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JACOB AALL BONNEVIE BJERKNES

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A Biographical Memoir by

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JACOB AALL BONNEVIE BJERKNES, or Jack Bjerknes as he was usually called, was one of the founders of modern meteorology. He entered the scientific scene at the age of twenty with the discovery of the structure of extratropical cyclones, which became of the greatest importance and formed the starting point of a fruitful development for theoretical meteorology as well as practical weather forecasting. It was Jack's father, the famous physicist and geophysicist Vilhelm Bjerknes, who set the stage for the research leading up to this discovery, but Jack was the principal performer.

FAMILY BACKGROUND

The name Bjerknes comes from a family farm in southeastern Norway where some of Jack's ancestors lived. Jack represented the third generation in a dynasty of scientists. His grandfather, Carl Anton Bjerknes, was professor of mathematics at the University of Christiania, as the Norwegian capital Oslo was called at the time. He showed both theoretically and by experiment that an ideal fluid would transfer Coulomb-type forces between pulsating spheres and thought that he was on the track of a hydrodynamical ether theory of electromagnetism.

Jack's father, Vilhelm Bjerknes, began his career as a physicist working with Heinrich Hertz in Bonn on electromagnetic resonance. In 1893 he married Honoria Sophia Bonnevie, a Norwegian science student in Christiania. They settled in Stockholm, where Vilhelm Bjerknes was appointed lecturer and later professor of mechanics and mathematical physics.

Jack Bjerknes was born in Stockholm and spent his childhood years there. He was named after his mother's father, Jacob Aall Bonnevie, a prominent civil servant and minister of education in Norway. Jack's aunt, Kristine Bonnevie, was Norway's first woman professor; her field was zoology. Young Jack thus grew up in an academic family.

In 1897, the year Jack was born, his father, Vilhelm Bjerknes, discovered the circulation theorem that bears his name. It generalizes Helmholtz's and Kelvin's theorem on vortex conservation in ideal fluids into a theorem on vortex formation in nonhomogeneous fluids. With this theorem, Vilhelm Bjerknes realized that he now was in possession of the complete set of hydrodynamic/thermodynamic equations that govern the motion of nonhomogeneous fluids. Encouraged by his Swedish colleagues, among them the famous chemist Svante Arrhenius and the oceanographer Otto Petterson, he set out to apply the theory to the motions in the atmosphere and the sea. He put forward the view that weather forecasting should be dealt with as an initial value problem of mathematical physics and carried out by numerical or graphical integration of the governing equations. This is nothing more than treating the atmosphere as a physical system; but at the time it was a revolutionary idea.

Vilhelm Bjerknes visited the United States in 1905. At the initiative of the renowned American meteorologist Cleveland Abbe, he gave a lecture in Washington, D.C., where he described his vision of scientific weather prediction. The lecture was enthusiastically received and resulted in a yearly grant from the Carnegie Institution of Washington, which he retained until the Second World War. The money could hardly have found a better use; it enabled Vilhelm to employ and educate a considerable number of research assistants, all of whom became well-known geophysicists.

In 1907, when Jack was nine, the family moved to Christiania, where Vilhelm was called to a chair at the university. In cooperation with his Carnegie assistants, the Swede Johan Sandström, and the Norwegians Olaf Devik and Theodor Hesselberg, he published a substantial work, *Dynamic Meteorology and Hydrography*. In Germany they were impressed and offered him a position as director of a new geophysics institute at the University of Leipzig. He accepted and with his family moved to Leipzig in 1913. Jack, however, stayed in Christiania to finish junior college and begin science studies at the Norwegian university.

IN LEIPZIG DURING WORLD WAR I

The Geophysics Institute in Leipzig started out successfully. Vilhelm Bjerknes brought with him his two Carnegie assistants, T. Hesselberg (later director of the Norwegian Meteorological Institute) and H. U. Sverdrup (later director of the Scripps Oceanographic Institution). In addition, there were several German doctoral students and research assistants, among them Robert Wenger, who followed Bjerknes as director of the Leipzig institute. Then World War I broke out, and many of the German students and staff were called to war service. Sverdrup and Hesselberg also left, and Vilhelm Bjerknes was in great need of help for his research.

In 1916 Jack Bjerknes, not yet nineteen, interrupted his studies in Norway and went to Leipzig to join his family and assist his father. With him went another Norwegian student, Halvor Solberg.

In Leipzig a German doctoral student, Herbert Petzold, had been studying convergence lines in the wind field. But Petzold was sent to the front and was killed at Verdun in 1916. Jack Bjerknes took over his research. He found that convergence lines may be thousands of kilometers long, tend to drift eastward, and are connected with clouds and precipitation. He reported these results in his first scientific paper, which appeared in print before he was twenty.

As the war went on, the situation for the Leipzig Geophysics Institute worsened, with lack of labor and food shortages. Through the intervention of the Norwegian oceanographers Fridtjof Nansen and Bjørn Helland-Hansen, a professorship was established for Vilhelm Bjerknes in Bergen in western Norway.

THE BERGEN SCHOOL

There was no university in Bergen at the time; but plans for a science faculty existed, and Bergen Museum served as a nucleus for such a development. Helland-Hansen held a position as professor of oceanography at Bergen Museum; he had for many years given international courses in ocean research. The establishment in 1917 of a new geophysics institute at Bergen Museum with a professorship for Vilhelm Bjerknes was an important step toward strengthening the academic milieu in Bergen.

Vilhelm Bjerknes left wartime Germany and arrived in Bergen in the summer of 1917 with two young assistants, Jack Bjerknes and Halvor Solberg. He realized that he would not have in Bergen the resources for a theoretical attack on the problem of weather prognosis and planned instead a push toward practical weather forecasting by offering a special summer forecasting service for agriculture. With support from the Norwegian government, he arranged for a nearly tenfold increase in the number of observing stations in southern Norway.

With these preparations, the forecasting started in the summer of 1918. Vilhelm Bjerknes did not himself take part in the map work but arranged to have Jack as forecaster in Bergen and Solberg in Christiania. The war was still on, and no weather data were received from France, England, or the Atlantic. From the improved data network in Norway, however, Jack could again identify convergence lines of the type he had studied in Leipzig, as they moved along the Norwegian coast. Moreover, he discovered that these convergence lines, which were later termed fronts, were connected with cyclones in characteristic manner. In a paper ("On the Structure of Moving Cyclones") written in the fall of 1918 before he was twenty-one, he presented his famous frontal cyclone model (see Figure 1). The fronts in the model were assumed to represent boundary surfaces separating cold air to the north and west of the cyclone center from warm air in the warm sector to the south and southeast. These frontal boundary surfaces were assumed to be sloping with the cold air on the underside, in accordance with a formula derived in 1903 by the Austrian meteorologist Max Margules. Furthermore, Jack stated in his paper that warm air ascends along the sloping frontal surfaces, causing bands of clouds and precipitation to form along the fronts, whereas the cold air sinks and spreads out along the ground. He noted that these vertical motions represent a reduction of the potential energy, which could account for the formation of the cyclone's kinetic energy, in agreement with Margules's theory published fifteen years earlier. Jack also mentioned in his paper the notion of cyclone series following the same path, with the trailing cold front after one cyclone serving as a warm front of a new

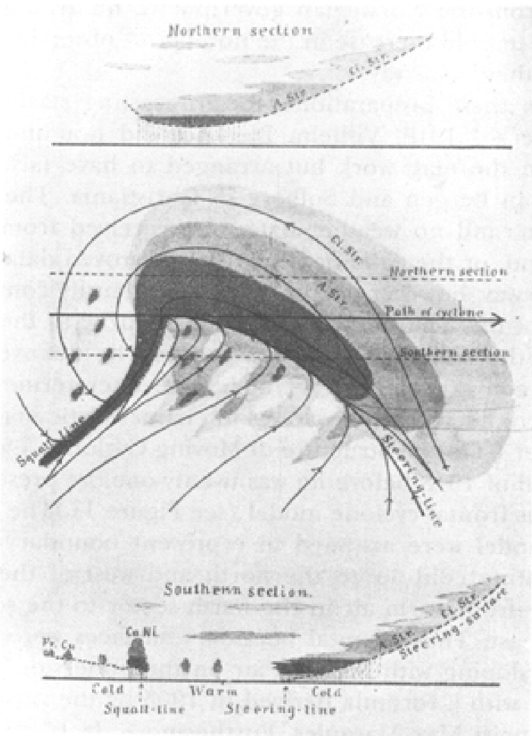

FIGURE 1 Jack Bjerknes's cyclone model: streamlines, clouds, and precipitation and vertical cross-sections north and south of the center. (From Bjerknes, 1919.)

cyclone farther west. He even discussed the role of cyclones in the general circulation of the atmosphere and ascribed to them a role as a link in the interchange of air between the polar regions and the equatorial zone.

On the whole, Jack's short paper of eight pages contained an abundance of very interesting thoughts and suggestions. It was a fantastic achievement for a twenty year old after a few months of work with weather maps from a limited part of Europe.

In the following years, Jack Bjerknes's frontal cyclone model was subject to intense study by the team consisting of Jack, Solberg, and Tor Bergeron, a Swedish student who joined the Bergen team in 1919. Solberg reanalyzed old weather maps from the Atlantic with many observations from ships. He found evidence that a polar front exists as an undulating line across most of the ocean, with new cyclones forming as growing waves on the front. Bergeron found that in a later stage of the cyclone's life, the cold front will overtake the warm front, lifting the warm sector air to higher levels, whereas the cold air spreads out along the ground. This process he called occlusion.

The Bergen team could now formulate a four-dimensional cyclone model, with a typical structure and a typical life cycle. As Theodor Hesselberg put it: "[The cyclone] is born as Solberg's initial wave on the polar front, develops into Jack Bjerknes's ideal cyclone, and finally suffers the Bergeronian occlusion death." It is noteworthy, however, that many of the features of the life cycle of cyclones were already contained in Jack's original paper, which he wrote in the fall of 1918.

In 1920 Jack Bjerknes was appointed head of the Weather Forecasting Office for western Norway. Here weather map analysis and forecasting were based on the frontal cyclone model. The frontal positions give information about winds, temperature, clouds, and precipitation; moreover, the shape of a frontal cyclone is indicative of its stage of development and can thus give information about its future behavior. The frontal cyclone model thus turned out to be an extremely useful tool in weather forecasting.

So far, the cyclone model was mainly based on observations from the ground; its vertical structure was mostly inferred from theory. In 1922 Jack Bjerknes went to Zurich in Switzerland as an invited consultant to the Swiss Meteorological Institute. By means of data from mountain peak observatories in the Alps, he could verify the existence of sloping frontal surfaces up to an altitude of 3,000 meters. For the paper he wrote about this investigation, he was awarded the degree of doctor of philosophy by the University of Oslo in 1924.

In 1928 Jack married Hedvig Borthen, daughter of a well-known ophthalmologist in Bergen. After some years, Jack and Hedvig settled into a house in Hop, south of Bergen, built on a lot bought from Hedvig's father.

THE UPPER WAVE

In the 1920s further exploration of air flow at higher elevations was hampered by lack of observations from these levels. However, during three consecutive days in December 1928 when two cyclones passed over Europe, P. Jaumotte, director of the Royal Belgian Meteorological Institute, launched thirty-one instrumented balloons at Uccle, Belgium. Of these, twenty-five were recovered. The recordings were analyzed by Jack Bjerknes, and the results were given in a paper that was one of his most brilliant. It contains probably the first description of the waves in the upper-tropospheric westerlies, which are connected with the cyclones at low levels. The wave trough was found to be located above the cold front at the ground, and the vorticity connected with this trough was correctly ascribed to vertical stretching as the warm air descends down the sloping cold front surface. This is the first attempt toward a dynamic treatment of the upper wave.

In 1931 Jack left the leadership of the Weather Forecasting Office in Bergen to Sverre Petterssen and took over a professorship of meteorology that was established for him at the Bergen Museum.

As radiosonde data in the 1930s became sufficiently numerous to make possible a systematic diagnosis of the motions in the upper troposphere, Jack was quick to exploit these new possibilities. In a number of papers, partly in cooperation with the Finnish geophysicist Erik Palmén, he constructed cross-sections through fronts and tropopause and showed how the cold front surface of one cyclone turns into the warm front of the next. In a paper from 1937 he pointed to the meridional gradient of the Coriolis parameter as an important quantity in the dynamics of upper waves. This work inspired Carl-Gustaf Rossby to derive his celebrated wave formula.

A close collaborator of Jack's in the 1930s was Carl Ludvig Godske, Vilhelm Bjerknes's Carnegie assistant who later succeeded Jack in the chair in Bergen. Godske and Jack wrote an interesting paper together on instability of fronts; and Godske wrote the greater part of an extensive volume titled *Dynamic Meteorology and Weather Forecasting*, coauthored by Godske, Bergeron, Jack Bjerknes, and R. C. Bundgaard. The book was planned by Vilhelm Bjerknes in the 1930s but was delayed by World War II and did not appear in print until 1959.

Jack Bjerknes's work in Bergen aroused the attention of his colleagues. He received visitors from many countries and went himself on trips to Switzerland, England, the Netherlands, Germany, Canada, and the United States as an invited guest lecturer.

WAR YEARS

In July 1939 Jack Bjerknes, with his family, went on what was supposed to be an eight-month lecture tour to the United

States. But on September 1 of that year, World War II began, and later came the German invasion of Norway. For Jack Bjerknes and his family, this had the consequence that they stayed in America and became U.S. citizens.

The threatening international situation made it imperative for the United States to educate a considerable number of meteorologists for military operations. Jack was asked to organize a training school for Air Force weather officers at the University of California. His wife recalls that he chose the Los Angeles campus for this undertaking in order to be near the Scripps Oceanographic Institution in La Jolla; he was of the opinion that cooperation with oceanographers was important. In 1940 he joined the faculty of the University of California at Los Angeles as professor of meteorology and head of the Section of Meteorology in the Department of Physics. He brought with him Jørgen Holmboe, a Norwegian meteorologist from the Bergen Weather Service who had spent three years in Rossby's department at MIT. During the war, Jack visited England, Italy, Hawaii, and Guam as a consultant to the U.S. Army Air Corps.

A NEW METEOROLOGY DEPARTMENT

In 1945 a new Department of Meteorology was established at the University of California at Los Angeles, with Jack Bjerknes as chairman. The new department grew fast and soon became one of the world's leading centers of teaching and research in the atmospheric sciences.

During the war, Jack, in collaboration with Holmboe, attempted to treat theoretically the problem of the growing cyclone with its associated upper wave. One cannot say they solved the problem, but they threw new light on it, and their work inspired their first doctoral student, Jule Charney, to come out with the first mathematical solution describing growing waves on a baroclinic current.

It had been known for many years that the atmospheric westerlies in middle latitudes increased with height and usually reached a maximum near the tropopause. For instance, a calculated distribution of the mean west wind in the meridional plane is given in *Physikalische Hydrodynamik,* the volume published by V. Bjerknes, J. Bjerknes, H. Solberg, and T. Bergeron in 1933. The improved wind measurements after the war revealed that the upper westerlies—the jet stream—are often much stronger than previously assumed. How was this strong current circumventing the earth, one in each hemisphere, maintained against frictional dissipation? The English mathematician and geophysicist Harold Jeffreys had already, in 1933, proposed an answer to this pressing question by suggesting that angular momentum could be transferred from low to middle latitudes by atmospheric waves and eddies. Based on Jeffreys's theory, Jack Bjerknes started a major research project on the general circulation of the atmosphere. His principal co-worker was Yale Mintz; but invited scientists from many countries participated. They collected data from the entire northern hemisphere and calculated meridional fluxes of angular momentum and energy and many other statistics. The results verified Jeffreys's thesis and were in reasonable agreement with results from Victor Starr and his group at MIT, who ran a similar project at the same time. Our quantitative knowledge of the general circulation was greatly advanced by these two research projects.

AIR-SEA INTERACTION ON A GLOBAL SCALE

Toward the end of the 1950s, when Jack Bjerknes was around sixty, he turned his mind to a new field of research that engaged him for the rest of his life—the interaction of atmosphere and sea.

Jack credits C. G. Rossby, H. U. Sverdrup, and Bjørn

Helland-Hansen for giving him inspiration and encouragement to take up this new field. These three scientists all died in 1957, when Jack was starting his oceanographic studies. Helland-Hansen belonged to an older generation; he had made pioneering studies of the Atlantic Ocean in cooperation with Fridtjof Nansen before and during World War I. Jack was his colleague in Bergen for twenty years and was familiar with his and Nansen's work.

Jack first took up the study of the warming of the North Atlantic Ocean at the beginning of the century and found that it could be explained by an increased wind drag that speeded up the Gulf Stream. The interannual variations of the sea surface temperature in the North Atlantic were his next study subject. He discovered that these temperature variations are connected with the strength of the westerlies. Years with particularly strong westerly winds in middle latitudes would display a typical pattern of sea surface temperature anomalies, with unusually cold water south of Iceland and Greenland and warmer water in the Gulf Stream outside the Grand Banks. In a series of papers he discussed the physical processes involved and gave qualitative explanations of the observed anomalies of the sea surface temperatures.

Jack's studies of the Pacific Ocean are even more remarkable. He began with an investigation of the El Niño phenomenon. Once every two to five years the cool nutrition-rich waters off the coast of Peru are replaced in the Southern Hemisphere summer by warmer sterile water, with a catastrophic result for Peruvian fishing and production of guano fertilizer from sea birds. These episodes are known as El Niño (the Holy Child, since they usually set in at Christmas time).

Jack found that El Niño is not a local phenomenon confined to the Peruvian coast but the manifestation of an oscillatory process that affects the atmosphere and the ocean over the entire tropical Pacific. During the El Niño years, a huge area of the eastern and middle equatorial Pacific may be as much as 2 K warmer than normal. To the atmosphere, such a disturbed Pacific Ocean must represent a very strong additional source of heat and moisture. The immediate effect is increased rainfall locally in the region of warm sea surface. But Jack also looked for manifestations of a strengthened Hadley circulation, and he found an increased west wind in the northern Pacific, with distant effects on the weather in North America and possibly also in Europe. These teleconnections over large distances recurred when new El Niño episodes occurred.

Jack also established a connection between the El Niño phenomenon and the southern oscillation, an irregular pulsation of atmospheric pressure between the Pacific and the Indian Oceans discovered by Sir Gilbert Walker in the 1920s. To account for variations in rainfall, Jack envisaged a vertical air circulation along the equator in the Pacific area, which he called the Walker circulation, since its strength would vary with Walker's southern oscillation. As a result of his investigations, we now have a coherent picture of these large-scale processes in the equatorial Pacific.

Jack Bjerknes's research on air-sea interactions is particularly important because these processes play an essential role in the theory of climate. Today, when the earth's climate is being threatened by human activities, research aiming at predicting possible climate changes is carried on vigorously in many countries. Such research, which is so vitally important to humankind, can build on Jack's results and the wealth of ideas contained in his papers.

CONCLUSION

Jack Bjerknes was active as a scientist for more than fiftyfive years. He was a modest and kind man, always generous with his time to listen to the problems of students and colleagues and always comforting them with his wise counsel and guidance. But he never wasted his time. His waking hours were devoted to work and studies of his problems, never in a great hurry but never stopping. He was very persistent; when he took up a problem, he would not let go of it until he had done his utmost to have it clarified.

Through the years many friends and colleagues enjoyed Jack and Hedvig's hospitality in their Santa Monica home. They also kept a house outside Bergen and often spent their holidays in Norway. Jack held contact with Norwegian colleagues, many of whom were invited to UCLA as visiting scientists.

More than any other atmospheric scientist, Jack Bjerknes managed to create order and system in a seemingly disorderly atmosphere. It is most remarkable that after seventy-five years his frontal cyclone model is still used as a principal tool in the world's weather services. Nobody knows how many lives have been saved through the years as a result of the improved methods of weather forecasting that Jack Bjerknes instituted.

IN PREPARING THIS MEMOIR I received very useful information and advice from Mrs. Hedvig Bjerknes and from Professors Morton G. Wurtele and Akio Arakawa. I also used information extracted from Robert Marc Friedman's book, *Appropriating the Weather* (Cornell University Press, Ithaca, N.Y., 1989). A very useful selection of Jack Bjerknes's papers, with a complete bibliography, was published by M. G. Wurtele (*Selected Papers of Jacob Aall Bonnevie Bjerknes,* Western Periodicals Co., North Hollywood, Calif., 1975).

HONORS AND DISTINCTIONS

Honorary Fellow, Royal Meteorological Society, 1932
Symons Medal, Royal Meteorological Society, 1940
Bowie Medal, American Geophysical Union, 1945
Meritorious Civilian Service Medal, U.S. Air Force, 1946
Royal Norwegian Order of St. Olav, 1947
Vega Medal, Swedish Society of Geography, 1958
International Meteorological Organization Prize, World Meteorological Organization, 1959
Carl-Gustaf Rossby Award, American Meteorological Society, 1960
Robert M. Losey Award, Institute of Aerospace Sciences, 1963
President, Meteorological Association, International Union of Geodesy and Geophysics, 1948-51
National Medal of Science, 1966
Honorary Member and Fellow, American Meteorological Society, 1966
Honorary Doctor of Laws, University of California, 1967
Member, Royal Norwegian Academy of Sciences, Royal Swedish Academy of Sciences, Danish Academy of Technical Sciences, Academy of Sciences (India), American Academy of Arts and Sciences, and National Academy of Sciences

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