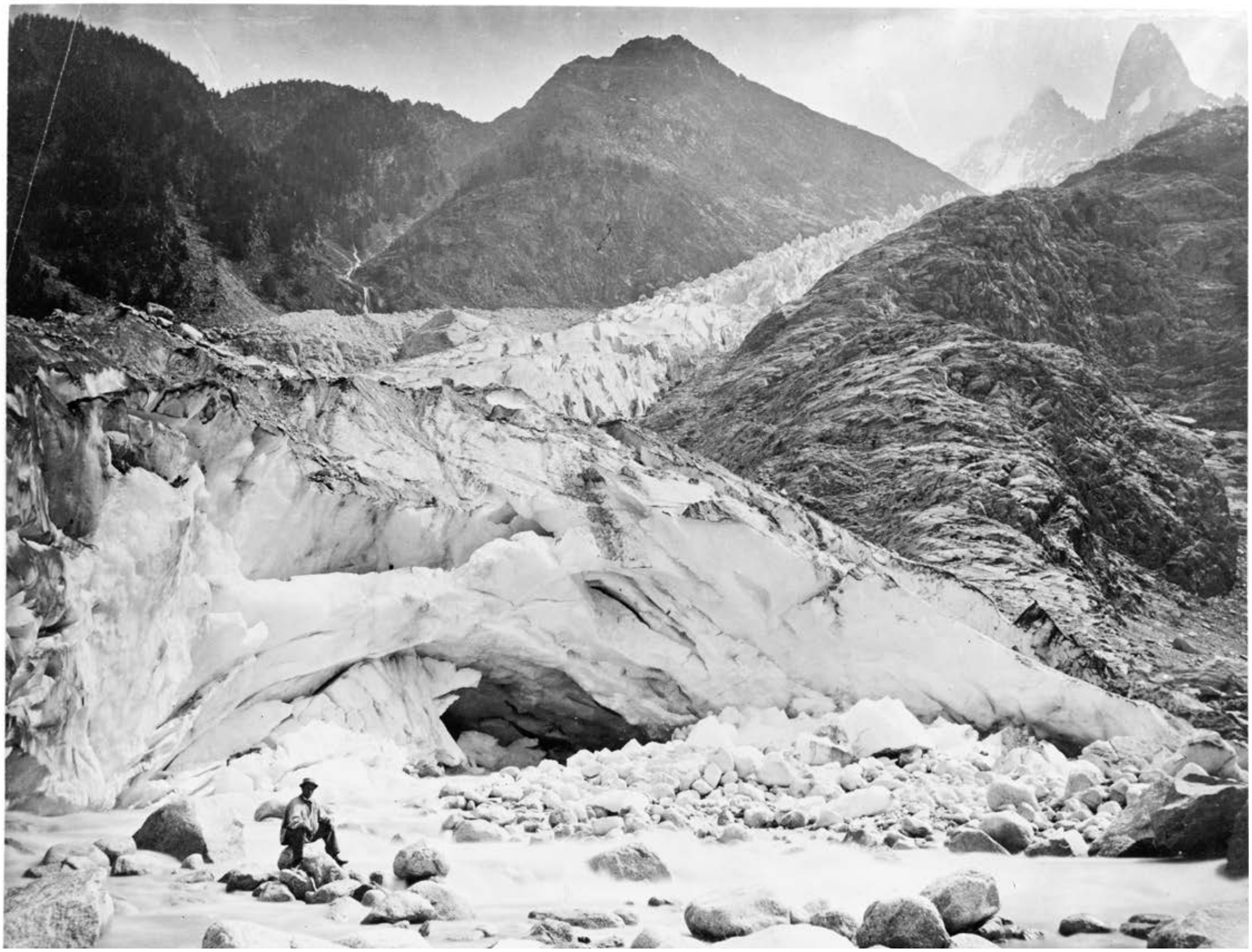


W I R E D

IT IS LIKE LAVA, ONLY COLD | JOHN HESSLER

Climate Change and the Glacial Science of James D. Forbes

A first step is simply to try to prove that the equations give rise to some solutions.... That doesn't give a real understanding of how fluids behave, but if you don't have that, you don't know anything. —Charlie Fefferman

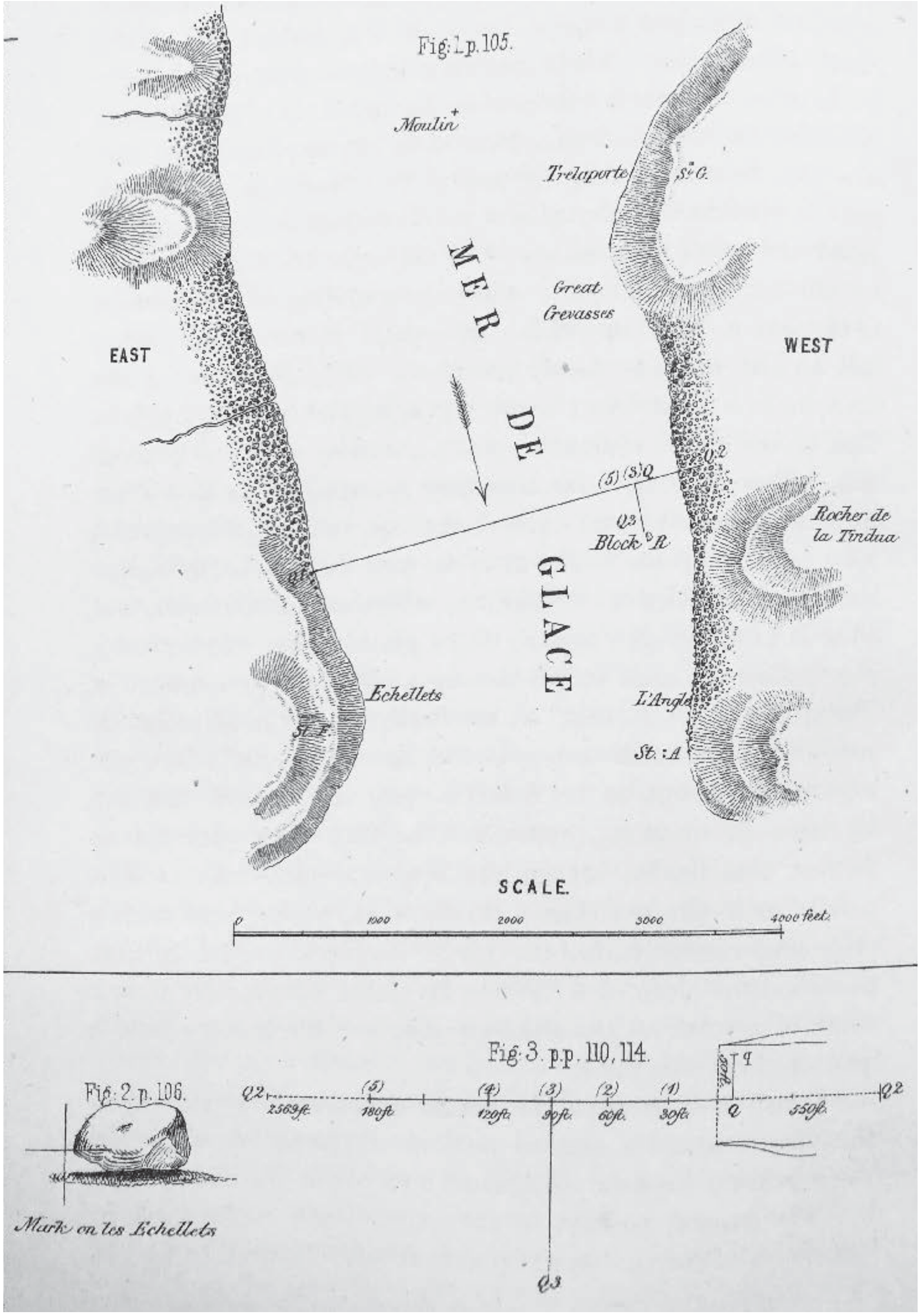
$$\rho[\frac{\partial V}{\partial t}+(V.\nabla)V]=-\nabla P+\rho g+\mu\nabla^2 V$$

A DEEP UNDERSTANDING OF this equation could win you a million-dollar prize from the Clay Mathematics Institute. The catch (and there is always a catch with a million dollars) is that it is among the most complicated and mysterious mathematical equations ever devised. Known today as the Navier-Stokes equation, it was derived nearly two hundred years ago to explain the maddening complexity and dynamics of a fluid in motion and, I would venture a guess, has never (until now) graced the pages of a mountaineering journal.

In the nineteenth century, the study of this kind of mathematics was a seriously complicated and intractable endeavor. And it still is today, even with modern supercomputers, as anyone who knows anything about the sciences of chaos or climate change realizes. Physicists use the Navier-Stokes equation to model the movements of fluids, from the gases that form storm patterns in the earth's warming atmosphere; to the liquid waves that churn in the ocean; or the frozen water that creeps over an ice sheet. Video game designers use simplified solutions of the equation when they animate characters moving through explosions, fire, or smoke, and when they try to create fluid-like effects around planes, boats, or cars racing through simulated air and water.

The mathematics of the equation starts simply and intuitively enough: combine Isaac Newton's ideas on forces and acceleration with pressure, along with the viscosity or resistance of the fluid to flow. Even with these simple beginnings, however, how and why the ice of a glacier—or any fluid, for that matter—moves, quickly becomes mind bending.

Predicting the future behavior and velocity of a flowing fluid is at the center of the Navier-Stokes equation. Despite the knottiness of the mathematics, it has proven very useful throughout the centuries in helping scientists understand how a fluid behaves in a wide variety of situations. Today, the Navier-Stokes equation



[Opening Page] **The source of the Arveyron river at the foot of the Mer de Glace—France's largest glacier—some time between 1860 and 1890. Today, the glacier is one of Chamonix's biggest tourist attractions, and a jarring image of climate change. Since 1850, the glacier has receded over a mile.** | [This Page] **Drawing from James David Forbes's *Illustrations of the Viscous Theory of Glacier Motion* (1846) that depicts Forbes's method for tracking nails on the glacier.** Library of Congress Collections (both)

has new and vital relevance as it is applied to the study of extreme weather and climate change. The predictions the equation makes, via sophisticated algorithms and the fastest computers in the world, are not completely understood, and the mistrust in what they foretell is the source of much of the controversy surrounding climate change modeling.

One of the inventors of the equations for fluid flow, George Gabriel Stokes (1819–1903), was a great mathematician who studied subjects as varied as optics and geodesy (a field devoted to calculating the shape and size of the earth). But as far as I can tell, he did not bother much with mountaineering or exploration in general. As the Lucasian Professor of Mathematics at Cambridge, from 1849 until his death in 1903, mountaineering and glacier travel were just not his thing. Stokes made many observations of fluid mechanics through laboratory experiments in order to compare empirical results against his calculations. In these experiments, Stokes sought to understand how the thickness of a fluid affects its behavior. But he never appeared to take too much notice of the vast fields of solid but moving ice that his equations would later be used to study.

For one of Stokes' contemporaries and correspondents, the Scottish physicist James D. Forbes (1809–1868), how ice and water behaved in the actual environment was an obsession. Forbes was by all accounts a born scientist. Just after entering the University of Edinburgh in 1825, he began contributing articles on astronomy to the *Edinburgh Philosophical Journal*. To keep the editors of the journal from knowing that the articles were authored by a teenager he wrote under the pseudonym Δ.

In 1833 he became a physics professor at the University of Edinburgh. But he was also an avid traveler who would spend much of his time in the European Alps, where, unlike Stokes, he couldn't help but wonder about the flow of liquids and heat, the properties of ice and what happens when you put a lot of frozen water in one place. During a family visit to Geneva in 1827, Forbes first set foot on a glacier. It was then, with his brother Charles, that he traveled to Chamonix and was captivated by the sight of the Mer de Glace. Massive boulders piled high on its edges seemed to defy gravity. Deep blue crevasses and the sheer size of the moving sea of ice fascinated James Forbes. It was a trip that he would not soon forget.

Of course, scientists were not the first to notice that ice moved. Early travelers, local shepherds and residents of the mountain regions of Europe saw with their own eyes the ebb and flow of glaciers. In Forbes's time, however, the empirical study of glaciers and their behavior was just beginning. This scientific research effort sent alpinists, speculators, geologists and physicists around the globe to look closely at the geology, physical morphology and the deep history of the earth itself.

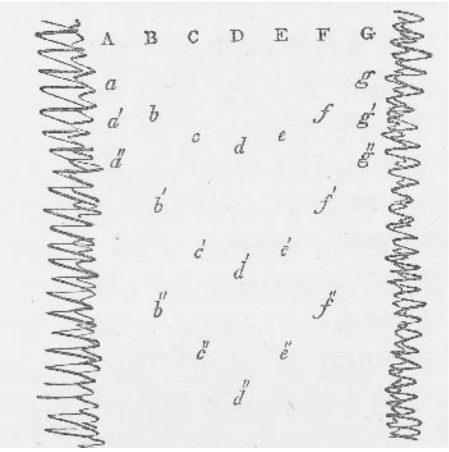
When Forbes began his study of glaciers, the prevailing notion of how and why they moved, popularized by the geologist Louis Agassiz (1807–1873), was termed the *dilation theory*. The dilation theory postulated that the motion of glaciers is not like a river of fluid, but more akin to that of a giant ice cube that grows through the refreezing of melt water. Theorizing that water seeps into small cracks, Agassiz

postulated that the refreezing and expansion would propel the glacier in the direction of least resistance, making it flow down into the lower valleys from the high mountain slopes.

Yet the dilation theory was a highly speculative idea, for it was not based on any field studies or experiments on such large quantities of ice. Forbes, always the physicist, was deeply skeptical of the idea, believing that this mechanism to describe glacial motion was, while imaginative, not scientifically sound: "Most of the arguments in favor of the progression [of glaciers] due to water being absorbed by capillary fissures, and then frozen so as to produce dilation in the whole mass, were deduced from consideration either à priori, or at least indirect," he reflected in *Travels Through the Alps.*

Reflecting on the theory, Forbes, a true empiricist, asked himself, "Have the laws of glacial and fluid motion been determined? Have we the data of the problem of which we seek for the solution?" His answer would be no. Mathematically understanding the movement of any fluid, even one creeping along as slowly as a glacier, requires a great deal of computation. As Forbes was without the help of the numerical and algorithmic techniques employed in our modern computer models, he needed to measure the movement of the ice itself.

In 1832 Forbes began his first scientific alpine excursion at Lake Geneva before moving on to Chamonix and the Swiss Alps. Prior to his departure, he reviewed what was known about glaciers and their behavior. "On studying the subject at home and leisurely," he later reflected in *Travels*, "I satisfied myself that experiments could be made upon the motion of the ice, which should, in a good degree, throw light upon the question. The question is reduced to one of pure mechanics, and should be treated as such by a rigorous analysis. The *motion* is the thing to be accounted for." In his reading, Forbes was struck by the fact that "no numerical tests had been applied to ascertain their insufficiency, or to prove their correctness." Later discussions of the theories of glacier formation and motion with other researchers, like Louis Agassiz, with whom he explored the Unteraar glacier in 1841, led him to devise a plan to try to characterize the speed at which glaciers moved. He was convinced that close surveys and experiments performed on the ice itself were necessary to uncovering the "*cause of progression* of glaciers."



[Image] **Illustration of the effects of friction on glacial flow from Forbes's *Sixth Letter on Glaciers* (1844), showing that nails affixed to the surface flow faster in the middle than on the sides of the glacier. In *Travels through the Alps* (1843) Forbes explained his motivation for field work, saying "in many parts of experimental science unexpected discoveries are made in a workshop," so the "book of nature, whose pages are open to all, is read but by a few."** Library of Congress Collections

Traveling in the alpine regions of Europe was not easy in the middle of the nineteenth century, with few good roads and even worse maps in remote areas. Even so, Forbes, driven by his interest in the mechanics of ice made tours of the French and Swiss Alps in 1832, 1841, 1846 and 1850. Forbes continually calls the area "one of the most frequented" in Europe, and although it was a popular stop on the Grand Tour of Europe taken by wealthy tourists, it was a much larger and more difficult to reach "sea of ice" in his day than now.

When Forbes began his serious glacier research in 1842, he chose to center his experiments on the great alpine glacier of the Mer De Glace and its tributaries near Chamonix, France. In the nineteenth century, the glacier reached all way down the valley to the little village of Les Bois. As Forbes's familiarity with the landscape increased, so, too, did his observations of the beauty of the landscape. Little details, he wrote, began to "impress" upon his "imagination": "the wear and polish of the rocks—the vast masses of travelled stone thrown up high and dry far above the present level of the ice, like fragments of wreck, indicating, by their elevation on the beach, the fury of the past storm—the pillars of ice, with their rocky capitals, studded over the plain like fantastic monuments of the Druid age—or the beautiful veined structure of the interior of the ice, apparent in almost every crevasse."

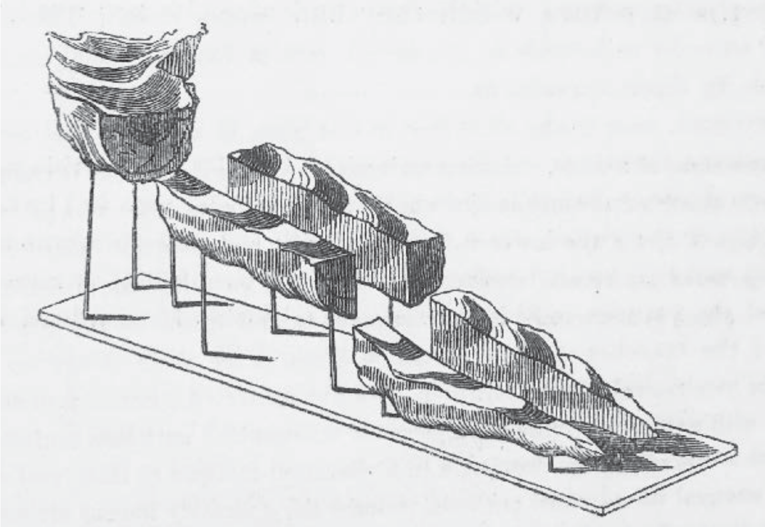
Forbes recounted his first measurements of glacial motion in *Travels Through the Alps of Savoy and Other Parts of the Pennine Chain* (1843). Before his experiments began, he made a detailed geodetic survey and mapped the glacier and its surroundings, producing one of the most exact glacier maps of the time. After placing sticks and nails at precisely measured points across the glacier's surface, Forbes used the map to track how far particular fixed points or individual pieces of scree and rock on the glacier's surface had moved. Twenty-six hours previously, he found that the glacier was sixteen and a half inches lower (that is more in advance). Although the result was, for Forbes, not unexpected, it was the first time that from actual surveys and observations that the diurnal motion a glacier had been measured empirically: a milestone in the history of glaciology.

PROPOSING MATHEMATICAL THEORIES OF natural phenomena and devising methods to test them is at the core of the scientific method. As Forbes took measurements of the ice's movement on the Mer de Glace over many weeks, he began to see patterns in the data that prompted him to question the prevailing dilation theory of glacial movement. But neither did his observations support a competing theory, put forth by the alpinist Horace Bénédict de Saussure. Saussure had also travelled extensively in the Alps and made the second ascent of Mont Blanc in 1787. He had surmised that glacial movement was caused principally by the mass of ice sliding along its bed under the force of gravity and overcoming the friction between the glacier and the earth below.

Forbes's measurements indicated that the entire glacier was not flowing at the same speed, but that the center of the glacier moved more rapidly than the sides; furthermore, the motion of the ice at the lowest elevation was faster than the flow of the ice at the highest portion of the glacier, while the middle section of the glacier moved at the slowest rate of speed. The kind of uniform movement that Saussure had proposed, Forbes realized, was not possible.

Forbes's measurements gave him most of the clues he needed to refute previous ideas relating to glacial motion. In drawing out his conclusions, he surmised that the difference in the velocity across the ice pointed to river-like behavior. In laboratory experiments, engineers and physicists like Stokes had demonstrated that, in pipes and canals, the center of a fluid flows faster than it does

at its sides. The difference in speed is caused by the friction of the fluid against the walls of whatever container it is flowing in, whether that be the banks of a river or a pipe. On a glacier, Forbes thought, the moraine and valley walls would work to slow down the movement of the ice on its sides. Forbes concluded, "The velocity of a river is greatest where it narrows, and is small in large pools. Just so in the Mer de Glace." To illustrate the kind of motion found in a valley glacier and the different velocity patterns generated by moving ice, Forbes made actual scale models of valleys and represented the ice of the glacier with a viscous mixture of plaster and glue. The mixture, he explained, "does not set readily" when poured down irregular channels made to look like alpine valleys.


[Image] **Illustration from *Travels* showing Forbes's laboratory model for simulating the flow of ice in a valley glacier. Glaciers move on average up to three feet per day.** Library of Congress Collections

In this way Forbes reproduced the glacier's banded or ogive structure, which is made of light and dark ice formed by the faster flow of the center of the glaciers just below icefalls. In his laboratory models, Forbes was able to reproduce the patterns of glacial motion that he observed in the field. "The results of the artificial sections of many of these experimental models," he observed, "were not to be distinguished from the glacier [cross] sections and… the results of my observations." In other words, all of his data pointed to glaciers behaving like viscous, flowing rivers. Although the idea that a glacier was a river was not completely original to Forbes, he was the first to confirm the theory through both empirical and experimental verification.

By 1845, the theory of the fluid motion of glaciers began to take hold in scientific circles. In other sub-fields of fluid dynamics, engineers were just beginning to theorize about the patterns of lava flow on volcanoes, drawn in part from field observations on Sicily's Mt. Etna. That year, Forbes published a paper in *Philosophical Transactions of the Royal Society of London*, where he compared the movement of glaciers to lava streams:

> *There is something pleasing to the imagination in the unexpected analogies presented by a torrent of fiery lava and the icy stream of a glacier…. This cause [of the analogy with lava and other fluids] I of course consider to be the laws and condition of their motion, the struggle of a semi-fluid mass of enormous weight creeping down a mountain side, in which fluidity and solidity are so curiously combined, that we should be at a loss in either case how to name it; a straining, crackling, splintering solid, heaved on by the internal energy of the latent fluidity which pervades it, and which at last succeeds in giving to the general character of the motion and the moving mass, those of fluid bodies subject to the law of gravity.*

While Forbes may have been describing the physics and dynamics of glacier flow, as a mountaineer, his chosen language could not have been accidental. A straining, cracking and splintering semi-fluid mass is something that every climber who has set foot on a glacier feels in his or her bones. Forbes scientifically explained both the solidity and fluidity of glaciers. Alpinists see this dual nature of the world of ice play itself out in the activity climbing itself. For mountaineers, a glacier's solidity can be a great refuge, where crampons and ice axes hold fast in its frozen surface. At the same time, the ice's fluidity produces a world of danger: collapsing seracs, crevasses and ice falls evidence the glacier's constant, never-ending motion.

TODAY WE ARE FACED with the mystery of climate change, which, like the question of glacier motion in the nineteenth century, links science, alpinism and fluid flow. How we answer it now, both scientifically and politically, may determine the fate of many of the high places that the readers of this magazine have come to know and to love. None of this is easy. The science of fluid flow, whether used to model a turbulent ocean or a warming atmosphere, is still a struggle to comprehend, as the press and policy makers around the world argue over the meaning of what the equations tells us about the future of the warming planet.

For glaciologists, these frozen fluid rivers have taken on a bigger role as global warming and climate change have radically altered the high mountain environments that, while dynamic, had for centuries seemed to be in equilibrium. Climate researchers see the water trapped in mountain glaciers and ice sheets as a kind of canary in the coal mine as they struggle to foretell our future climate using sophisticated algorithms, mass balance equations and the mathematics of fluid flow invented by Navier and Stokes. All of this science and technology is used to quantify what every climber from the Alps to the Himalaya has noticed in the last few decades. Ice is disappearing. Since 1820 the Mer de Glace has lost more than 150 meters of thickness at the Montenvers Station, where Forbes and countless climbers, hikers and tourists begin their explorations. The glacier is now over two kilometers shorter than it was 150 years ago. Scientists have predicted that by 2040 the glacier will lose an additional 1200 meters of its length. In a few years, if these estimates are correct, the place would be unrecognizable to someone like Forbes.

Today there is no simple equation that will mitigate the effects of climate change or change the behavior of very complex environmental systems, whether they be storms in the atmosphere or the melting of ice sheets. Nor is there any scientific test that might give us an easy way around the difficult decisions that the future may hold. The only certainty is that in our modern and rapidly changing world, the fate of mountains, alpinists and ice are linked together as never before—all of us subject to the deterministic laws of nature and the subtleties of the flow of human behavior and ideology. And so like a teetering serac, the world of alpinism hangs in the balance. ■