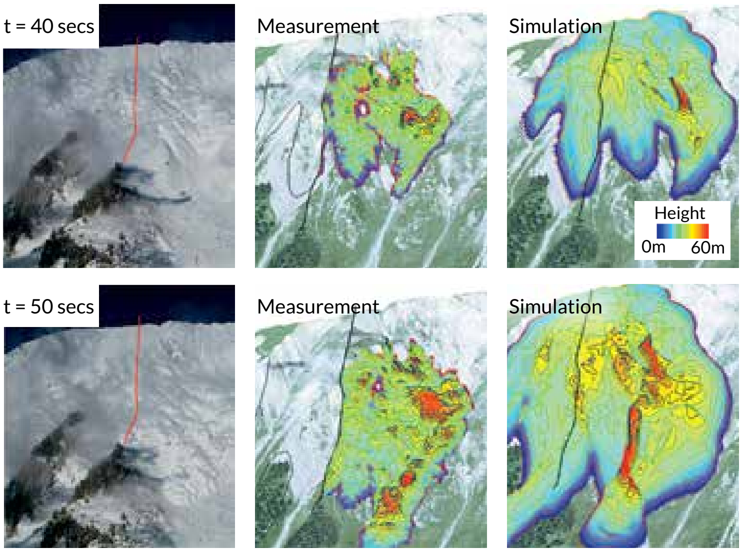
In the end, all the avalanche science in the world won't help if the people on the front lines of danger can't put it into practice. Ski patrollers and highway engineers often set off intentional avalanches, perhaps early in the morning or along a closed road, to defuse danger for future visitors. Officials can also build dams or other structures to deflect avalanches as they come down, construct snow fences to keep drifts from accumulating in dangerous places or ban buildings altogether in areas of danger.

In Colorado, where more people die in avalanches than in any other state, Jeffrey Deems, a snow scientist at the National Snow and Ice Data Center in Boulder, is trying to bridge the gap between science and public safety.

In Arapahoe Basin, a popular ski area west of Denver, Deems has pioneered the use of high-tech lasers to help ski patrollers save lives. He travels to the slopes in the summer, when they are snow-free, and uses a laser system to scan the landscape in extraordinary detail. It generates a three-dimensional cloud of points, each representing a spot on the slope. The point cloud appears as a ghostly mimic of the hillside, but one that Deems can click and drag around on his computer into any

Wet flows (top) often threaten infrastructure, whereas dry avalanches (bottom) are more dangerous to people.

BOTH: ARCHIVE SLF



Simulating slides The RAMMS avalanche software simulates (right) how a powder avalanche in Switzerland (left) flows. At center are measurements of the avalanche movement (where red represents deeper snow) taken from photographs.

SLF

orientation, getting fresh views of where exactly the snow might build up into deep drifts, ridges and pillows.

During snow season, Deems goes back to Arapahoe Basin and scans the hillsides again, before and after snowstorms. By comparing the two sets of data, he can show the local resort's ski patrollers precisely where snow has piled up. Even patrollers who know the mountain intimately are often surprised by the insights from the laser mapping, he says. "It's fascinating to look at a high-resolution map of terrain you're really familiar with," he says. "You can see [ski patrollers] start to see things that don't fit with their mental map."

Patrollers typically trigger avalanches by skiing carefully back and forth above an unstable drift, or by setting off small explosive blasts in deliberately chosen locations. The laser data showing where snowdrifts have built up allow them to better pinpoint those trigger points. With laser mapping, Deems can also go back after the fact and check why an explosive might not have set off an avalanche as it was supposed to — perhaps it was set in a particularly deep pillow of snow. Such surveys may allow resort managers to make research-based decisions about what areas to close off, he and his colleagues write in the December *Cold Regions Science and Technology*.

Avalanches are not just a problem at resorts. This winter, Deems plans to work with the Colorado Department of Transportation to laser-scan areas where highway engineers use remote-controlled exploders to detonate blasts along mountain passes. The idea is to keep slopes free enough of snow so that heavy avalanches won't close the highways — or harm drivers. This is the first year the department will use remotely detonated explosives; in 2014, an explosive went off prematurely in the gun of an avalanche control system, injuring two people. But the engineers are ready to try again with the remote control. Deems will use the laser scans to assess snow before and after the blasts, to see how well the remote exploders work.

Deems isn't just working to make avalanche country safer today; he is trying to prepare for a future when there may be more avalanches. With fieldwork and satellite imagery, he has documented how snow has been growing dirtier, thanks to soot from power plants and dust blown in from deserts. In southwestern Colorado, where the snowpack is a major source of water for many states and cities downstream, the snowpack is getting darker every year. Dust changes surface roughness and reflectivity, warming the surface and causing additional melt in the spring — which in turn weakens the snow layers and makes them more prone to launching wet avalanches.

"There's a lot of concern now about climate change, especially the possibility of wet snow avalanches," says Bartelt. Researchers aren't entirely sure how avalanches might change as global temperatures rise, but in general, they expect more rain and snowfall in some mountain areas.

"Even if global temperatures change slowly, if we start seeing more extreme weather patterns, that can lead to more extreme avalanche conditions," says Karl Birkeland, director of the U.S. Forest Service's National Avalanche Center in Bozeman. Some of the worst conditions for avalanche danger are an early-season snowfall, followed by a warm period when the top of the snow begins to melt, then refreezes and gets covered with cold heavy snows. That results in a lot of fresh snow sitting atop an older weak layer — prime conditions for the snow to detach and begin sliding.

Avalanche science may also become more important this winter, when a strong El Niño is expected to bring more snows to the Rockies, Alaska and other avalanche-prone areas.

As in other winters, avalanche researchers will be waiting. ■

Explore more

- National Avalanche Center: www.fsavalanche.org
- National Snow and Ice Data Center: www.nsidc.org
- W. Steinkogler *et al.* "Granulation of snow: From tumbler experiments to discrete element simulations." *Journal of Geophysical Research: Earth Surface.* June 2015.