Tor Harold Percival Bergeron

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Bergeron, Tor Harold Percival (*b*. Godstone, Surrey, England, 15 August 1891; *d*. Uppsala, Sweden, 13 June 1977), *synoptic meteorology, cloud and precipitation physics, weather forecasting*.

Bergeron was one of the principal scientists in the Bergen School of Meteorology, which transformed this science by introducing a new conceptual foundation for understanding and predicting weather. While developing innovative methods of forecasting, the Bergen scientists established the notion of weather fronts and elaborated a new model of extratropical cyclones that accounted for their birth, growth, and decay. Bergeron is credited with discovering the occlusion process, which marks the final stage in the life cycle of an extratropical cyclone. Bergeron also contributed to cloud physics, most notably the description of the Bergeron–Findeisen process by which precipitation forms inside a cloud containing both ice crystals and water droplets.

The Early Years

Bergeron was born in England to Swedish parents and raised in Sweden. His mother knew Nils Ekholm, director of the Swedish Meteorological Institute (SMI), which proved valuable for the young Bergeron. After receiving his B.Sc. from the University of Stockholm in 1916, Bergeron spent the summers taking observations of visibility at different locations around Sweden and returning to SMI in Stockholm during the autumn to complete his research. He found that changes in visibility seemed to be related to wind-shift lines (what would be later called fronts). On 1 January 1919, Bergeron received the title of "extra assistant meteorologist" at the reorganized SMI, now called the Swedish Meteorological and Hydrological Institute (SMHI). Within a few months, the tiny core of the incipient Bergen School, father and son Vilhelm and Jacob Bjerknes and Halvor Solberg, recruited Bergeron to Bergen, Norway to join a new weather forecasting service.

The Bergen School and the Occlusion Process

In 1917, the Bergen Museum (precursor for Bergen University) called Vilhelm Bjerknes to a new professorship in meteorology. Bjerknes had been working in Leipzig on a research program for creating an exact physics of the atmosphere and ocean. In contrast, meteorologists at the time predicted weather primarily by often inaccurate empirical rules of thumb and statistical insight. Upon coming to Bergen in 1918, Bjerknes organized an experimental weather prediction service, directing a number of enthusiastic young scientists in developing new forecasting practices based on insight into physical processes. The impact of the work performed in Bergen, combined with the incubation of several high-quality scientists, had an immense impact internationally on the burgeoning scientific field of meteorology.

Much of the earliest work in Bergen focused on understanding the structure of extratropical cyclones. Based on the first summer's forecasting, Jacob proposed in November 1918 a new model for these disturbances which accounted for their asymmetric distribution of precipitation (Fig. 1). The basic structure was described as a counterclockwise swirl of air around the low-pressure center. Warm air advancing from the south rose up over cold air retreating northward on the east side of the low center.

The boundary between the two was ultimately called a *warm front*. On the southwest side of the low center, dense cold air advancing from the north lifted the warm air, forming a boundary later called a *cold front*. The recently ended World War I inspired using the word *front* to describe battle lines of advancing and retreating air masses. [Bergeron would later suggest the symbols now used for cold and warm fronts (lines with filled triangles and semicircles, respectively) on a postcard to Jacob Bjerknes on 8 January 1924.]

During the fall of 1919, Bergeron noticed that the cold front at times seemed to catch up to and overtake the warm front, what he dubbed *sammenklapping* (roughly "coming together" or "closing up"). He intuited that the cold front probably rode aloft over the warm front, but he remained puzzled over the nature and significance of this finding. It was not clear whether *sammenklapping* entailed an evolutionary component of extratropical cyclones or simply a local geographical effect. Furthermore, Jacob resisted changes to his model.

While in Stockholm and Bergen, Bergeron returned on occasion to this baffling phenomenon. International efforts to increase the amount and frequency of weather data enabled Bergeron to bring into clearer focus the cyclone's structure. He arrived at a convincing three-dimensional representation by which a cold front and warm front merged, resulting in the previously sandwiched warm air being lifted aloft. Without access to the warm air fueling the storm, such a cyclone would weaken. Eventually, Bergeron used the term *occlusion* for this process, and the resulting boundary between the two cold air masses was called an *occluded front*. By 1922, he convinced Jacob of the importance of this process to the evolution of extratropical cyclones. This discovery, along with Solberg's concept of cyclone families, changed the Bergen cyclone model from a static conceptualization (Fig. 1) into one that featured the entire life cycle of birth, maturity, and death (Fig. 2). Forecasters and theoreticians now had a model to help them understand the processes affecting storm intensification and decay.

Occlusion is a seminal feature of the classic 1922 paper by Jacob and Solberg, "Life Cycle of Cyclones and the Polar Front Theory of Atmospheric Circulation," yet Bergeron was not a co-author. At the time, Bergeron was in Stockholm where he was preoccupied with other tasks, including preparation of a supplemental manuscript, which never was completed. Bergeron was a perfectionist, oftentimes not completing publications for want of further analysis. And whereas Solberg and the Bjerkneses accepted the need to simplify when presenting the new findings, Bergeron aimed to depict all the new insights in their full complexity. By temperament and principle, he could not easily collaborate with the others in writing what he considered a much too hastily prepared publication. Although he was not a co-author, his Bergen colleagues always gave him full credit in discovering occlusion, the capstone of the Bergen school's early achievements.

Indirect Aerology and Air-mass Analysis

To convince others of the reality and importance of fronts, the Bergen meteorologists needed to create systematic methods to reproduce them reliably in daily forecasting work.

Although all members of the emerging Bergen school contributed towards this goal, Bergeron played a crucial role in establishing innovative forecasting practices.

Bergeron collaborated with Swede and close friend Ernst Calwagen to bring greater clarity to an ever-growing number of new but elusive phenomena emerging from the analysis of weather maps. To achieve this goal, they sought to refine and systematize the Bergen group's innovative methods for observing and analyzing weather. They brought to maturity a method of *indirect aerology*, which allowed identifying fronts and tracking the life history of large homogeneous bodies of air called air masses. At a time when direct measurement of the atmosphere through weather balloons and kites above the surface (aerology) was not available for daily forecasting, this method combined observation of the clouds and sky overhead with analyses of phenomena plotted on the weather map to envision the physical processes occurring in a three-dimensional atmosphere. With the help of the Norwegian military air forces, Calwagen began to supplement the indirect aerological methods with direct vertical measurements in the atmosphere. While taking observations on 10 August 1925, Calwagen was killed after the airplane fell apart in mid-air. Calwagen's death deeply affected Bergeron—he never flew again. Bergeron took over his friend's work, integrated it with his own, and helped bring the methods of air-mass analysis to maturity. Indirect aerology enabled the Bergen meteorologists to achieve more accurate and detailed predictions, as well as to gain insight into the nature of fronts, cyclones, and air masses. For Bergeron as well as other members of the Bergen school, so-called synoptic meteorology was a legitimate means for winning new knowledge of the atmosphere, an equal partner to theoretical and mathematical study.

The Bergeron–Findeisen Process

When Bergeron returned to Bergen in 1922, he stopped for several weeks at a health resort at Voksenkollen, a hill north of Oslo often enclosed by fog. Bergeron noted that when the temperature was well below freezing the roads through the forest were clear of fog (Fig. 3). When the temperature was above freezing, however, the fog would extend down to the ground (Fig. 3). Bergeron recognized that the saturation water-vapor pressure over water is higher than that over ice at temperatures below freezing. Thus, he surmised that diffusion of water vapor from evaporating supercooled liquid-water droplets in the fog to frost growing on the trees might have been occurring to disperse the fog. Although Alfred Wegener had already argued in 1911 that such growth was possible in a cloud with both ice and water droplets, Bergeron was the first to recognize that this could lead to precipitation. These ideas would be briefly developed in his doctoral thesis in 1928, and presented more fully in 1933. Coupled with experimental confirmation by the German Walter Findeisen in 1938, this process of forming precipitation in a cloud possessing both ice crystals and supercooled liquid water droplets was eventually called the Bergeron–Findeisen process (sometimes called the Wegener–Bergeron–Findeisen process). This discovery promoted the subsequent growth of cloud physics as a vital subdiscipline, not the least by providing a means to dissipate fog and a physical mechanism for precipitation enhancement through cloud seeding.

Apostle of the Bergen School

More than any other member of the Bergen School, Bergeron provided the detailed case studies, lectures, and travel needed to develop grassroots support abroad for the Bergen School concepts and methods. His role as apostle was facilitated by his linguistic talents: he spoke seven languages and knew some of three others.

While employed during the early and mid 1920s by the Norwegian Meteorological Institute, Bergeron spent time in Leipzig, working with Gustav Swoboda to demonstrate the applicability of the Bergen School concepts in an analysis of a weather event over Europe. "Wellen und Wirbel an einer quasistationären Grenzfläche über Europa" [Waves and Vortices at a Quasistationary Frontal Surface over Europe] (1924) was the first detailed publication to use the methods developed in Bergen. Bergeron wrote Part I of his "Über die dreidimensional verknüpfende Wetteranalyse" [Three-Dimensionally Combining Synoptic Analysis] in 1928, for which he received a doctoral degree from the University of Oslo. That paper covered many disparate topics, including air-mass analysis and frontogenesis (the process of forming and strengthening a front). Bergeron recognized that fronts were found in regions where the streamlines in the horizontal flow of air form a hyperbolic deformation field. What had been considered an uninteresting singularity in the field of flow—the neutral point or col—held the key for understanding where and when fronts form. Bergeron showed that such flows tended to occur between the semi-permanent highs and lows, explaining the climatological locations of fronts around the world.

After completing his doctorate, Bergeron traveled to Malta and the Soviet Union to lecture on the Bergen School methods. Part II of his doctoral thesis on fronts and their perturbations was published in Russian in 1934. But his overly critical demands impeded publishing his own research and completing several books. Still, he produced several texts that played critical roles in the diffusion of the Bergen meteorology. Although many of Bergeron's papers remain unpublished, his popular lecture notes served as foundations of major textbooks on synoptic meteorology written by his colleagues in Russian, English, and German.

In 1935 Bergeron failed in his bid to be appointed professor of meteorology at Uppsala University. Bergeron and his many supporters from abroad could not overcome local bias against synoptic meteorology, which was considered inferior to laboratory-based research, as well as a long-standing resentment against Bjerknes and the 'Norwegian' achievements with which he was intimately associated. Bergeron returned to Stockholm in 1936, initially as a meteorologist, but eventually scientific chief of SMHI. He began giving lectures and exercises based on the Bergen methods. These proved popular, although at times his perfectionist goals for precision in map analysis and in the wording of predictions created tension. Legend has it that he insisted on the exclusive use of a particular brand of colored pencils if accurate weather maps were to be drawn. Within two years, however, the quality of Swedish forecasting had significantly improved. Often, meteorologists came from abroad to Bergeron for training. During this time, Bergeron also served on the Commission of Synoptic Meteorology of the World

Meteorological Organization, being influential in the development of the international terminology and classification of clouds and precipitation.

Uppsala University

By the time World War II ended, Sweden had a great shortage of meteorologists, especially for its rapidly growing aviation interests. Practical weather forecasting classes were not offered at the universities, and an official report indicated the need for a professorship in this subject. Although efforts were underway to create such a professorship for him in Stockholm, in 1947 Bergeron became professor and head of the Department of Synoptic Meteorology at Uppsala University. Despite Bergeron's reputation, finding students was difficult, especially after Carl-Gustaf Rossby established an active department at Stockholm. Nevertheless, he persisted in lecturing and writing on the principles of meteorology.

Slowly, he returned to the topic of cloud physics. Bergeron posited that ice crystals could fall from high-altitude clouds into liquid-water clouds below. Such a *seeder–feeder process* could enhance precipitation at the ground. He also wrote about the feasibility of artificially stimulating the production of precipitation from a synoptic and cloud-physics perspective.

In 1953, Bergeron started Project Pluvius, a research program designed to better understand precipitation by establishing high-resolution surface rainfall networks. Among its rich research results, Project Pluvius showed that modest orography of only

40–70 m could produce orographic precipitation enhancement. Bergeron retired in 1961, but continued to work on Project Pluvius. He spent more time traveling and lecturing worldwide, including several trips to the United States. He died in 1977 of pancreatic cancer, the last of the original Bergen School meteorologists to pass away.

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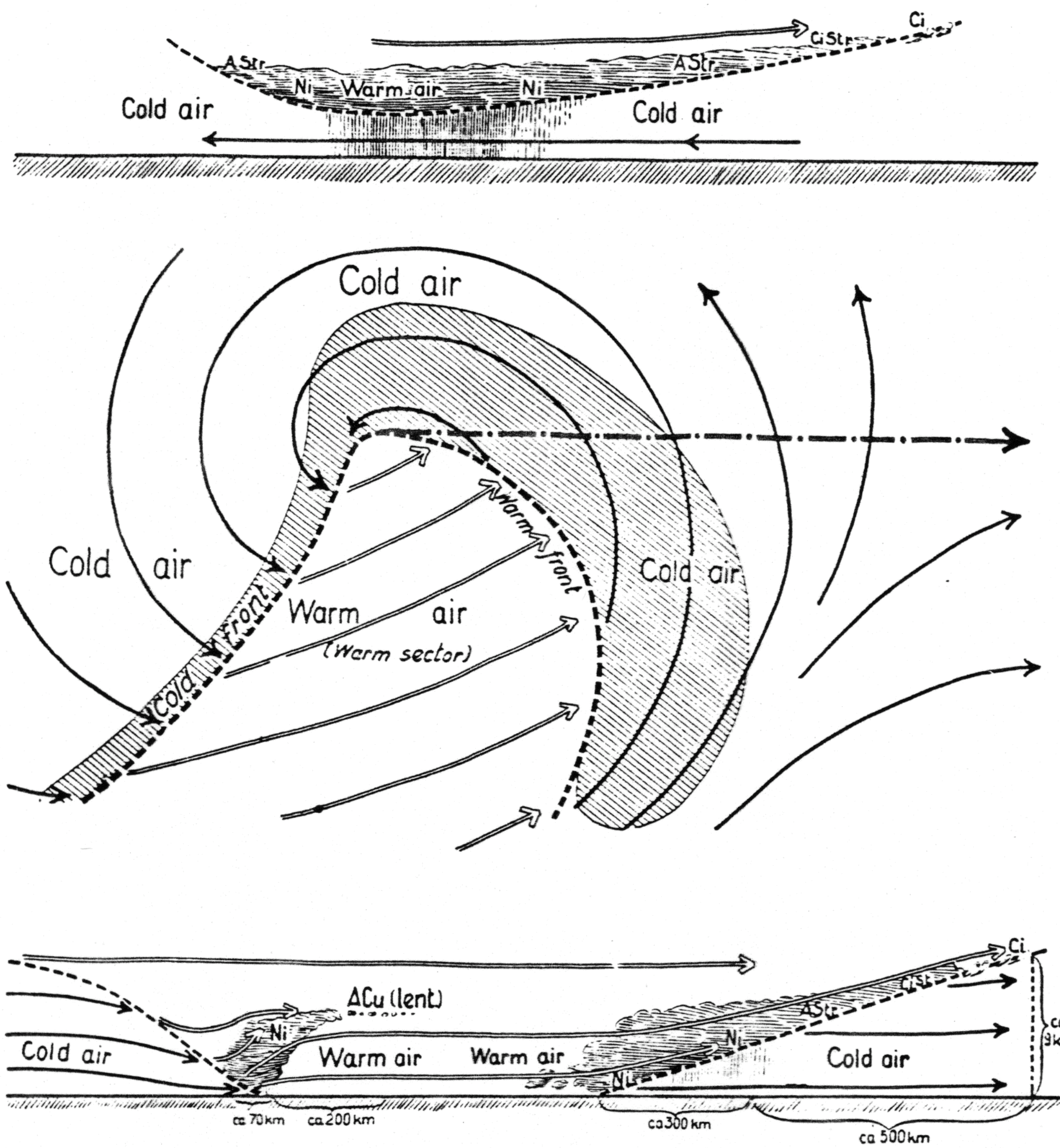

Figure 1. Schematic of the extratropical cyclone model proposed by the Bergen School of Meteorology. (From Bjerknes, Jacob, and Halvor Solberg. "Meteorological Conditions for the Formation of Rain." *Geofysiske Publikasjoner* 2 (3, 1921): 3–60.)

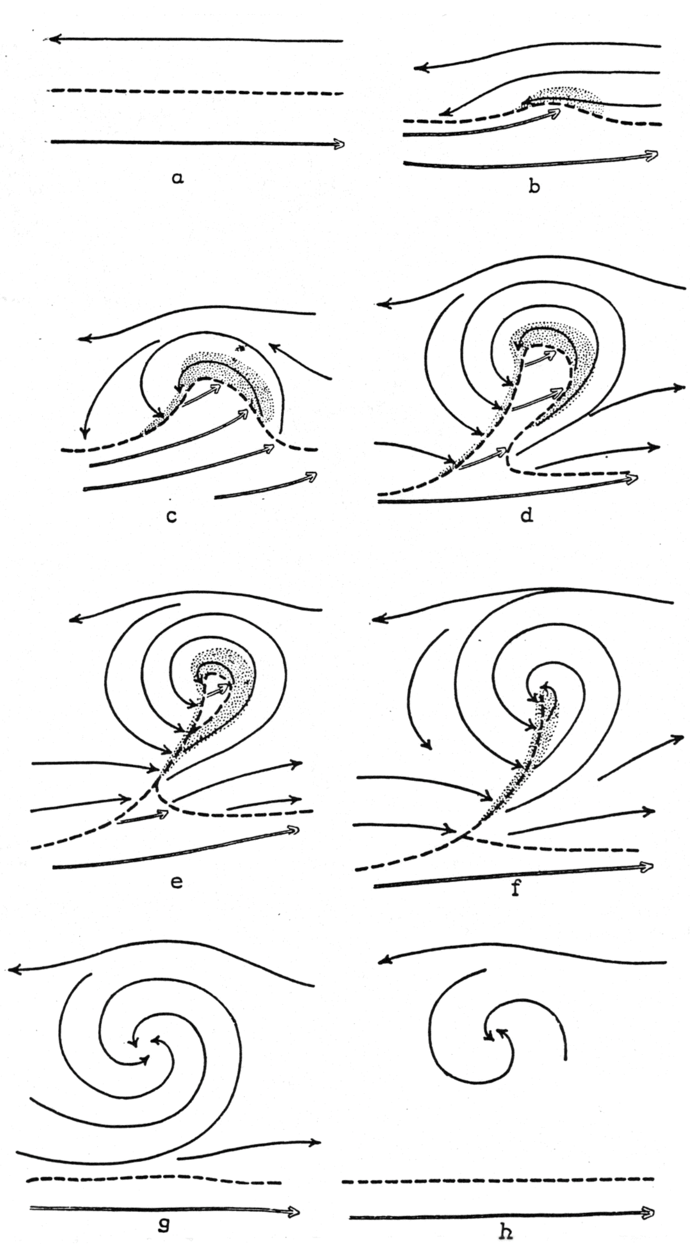

Figure 2. Schematic life cycle of the extratropical cyclone model proposed by the Bergen School of Meteorology. Dashed lines represent surface fronts; arrows represent streamlines of the flow. (From Bjerknes, Jacob, and Halvor Solberg. "Life Cycle of Cyclones and the Polar Front Theory of Atmospheric Circulation." *Geofysiske Publikasjoner* 3 (1, 1922): 3–18.)

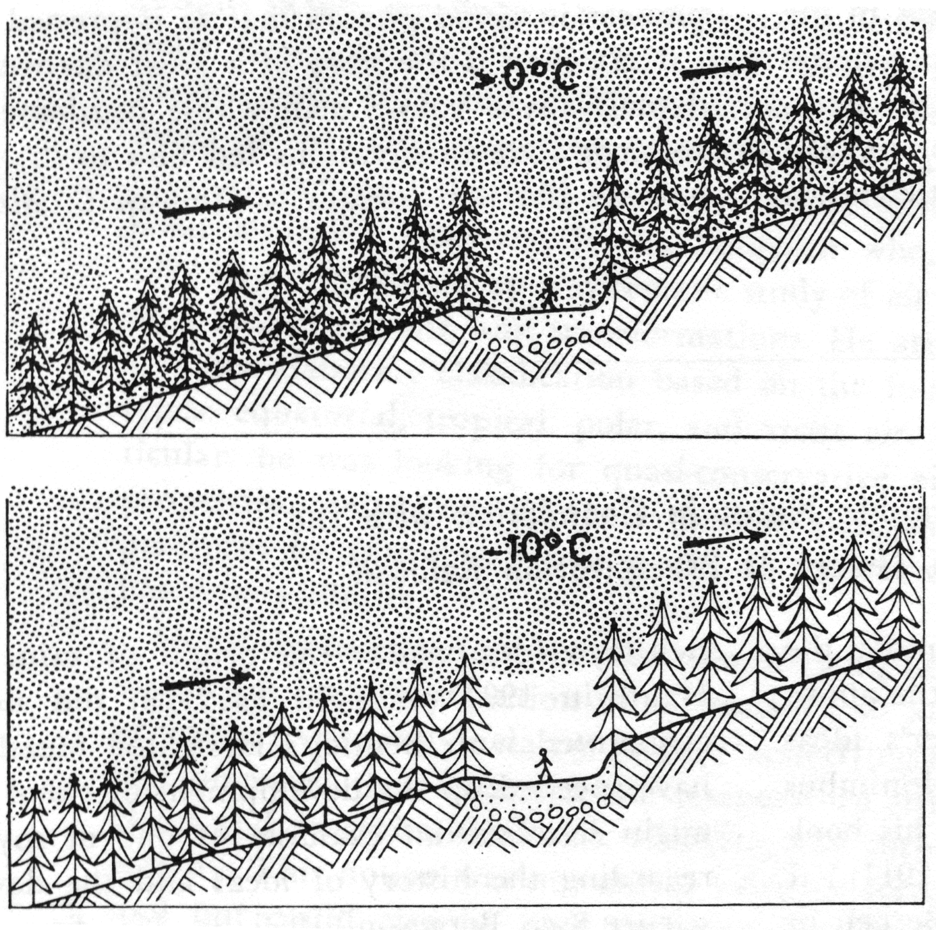

Figure 3. Sketch of the conditions (top) not favoring and (bottom) favoring the Bergeron–Findeisen process. Dotted areas represent clouds composed of liquid water droplets. (From Bergeron 1978).