# ONE

# The Fabric of a Vision

Our story begins at the end of the nineteenth century in the twilight years of the theory of the "ether": a theory of space, time, and matter, which was soon to be superseded by Einstein's theory of relativity and by the theory of quantum mechanics. A Norwegian scientist made a remarkable discovery while working on the ether theory, a discovery that was to lead to a new beginning in meteorology.

## A Phoenix Arises

A pensive, thirty-six-year-old Vilhelm Bjerknes peered through a quarter-pane of his window at a city shrouded by a sky as gray as lead. It was a bitterly cold afternoon in November 1898 and Stockholm was preparing itself for a taste of winter. Snow had been falling gently since early morning, but a strengthening northerly wind began to whisk the flurries into great billows that obliterated the skyline. We may imagine Bjerknes returning to the fireside with anticipation of the warmth keeping the chill at bay, relaxing in a chair, and allowing his thoughts to wander. As the fire began to roar and the blizzard strengthened, his growing sense of physical comfort was accompanied by a feeling of inner contentment: he was at one with the world. However, this wasn't just the simple pleasure that comes from finding sanctuary from the winter's rage; it was deeper and much more profound.

Bjerknes gazed at a spark as it flickered and swirled up the chimney. The tiny cinder disappeared from view, carried into the even greater swirl of the wind and snow outside. He continued to watch the dance of

**Figure 1.1.** Vilhelm Bjerknes (pronounced Bee-yerk-ness), 1862–1951, formulated weather prediction as a problem in physics and mathematics.

the smoke and flames, and listen to the howl of the storm. But he did so in a way that he had never done before: the spiraling of smoke above the fire, and the intensification of the storm—events that had been witnessed by mankind since the dawn of civilization—were two manifestations of a new theorem in physics. It would amount to a small landmark—not quite as prominent in the timeline of science as Newton's laws of motion and gravitation—but all the same it would explain fundamental features of weather. The salient idea had remained hidden, locked away from meteorologists behind the heavy door of mathematics. The new theorem was due to Vilhelm Bjerknes, but it was destined to do much more than carry his name; it would propel meteorology into a cutting-edge science of the twentieth century and pave the way to modern weather forecasting. And it would do this because, above all else, it would first change his vocation.

But the irony was that Bjerknes never intended his ideas to shape history, or his own destiny, in this way at all. Indeed, while he relished the excitement of opening a new window onto the laws of nature, he agonized over his priorities and ambitions, and he began to question the future of his career. His newfound vision was borne out of a rapidly waning and increasingly unfashionable development in theoretical physics. For more than half a century, a group of leading physicists and mathematicians had been trying to decide if phenomena such as light and forces such as magnetism travel through empty space or whether they travel through some sort of invisible medium.

By the 1870s there was a growing consensus that empty space must in fact be filled with an invisible fluid, which was called the ether. The basic idea was very simple: just as sound waves travel through the air, and just as two boats passing each other feel their mutual presence because the water between them is disturbed, light waves and magnetic forces should travel through some sort of cosmic medium. The scientists trying to understand and quantify the properties of such an ether believed that there must be some similarity to the way water, air, and other fluids affect and are affected by objects that move within them. By showing how experiments with objects immersed in water replicate the type of effects that are familiar from experiments with magnets and electrical devices, they conceived of demonstrating the existence of this ether.

In 1881, at the prestigious Paris International Electric Exhibition, which attracted the likes of Alexander Graham Bell and Thomas Alva Edison, a Norwegian scholar by the name of Carl Anton Bjerknes, a professor of mathematics from the Royal Frederick University in Christiana (now called Oslo), and his eighteen-year-old son, Vilhelm, exhibited their experiments aimed at verifying the existence of the ether. Observers, who included some of the most outstanding scientists of the times such as Hermann von Helmholtz and Sir William Thomson (who became Lord Kelvin), were clearly impressed. Bjerknes and his son won a top accolade for their exhibit, and this success placed them firmly in the spotlight of the international physics community.

Their rising fame and status inevitably led to the gifted young Vilhelm following in his father's footsteps, not only as a mathematician and physicist but also as one of the proponents of the theory of the ether. Research on this hypothesis was refueled in the late 1880s when Heinrich Hertz, in a series of extraordinary experiments, demonstrated the existence of electromagnetic waves propagating through space, as predicted by the Scottish theoretical physicist James Clerk Maxwell. In 1894 Hertz published (posthumously) a book outlining his ideas for how the ether should play a crucial role in formulating the science of mechanics.

Now this was no small undertaking. We are taught that the science of mechanics was born when Galileo introduced the concept of inertia, and Newton quantified the laws of motion by relating force to acceleration, and so on. We court triteness to mention the success of mechanics in describing the motion of everything from ping-pong balls to planets. But Hertz believed there was something missing; that is, the great bastion of Newtonian mechanics appeared to rely on some rather intangible concepts. So he set out, in an axiomatic way, a general strategy for explaining how actions within the ether could explain phenomena that hitherto required the more elusive ideas of "force" and "energy" that appeared to influence our world without any tangible mechanism for doing so. The general principles set forth in Hertz's book appeared to systematize the program Vilhelm's father had initiated. Carl Bjerknes's work lacked any underpinning rationale, but the Hertzian thesis promised to change all that and, in so doing, would vindicate his life's work. This was an important motivation for his son; Vilhelm, captivated by Hertz's profound ideas, decided to devote his energies to this worldview.

Vilhelm also realized that success with this program would place him at the forefront of physics—an attractive prospect for a determined and ambitious young scientist. The nineteenth century had already seen some remarkable marriages of ideas and theories. In a paper published in 1864 Maxwell unified electricity and magnetism, two hitherto apparently unrelated phenomena. The concepts of heat, energy, and light had also been placed on a common basis, and Vilhelm envisaged that this process of unifying seemingly disparate parts of physics would continue until the entire subject lay on the sure foundations of mechanics—a "mechanics of the ether." He alluded to this vision in his defense of his thesis in 1892, at the age of thirty. Two years later, with his ideas vindicated by Hertz, he embarked on the road to fulfilling this dream.

Bjerknes's work had already taken him to the point of rubbing shoulders with others who sought a unified view of nature via the existence of the ether. One such person was William Thomson, Baron Kelvin of Largs. Thomson was born in Belfast in 1824 and moved to Glasgow in 1832. As a teenager, his curriculum vitae made impressive reading. He took courses at Glasgow University at the age of fourteen, continuing his education at Cambridge University at the age of seventeen. On graduating from Cambridge he spent a year in Paris engaging in research with some of the outstanding mathematicians and physicists of the era. Thomson then resumed his career in Glasgow where, at the age of twenty-two, he was appointed as a full professor to the Chair of Natural Philosophy. Although he was primarily a theoretician of the highest caliber, he had significant practical abilities, which were to create the basis of his considerable wealth. He divided his time between theoretical physics and making money from his expertise in telegraphy: he patented what was later to become the standard receiver used in all British telegraphy offices. Thomson was knighted in 1866 for his work on the transatlantic cable, which transformed communication between Europe and the United States, and fairly soon between other countries around the world. This achievement also facilitated rapid communication between meteorological observers. In the United States he was made a vice president of the Kodak company, and back home his achievements were honored by the public for a second time with an elevation to the peerage in 1892, whereupon he gained the title of Lord Kelvin.

So Kelvin (as he is usually known) was wealthy and held high office—indeed, he was one of the first to make a huge success of combining an academic career with industry—but he was undoubtedly preoccupied with the one thing that had created his good fortune: science. His contribution to theoretical physics was enormous. Kelvin played a leading role in explaining heat as a form of energy when he came to support the

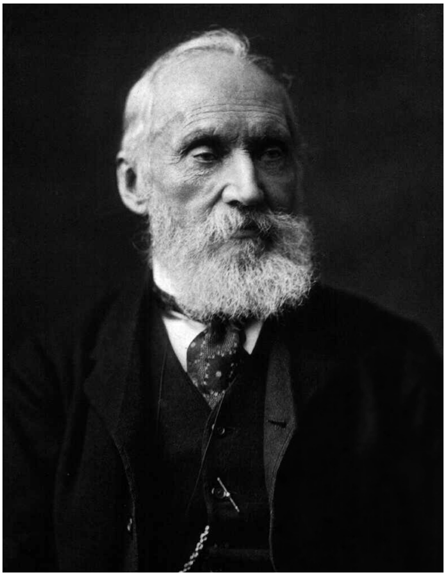

**Figure 1.2.** Sir William Thomson, later Lord Kelvin (1824–1907), a distinguished professor at the age of twenty-two, continued to dominate science for the rest of his life. He published more than six hundred papers and was serving a third term as president of the Royal Society of Edinburgh at the time of his death. Kelvin made a considerable fortune from his work on the transatlantic cable: he bought a 126-ton yacht, the *Lalla Rookh*, as well as a fine house in the Scottish coastal town of Largs. He is buried in Westminster Abbey, next to Sir Isaac Newton.

somewhat radical and abstract view for its day, that energy, not force, lay at the heart of Newtonian mechanics. Indeed, the concept of energy would ultimately lie at the heart of science. He was also an enthusiastic supporter of the concept of the ether; in fact, his views on the role of this entity went much further than those of many of his colleagues.

While studying the basic equations of fluid mechanics—Newton's laws applied to the motion of liquids and gases—Kelvin had become particularly interested in a result that had been published in 1858 by Hermann von Helmholtz. In his analysis of fluid motion, Helmholtz conceived of the idea of a "perfect fluid"—a liquid or a gas that is assumed to have some very special properties. The term "perfect" alludes to the idea that the fluid is assumed to flow without any resistance or friction, hence, no loss of energy into heat or anything similar. Although such a concept is artificial—a product of good old ivory-tower academe—Helmholtz's analysis of its motion revealed something quite remarkable. Instead of analyzing motion in terms of the speed and direction of the fluid flow (the fluid velocity), he studied an equation for the change in the vorticity, or "swirl," of the fluid caused by a "perfect eddy"—that is, one that rotates like coffee in a cup stirred uniformly. To his amazement, this equation showed that if the fluid possessed swirl to begin with, then it would continue to swirl forever. Conversely, if the perfect fluid did not possess swirl, then it would never spontaneously begin to swirl.

Kelvin sought to transfer these ideas and interpret them in the context of the ether. He envisaged the ether as a perfect fluid, and matter as composed of "vortex atoms." That is, he imagined that tiny vortices in the ether were the very building blocks of matter. In 1867 he published (under the name William Thomson) an eleven-page paper entitled "On Vortex Atoms" in the *Proceedings of the Royal Society of Edinburgh*. Naturally, the question arose as to how the vortices, or his "atoms of idealised eddies," had been created in the first place, given that they must be permanent features of a perfect fluid. To appreciate Kelvin's answer to this question, we should remember that the mid-1800s was a turbulent time for science and society; a considerable wake had been created in philosophy and religion by Darwin's ideas on evolution, and this had resulted in rifts between science and the Church. Kelvin, as a devout Presbyterian, saw a way of healing some of these wounds if the creation of the vortices in the ether could be attributed to the hand of God. So, with some exact mathematics on one hand and a clear role for God on the other, Kelvin became committed to the view that the ether was at the heart of all matter and therefore of all physics.

But true to the form that had led him to patent his "phone calls across the Atlantic" ideas, Kelvin did not confine his interest in the ether to wide-eyed speculation. He took Helmholtz's theory of vortex motion and reexpressed it as a theorem that showed how a quantity that measures the strength of vortex motion, which is called circulation, is *unchanging* as the flow of fluid changes. Since circulation plays a major role in understanding weather, we return to discuss it more carefully in chapter 3. For now, we just say that the circulation of an ideal circular eddy (or whirlpool) is the magnitude of the swirling velocity multiplied by the circumference of the circle that the fluid flows around.

Although the ether theories were ultimately doomed, Kelvin's intuition to focus on the circulation in a fluid was of major importance—Kelvin's theorem is a main result in present-day university courses on ideal fluid flow. Bjerknes tried to use these ideas to explain some of his recent experimental results. He had been studying what happens when two spheres are immersed in a fluid and set spinning. Depending on their relative motion, the spheres will either attract or repel each other due to the motion they create in the fluid. Bjerknes was analyzing this theory and trying to show how it might explain forces such as magnetism; however, it was not long before he ran into trouble. His experiments and calculations indicated, contrary to the results of Helmholtz and Kelvin, that vortices might be created in a perfect fluid when spheres were set in rotation adjacent to one another.

This conundrum vexed Bjerknes for some time: Kelvin's result was mathematically sound, so how could the results he obtained from his own experiments be wrong? In the meantime, Bjerknes had obtained a position at the new Swedish högskola in Stockholm. The privately funded university held pure research in the highest regard, and Vilhelm's new position offered him plenty of opportunity to pursue his interests. One day in early 1897, while walking home from the högskola, he realized that Kelvin's theory, while correct, would not apply to the experiment (and problem) he was studying. The key fact was that Kelvin's circulation theorem made no allowance for the possibility that pressure and density might vary independently of one another in the fluid, as they do in the atmosphere. Such variations in Bjerknes's experiment would invalidate the application of Kelvin's theorem. Bjerknes immediately set about trying to modify Kelvin's theory to allow for independent variations in the pressure and density, and he succeeded in showing how circulation might be created, strengthened, or weakened, even for perfect fluids. The result is known as Bjerknes's circulation theorem.

This was a major breakthrough. By the end of the nineteenth century, mathematicians and physicists had known for nearly 150 years how to apply Newton's laws of motion to study and quantify the dynamics of fluids. The problem, however, was that the equations involved, even for perfect fluids, were horrendously difficult to solve, and by the late 1880s only a few very special and idealized solutions had been found. By concentrating on vorticity and circulation rather than on the speed and direction of fluid flow, Helmholtz and Kelvin opened the door to "back of the envelope" (or very simple) calculations to work out how vortices—ubiquitous features of fluid motion—move and change with time. Calculations that would be hugely complicated if we had to work out how the speed and direction of all the particles of the flow would change directly from the laws of motion were now reduced to a few relatively easy steps.

Bjerknes extended these ideas, and his theorem enables us to deal with much more realistic situations than those covered by the work of Helmholtz and Kelvin. In particular, this new theory allows us to work out how vortices in the atmosphere and oceans behave because in these nearly perfect fluids pressure, temperature, and density are all interconnected. Consequently, without even attempting the impossibly complicated task of solving the basic laws of motion for the details of the entire fluid, we get a holistic view of how these vortex patterns will morph and change with time. In turn, this helps us to explain the basic swirling structure of weather systems, which are often most obvious in pictures taken from satellites (such as that in figure 1.3, and in figure CI.2 in the color section, which shows similar eddies in the Gulf Stream). The persistence of these large swirling eddies of air and clouds in the atmosphere is an example of Kelvin's theorem at work, modified by the actual temperature and density variations as proposed by Bjerknes. In the Gulf Stream, the saltiness (or salinity) of the water acts to change the density, and so modifies its eddy behavior in a similar fashion.

Bjerknes was overjoyed with his advances and began to discuss his findings with his colleagues. In late 1897, before the Stockholm Physics Society, he presented his generalizations of Helmholtz and Kelvin's theories. It was at this point that serious interest in his work was aroused,

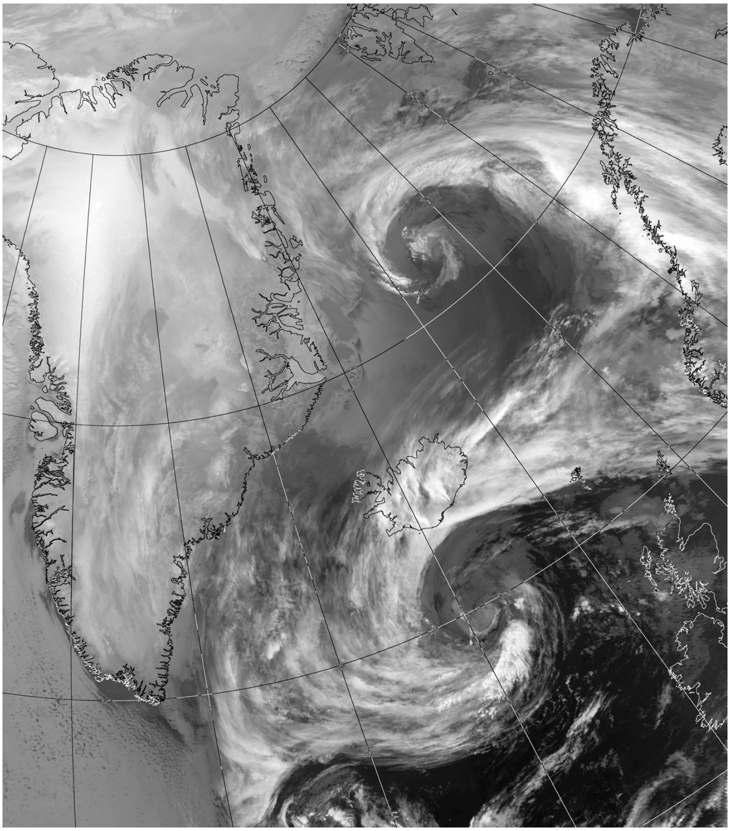

**Figure 1.3.** A cyclone, or low-pressure system, is a large rotating mass of air, about one thousand kilometers in diameter, that moves through our atmosphere changing the weather. These weather systems often bring rainfall and squally winds. The name cyclone comes from the Greek for the coiling of a serpent. © NEODAAS / University of Dundee.

not from among the dwindling supporters of the theories of the ether but from scientists in very different, important, and emerging areas of physics. Svante Arrhenius, a fellow member of the Physics Society, was interested in applying such ideas from mainstream physics to problems that were becoming particularly well defined in atmospheric and oceanic sciences. He was a distinguished chemist and was among the first to discuss the greenhouse effect of carbon dioxide.

Both the predictable and the unpredictable features of the oceans and the atmosphere have stimulated scientific thinking since science began, but serious scrutiny of atmospheric science proved difficult, and only a few individuals working mainly in isolation had managed to contribute to the subject in any substantial way before the end of the nineteenth century. One of the reasons for the lack of solid progress in atmospheric science compared to astronomy in the eighteenth and nineteenth centuries was the intractability of the mathematics involved in solving the equations that describe fluid motion. By the late nineteenth century, few scientists had even begun to think about the motion of the atmosphere in terms of a problem for mathematical physics. It was just too difficult!

In Stockholm, Nils Ekholm, a meteorologist who was interested in the formation of cyclones (one of the major discussion points in meteorology since 1820), became a close colleague of Bjerknes. Ekholm had studied the development of these cyclones, the swirls of air visible in figure 1.3, by plotting charts showing how air pressure and air density vary from one location to another. However, he lacked any method for linking his observations to a theory of dynamics until Bjerknes started to talk about his work. Another of Ekholm's interests was ballooning, for which it is necessary to estimate the state of the weather at a given altitude because balloons have to navigate aloft. At that time, very little was known about the structure of our atmosphere at different altitudes (such as how temperature varies with height), but there was an eagerness to acquire that knowledge.

Balloons featured prominently in many intrepid adventures. The Norwegians and Swedes had an enviable record of polar exploration. Fridtjof Nansen, the noted Scandinavian explorer, captured the world's imagination when he traveled by ship around the Polar Sea to the north of Russia and Siberia in the early 1890s. So in 1894 the idea was put forward to reach the North Pole by balloon. Three years of planning and fundraising—which won the financial support of the King of Sweden and Alfred Nobel (of the Prizes fame)—led to an attempt in July 1897. Ekholm was involved in the preparation and in forecasting the weather for the trip, but he did not join the crew. This was very fortunate for Ekholm because the balloon, with its crew of three, disappeared (see figure 1.5). This tragic loss was a great blow to Scandinavian national pride. A rescue mission was considered, but no one knew where to search. Because there was scarcely any knowledge of the winds aloft, any clues as to where the balloon might have gone were down to pure guesswork.

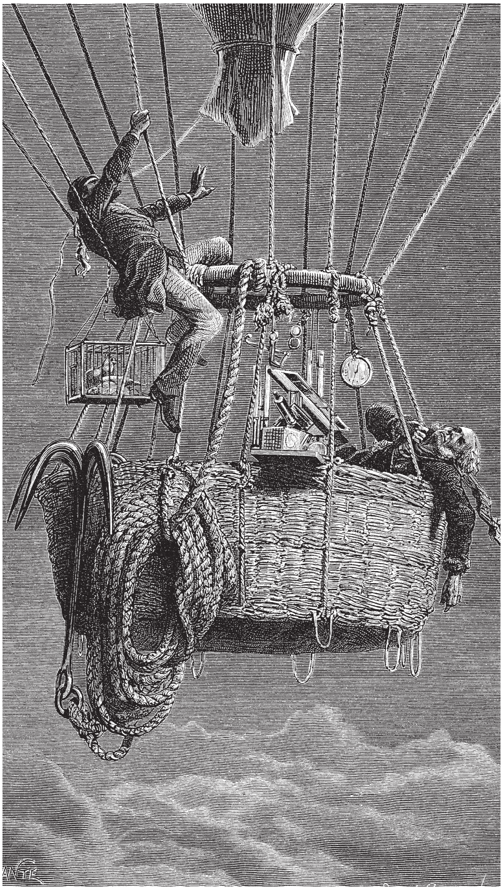

**Figure 1.4.** The British meteorologist James Glaisher made several balloon ascents in order to study the upper atmosphere. During one ascent in 1862 he and his pilot, Henry Coxwell, reached ten thousand meters—and very nearly died in the process. The freezing temperatures, combined with tangled rigging between the basket and the balloon, made it difficult to operate the balloon's control valve. The balloon was ascending rapidly and Glaisher lost consciousness in the thin air. Coxwell began to suffer from frostbite and he could not use his hands to pull on the cord to release the valve. Eventually he managed to scramble out of the basket, into the rigging, and caught the cord between his teeth and opened the valve. The balloon began to descend and Glaisher regained consciousness. On landing safely, Glaisher walked more than eleven kilometers to find help to recover the balloon and their equipment.

On hearing Bjerknes's lecture in late 1897, Ekholm must have felt like shouting "eureka!" It dawned on him that information about winds and temperature in the upper atmosphere could be obtained by using the circulation theorem together with readings of pressure and wind velocity at ground level, and such information might very well have enabled the balloonists to be rescued. Ekholm had understood that Bjerknes's theorem explained the circulation of entire swirling masses of air, such as cyclones and anticyclones. Because the circulation theorem is based on a formula that relates the strengthening or weakening of circulation to the varying patterns of pressure and density, the structure of cyclones could be estimated. Consequently, observations of a small part of that

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