V. Bjerknes

Ann. Rev. Fluid Mech. 1982. 14:1-11

VILHELM BJERKNES AND HIS STUDENTS

Arnt Eliassen
Institute of Geophysics, University of Oslo, Norway

Vilhelm Bjerknes' influence upon the advance of meteorology was only in part the result of his own scientific contributions in the field. These contributions were significant, and marked by his attitude as a theoretical physicist. However, of equal importance was his remarkable ability to attract and stimulate bright students and create an enthusiastic milieu around him. In this way he brought about a favorable recruitment of able scientists into the fields of meteorology and oceanography, without which these sciences would have been much poorer indeed.

Vilhelm Bjerknes' father, Carl Anton Bjerknes, was professor of mathematics at Norway's only university in Oslo, or Christiania as the city was called at the time. He was exploring the forces between bodies moving in a fluid, and found a striking analogy between these forces and electrostatic and magnetic forces. In particular, he found that two spheres submerged in water, pulsating at the same frequency, would be acted upon by attractive or repellant pressure forces which would satisfy Coulomb's law, except that they would have the opposite direction: attraction would result when the pulsations were in phase, repulsion when the phases were opposite. Moreover, the streamlines in the fluid would have the same shape as the lines of force between electric charges. Likewise, the forces between rotating cyclinders in a fluid would be similar to the forces between electric currents.

As a young student, Vilhelm Bjerknes closely followed his father's research and assisted him in hydrodynamic experiments which successfully verified the theory. This was at a time when electromagnetic action at a distance and the existence of an "aether" were much debated, and C. A. Bjerknes thought that he might be on the track of a kind of hydrodynamic theory of electromagnetism.

Vilhelm Bjerknes studied science at the University of Christiania. After graduating he spent two years with Heinrich Hertz at Bonn. During these years he made valuable (but now probably forgotten) contributions to the

0066-4189/82/0115-0001$02.00

theory of electromagnetic waves and resonance. In 1893 he came to the University of Stockholm where he two years later was appointed professor of mechanics and mathematical physics.

In Stockholm Vilhelm Bjerknes took up his father's ideas and spent several years trying to carry the theory of the hydrodynamic-electromagnetic analogy to a completion. It was in connection with these investigations that in 1897 he discovered the circulation theorem which carries his name, and which ex'
in a fluid will change as a result of baroclinicity (V. Bjerknes 1898). This discovery caused Bjerknes to enter the field of geophysics. He immediately saw that his theorem was just what was needed to explain the formation of circulatory motions in the atmosphere and the ocean, and he set out to exploit the idea.

The classical hydrodynamics at the time was based on Helmholtz' and Kelvin's theorems on vortex conservation (in the absence of viscosity). These conservation theorems were based on a fluid model in which baroclinicity was not possible; even the concept seemed to have been left out of consideration. Either the fluid was assumed homogeneous and incompressible, or, if compressible, it was assumed that the density would depend upon pressure only, and in the same manner for all fluid particles.

Bjerknes realized that such fluid models, which he later termed *autobarotropic,* are too restrictive to represent air or seawater in motion. To explain the maintenance of circulatory motions in the atmosphere or the ocean, a *general fluid model* is required, in which the pressure of a particle does not determine its state, or density. The density of a particle changes not only because of pressure changes, but also as a result of heat sources. Thus a link between the motion and the heat sources was established; the relevant theory is a combination of hydrodynamics and thermodynamics, which Bjerknes called *physical fluid dynamics.*

As an intermediate fluid model, Bjerknes introduced the *piezotropic fluid*, where the density of every particle is a unique function of its pressure, but where this relationship in general is different for different particles. This model permits baroclinicity and is suited for the study of oscillations and waves. Bjerknes' classification of fluid models is very useful, and, in the author's opinion, it is unfortunate that his terminology has not been generally adopted in fluid dynamics.

With the circulation theorem and the concept of a general fluid for which the density would change as a result of heating (and possibly also by change in composition), Bjerknes realized that he could for the first time formulate a complete set of hydro- and thermodynamic equations that govern the processes in the atmosphere. Consequently he proposed (Bjerknes 1904) attacking the problem of weather prediction as an initial-value problem of mathematical physics, where the initial state was to be determined from observations, and the future change from integration of the governing equations. In 1905 he got the opportunity to lecture about this bold program in Washington, D.C. This resulted in a yearly grant from the Carnegie Institution, which he retained for about 35 years, until the Second World War. The money could hardly have found a better use. During the years, it enabled Bjerknes to employ a considerable number of research assistants, all of whom later became well-known geophysicists.

In the years 1893—1896, Fridtjof Nansen and his crew crossed the Arctic Ocean, partly on board the FRAM, and partly on skis. He returned with a wealth of observations and experiences, and also with many unexplained problems. One question which Nansen discussed with Vilhelm Bjerknes was the so-called "dead-water" phenomenon. This is a mysterious ship resistance that occurs suddenly, as if the ship were held back by an evil ghost. The phenomenon had been observed on the FRAM near the Siberian coast. Bjerknes suggested that it was a wave resistancc due to internal waves on the interface between relatively fresh surface water and more saline water underneath. He gave the problem to his young Swedish student Vagn Walfrid Ekman, who made a thorough laboratory study of the phenomenon, and also a theoretical investigation, based on the work on surface waves by Stokes and Kelvin. Ekman's results, which were published as part of the scientific results of the FRAM expedition, fully confirmed that the dead-water phenomenon was indeed caused by internal gravity waves.

Today Ekman's name is connected with his analysis of the viscous boundary layer in the presence of rotation. This work, too, emerged from a discussion, in the year 1900, between Nansen and Bjerknes. During FRAM's drifting in the arctic ice, the direction of the ice drift showed a systematic deviation to the right relative to the wind direction. Nansen attributed this deviation to the earth's rotation and correctly concluded that, for the same reason, the deviation angle of the current direction must increase downwards in the sea. Bjerknes proposed that Nansen also give this problem to Ekman. He was called, and came out the same evening with the celebrated Ekman spiral equations.

Ekman was early aware (in a paper from 1906) that his theory was applicable also to the atmospheric boundary layer. He noticed, however, that the angle between the surface wind and the isobars was considerably less than the 45° demanded by his theory. This discrepancy he correctly explained as a result of a downwards decrease of the eddy viscosity in the lowest air layers. He suggested that this could be accounted for by introducing a slip at the earth's surface in the direction of the spiral tangent; this would reduce the angle between the surface wind and the isobars. G. I. Taylor proposed the same theory in 1915, without knowing Ekman's work.

In 1910 Ekman was appointed professor of mechanics and mathematical physics at the University of Lund (Sweden). In his later work on ocean currents, he aimed towards a theory that would combine the effects of surface wind stress, bottom friction, and horizontal pressure gradients.

Another of Bjerknes' students in Stockholm was Johan Wilhelm Sandström. In contrast to Ekman, who had grown up in an academic milieu, Sandström came from a small farm in Northern Sweden. For many years he assisted Bjerknes in calculating tables and graphs for the practical application of the circulation theorem in meteorology and oceanography. Sandström was employed as Bjerknes' first Carnegie assistant. Their cooperation resulted in the first volume (*Statics*) of the work *Dynamic Meteorology and Hydrography*, which appeared in 1910. It contained, among other things, a detailed description of how to construct topographic maps

Vagn Walfrid Ekman

for a set of isobaric surfaces in the atmosphere by starting at the surface and working upwards by successively adding maps of relative topography. The method secures a vertical consistency that is not always present in the methods of analysis used today.

Sandström later worked in the Swedish Meteorological-Hydrological Service. Among his scientific contributions was a theorem which states that the maintainance of a thermal circulation against frictional dissipation requires the heat source to be located at a lower level than the cold source. He went on oceanographic expeditions in the North Atlantic and studied the effect of the warm Gulf Stream on the climate of Western Europe.

In 1907 Vilhelm Bjerknes was called to a chair at the University of Christiania. The next year he employed two young Norwegian science students as his Carnegie assistants: Theodor Hesselberg and Olaf Devik. The latter was succeeded in 1911 by another science student, Harald Ulrik Sverdrup. These three men all became prominent geophysicists in three different fields: Hesselberg in meteorology, Sverdrup in oceanography, and

Harald Ulrik Sverdrup

Devik in hydrology. With the assistance of Hesselberg and Devik, Bjerknes in 1911 published the second volume (*Kinematics*) of *Dynamic Meteorology and Hydrography.* A third volume (*Dynamics*) was planned, but never finished.

Hesselberg and Sverdrup worked for some years in close cooperation, resulting in a series of joint papers, in particular on turbulent friction and variation of wind with height. Much of this work was done at the new Geophysical Institute in Leipzig which was established in 1913 with Bjerknes as Director.

One of Hesselberg's papers from this time is remarkable in that it anticipates the modern theory of the geostrophic momentum approximation. In 1915 Hesselberg went to Oslo to take over as Director of the Norwegian Meteorological Institute, a position he held for forty years. In these later years he studied recent climate variations. Together with his associate B. J. Birkeland, he was one of the first to detect and map the great warming trend of the first half of our century. Hesselberg also did much to further international cooperation which is so important in meteorology, and he was President of The International Meteorological Organization from 1935 to 1947.

Theodor Hesselberg

H. U. Sverdrup's main work during the time he spent in Leipzig was his very thorough meteorological study of the structure of the North Atlantic trade-wind region. In another remarkable paper he estimated the average dissipation of mechanical energy into heat in the atmosphere to be 4 watts m^{-2}, which is not far from modern estimates.

Sverdrup's later career is remarkable indeed. He spent seven years with Roald Amundsen's polar expedition on the MAUD, in charge of the scientific investigations, ten years as professor in Bergen, then twelve years (1936–1948) as Director of Scripps Institution of Oceanography in California, and finally his last nine years in Oslo as Director of the Polar Institute and professor at the University. His scientific contributions cover a broad spectrum of the geophysical sciences, with physical oceanography as the main theme. It is not possible here to describe his many-sided activities; readers are referred to a biographic article by Revelle & Munk (1948).

Let us now return to Vilhelm Bjerknes in Leipzig. When Hesselberg and Sverdrup left, Bjerknes employed two young Norwegians as his next Carnegie assistants; they were his son Jack Bjerknes and Halvor Solberg.

Halvor Solberg

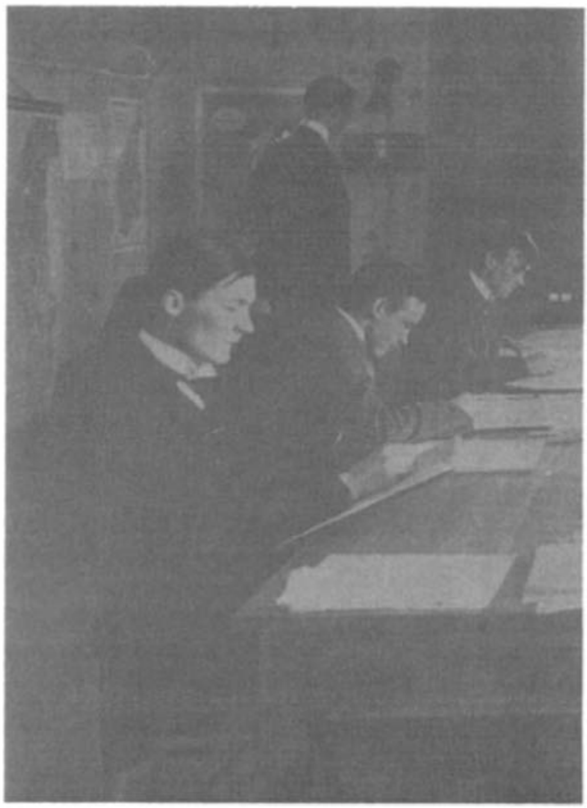
This was during the First World War, and the situation at the Geophysical Institute became difficult. Most of the German students and associates were called to the front. In 1917, Bjerknes left Leipzig and went with his two Carnegie assistants to Bergen where he had been invited to found a Geophysical Institute.

Thirteen years had elapsed since Bjerknes had put forward his ambitious program to forecast the future states of the atmosphere by integrating the governing differential equations. Undoubtedly, he had thought much about how to solve the mathematical problem, but at this stage he had not proceeded very far. The complicated nonlinear equations would not easily disclose the information which they contained. In this situation, Bjerknes began to study the simpler linearized equations. Cyclones, he reasoned, must in their formative stage necessarily be weak and therefore tractable by linear equations. He writes (Bjerknes et al. 1933, p.785, the author's translation): "However, linear equations always seem to have as solutions stable or unstable *wave motions. Also the atmospheric perturbations, the cyclones, must therefore begin as waves.* So far, I had not the slightest idea of how the transition from the as yet unobserved wave to the well-known vortex was to be conceived."

This mysterious transition, however, was soon after found on the weather map. In Bergen, Jack Bjerknes put forward his model of the frontal cyclone. Solberg studied old weather charts over the North Atlantic and could demonstrate the existence of the polar front and the formation of frontal-wave disturbances which grew into frontal cyclones of the type found by Jack Bjerknes. The picture was completed by the Swede Tor Bergeron, who in 1919 joined V. Bjerknes' Bergen team. He found that as the cyclone grew older, its warm sector would collapse or occlude so that finally the cold air would cover the whole cyclone at low levels, while the warm air had been lifted to higher levels. The result was a four-dimensional cyclone model, with a typical change of structure during its life cycle. As Hesselberg once put it: "The cyclone is born as Solberg's initial wave on the polar front, develops into Jack Bjerknes' ideal cyclone, and finally suffers Bergeron's occlusion death."

In an attempt to recruit new meteorologists, Vilhelm Bjerknes went to Sweden and offered jobs in Bergen for interested students for the summer 1919. One of those who responded was Carl-Gustaf Rossby, who at the time was studying mathematics, mechanics, and astronomy in Stockholm. According to Bergeron (1959), in his masterly biographic article about Rossby, it is quite unlikely that Rossby would have become a meteorologist without Bjerknes' intervention. On the other hand, although Rossby got his first meteorological training in Bergen, he did not stay there long, and it may be misleading to call him a student of Vilhelm Bjerknes. Rossby never quite accepted the Bergen ideas with the polar front as the principal weather-producing agent. When the upper-air weather maps became available in the 1930s, Rossby directed his attention towards motion systems of larger scales, in particular the long waves of the upper westerlies. His barotropic model and famous wave formula formed the basis for new ideas which have been of the greatest importance for meteorology and oceanography.

During the 1920s and 1930s the three creators of the polar-front meteorology extended and deepened their concepts and ideas. Jack Bjerknes studied the three-dimensional structure of the frontal cyclones and the air flow in the upper troposphere. From 1940, Jack Bjerknes was professor of meteorology at the University of California, Los Angeles. Under his direction in cooperation with Jörgen Holmboe, the Meteorology Department at UCLA became one of the leading research centers in the field. Holmboe, also, had started his meteorological career as one of Vilhelm Bjerknes' Carnegie assistants; at UCLA, he worked with Jack Bjerknes on cyclone



Tor Bergeron, Carl-Gustaf Rossby, Svein Rosseland (left to right), Vilhelm Bjerknes (standing) dynamics. For further information about Jack Bjerknes' remarkable research activity, the reader is referred to articles by Charney (1975), Mintz (1975), and Namias (1975).

Tor Bergeron, likewise, became one of the great meteorologists of his generation. After the war he was professor of meteorology at the University of Uppsala, Sweden. One of his many contributions, in particular, was his explanation of how fronts are formed in the atmosphere. Moreover, he laid the basis for air-mass analysis and developed this into a very useful prognostic tool. His work in cloud physics has been of fundamental importance for the development of that field (biographic notes: Eliassen 1978, Blanchard 1978).

Following the empirical discoveries of the Bergen school, Solberg attacked the problem of the growth of frontal waves mathematically, on the basis of linearized equations. He began with a systematic investigation of wave motions. In addition to the known acoustic and internal gravity waves, his equations indicated the existence of a third wave type, provided the fluid was rotating. A physical interpretation of these inertia waves was given in 1929 by Vilhelm Bjerknes and Solberg in a joint paper. Here they demonstrate that a barotropic vortex possesses an internal stability if its specific angular momentum increases with increasing distance from the axis. Strangely enough, they were not aware that Rayleigh had given the same criterion for rotational stability already in 1916. However, Solberg was probably the first to give a mathematical treatment of internal inertia waves.

Solberg proceeded to study waves on a sloping "front" or interface between two zonal air currents of different density. Among several different wave types, he found one which he considered to correspond to a growing cyclone wave. It is difficult today to judge his work. He was not able to satisfy the boundary condition for a level ground which intersects the sloping interface, and introduced, instead, two sloping rigid boundaries parallel with the undisturbed interface. As we now know from the work of Charney & Stern and Pedlosky, such a change of boundary conditions may change the quasi-geostrophic stability properties of the system. However, the growth of frontal waves has later been convincingly demonstrated theoretically by E. Eliasen and Orlanski. Of Solberg's later work, his 1936 analysis of the "symmetric" stability of a baroclinic circular vortex is particularly important.

In 1926, Vilhelm Bjerknes came to the University of Oslo as professor of mechanics and theoretical physics. Together with his Bergen team he published a textbook on physical fluid dynamics which contained a comprehensive account of the results and methods of the Bergen school, including much of Solberg's wave theory, and, in addition, two chapters on the old hydrodynamic-electromagnetic analogies (V. Bjerknes et al. 1933). In this work he had valuable help from his Carnegie assistant Carl Ludvig Godske, who later took over the chair in Bergen that became vacant when Jack Bjerknes went to UCLA. Godske took up agro-meteorology and micro-climatology as his special field of research.

Vilhelm Bjerknes' last Carnegie assistant (from 1935) and collaborator for many years was Einar Høiland. Together they held weekly seminars on meteorology, hydrodynamics, thermodynamics, and statistical physics which attracted inquisitive students. Both Ragnar Fjørtoft and the author of this article were captured for meteorology in this way. After the war, Høiland became professor of hydro- and aerodynamics at Oslo. Like his teacher Vilhelm Bjerknes, he too had a great talent for attracting and inspiring students.

Vilhelm Bjerknes was born in 1862. Biographical articles about him by Bergeron, Devik, and Godske (1962) are found in the *V. Bjerknes Centennial Volume* of *Geophysica Norvegica*. For several years after the war, when Bjerknes was in his eighties, he still came every day to his office in the Astrophysics Building, which also housed the geophysicists at the University of Oslo. He was an ardent listener to seminars and thus gave his encouragement and moral support to the research activity around him. He remained, as he had always been, a source of inspiration to younger generations.

Literature Cited

Bergeron, T. 1959. The young Carl-Gustaf Rossby. In *The Atmosphere and the Sea in Motion* (The Rossby Memorial Volume), ed. B. Bolin, pp. 51–55. New York: The Rockefeller Institute Press

Bergeron, T., Devik, O., Godske, C. L. 1962. *Geof. Publ. 24*: 7–25 (*V. Bjerknes Centennial Volume*)

Bjerknes, V. 1898. Über die Bildung von Circulationsbewegungen und Wirbeln in reibungslosen Flüssigkeiten. *Videnskabsselskapets Skrifter. I Math. Naturv. Klasse, No. 5*

Bjerknes, V. 1904. Das Problem der Wettervorhersage, betrachtet vom Standpunkte der Mechanik und der Physik. *Meteor. Zeitschr.* 21:1–7

Bjerknes, V., Bjerknes, J., Solberg, H., Bergeron, T. 1933. *Physikalische Hydrodynamik*, pp. 777–90. Berlin: Springer. 797 pp.

Blanchard, D. C. 1978. Tor Bergeron and his autobiografic note. *Bull. Am. Meteorol. Soc.* 59: 389–92

Charney, J. G. 1975. Jacob Bjerknes—an appreciation. In *Selected papers of Jacob Aall Bonnevie Bjerknes*, ed. M. G. Wurtele, pp. 11-13. North Hollywood, Calif: Western Periodicals Company. 606 pp.

Eliassen, A. 1978. Tor Bergeron. *Bull. Am. Meteorol. Soc.* 59: 387–89

Ekman, V. W. 1906. Beiträge zur Theorie der Meeresströmungen. *Ann. Hydrogr. Marit. Meteor.* 1906: 1–50

Mintz, Y. 1975. Jacob Bjerknes and our understanding of the atmospheric general circulation. In *Selected papers of J. Bjerknes*, ed. M. G. Wurtele, pp. 14–15. North Hollywood, Calif: Western Periodicals Co. 606 pp.

Namias, J. 1975. The contributions of J. Bjerknes to air-sea interaction. In *Selected Papers of J. Bjerknes*, ed. M. G. Wurtele, pp. 16–18. North Hollywood, Calif: Western Periodicals Co. 606 pp.

Revelle, R., Munk, W. 1948. Harald Ulrik Sverdrup—an appreciation. *J. Marine Res.* 7:127–31.