BAMS Article

Defender and Expositor of the Bergen Methods of Synoptic Analysis

Significance, History, and Translation of Bergeron's (1928) "Three-Dimensionally Combining Synoptic Analysis"

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ABSTRACT: Tor Bergeron was a key member of the Bergen School of Meteorology that developed some of the most influential contributions to synoptic analysis in the twentieth century: airmass analysis, polar-front theory, and the Norwegian cyclone model. However, the eventual success of these so-called Bergen methods of synoptic analysis was not guaranteed. Concerns and criticisms of the methods—in part from the lack of referencing to prior studies, overly simplified conceptual models, and lack of real data in papers by J. Bjerknes and Solberg—were inhibiting worldwide adoption. Bergeron's research output in the 1920s was aimed at addressing these concerns. His doctoral thesis, written in German, was published as a journal article in *Geofysiske Publikasjoner* in 1928. Here, an accessible and annotated English translation is provided along with a succinct overview of this seminal study. Major interlaced themes of Bergeron's study were the first comprehensive description of the Bergen methods: a vigorous defense of cyclogenesis as primarily a lower-tropospheric process as opposed to an upper-tropospheric–lower-stratospheric one; a nuanced explanation of the assertion that meteorology constituted a distinct and special scientific discipline; and, very understandably, a thorough account of Bergeron's own contributions to the Bergen School. His contributions included identifying how deformation results in frontogenesis and frontolysis, classifying the influence of aerosols on visibility, and explaining the role of the ambient conditions in the onset of drizzle as opposed to rain showers—a distinction that led the formulation of the Wegener–Bergeron–Findeisen process.

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Starting in 1918 and continuing into the 1920s, the ground-breaking concepts of airmass analysis, polar-front theory, and the model of cyclone structure and evolution known as the Norwegian cyclone model were developed and published by the members of the Bergen School of Meteorology. These concepts are the basis for modern synoptic meteorology, but their eventual global success was not preordained. Although some individuals at national weather services initially thought that the concepts might be useful and even embraced them, others were less sure or even antagonistic toward them.

Davies (1997, his section 4.4) has summarized many of the objections to the new model at that time, but quite frankly the Bergen School members "were trying to market an incomplete product" (Friedman 1989, p. 198). The conceptual model presented in Bjerknes (1919) and Bjerknes and Solberg (1922) lacked sufficient observational evidence to justify their model, having "excessive claims and oversimplification" (Douglas 1952, p. 6). Specifically, "Due largely to the absence of definite guidance on how to locate 'fronts' on the weather map, considerable misunderstanding of polar front methods has arisen" (translator's note in Björkdal 1931, p. 275). *Monthly Weather Review* editor Alfred Henry argued that the different geographies between Norway and the United States meant that the Norwegian cyclone model was not necessarily applicable (Henry 1922a,b), as discussed in Newton and Rodebush Newton (1999). The idea of a cyclone being a "wave" on a front was questioned (Willett 1926). In yet another example, one of the Bergen School's own wrote (Rossby 1925, p. 153),

> "the partly rather hot struggle ... could probably have been largely avoided if endeavours had been made to a greater extent from the Norwegian side to illustrate the idealised cyclone models with real examples, taken from weather maps. As the theories are now published, the readers—who have often been completely without insight in the Bergen method of analyzing synoptic charts (sometimes summed up in the scarcely fortunate term of frontology)—have been left to convince themselves of the applicability of the models, and the result has naturally often been negative."

Schwerdtfeger (1981, p. 501) wrote, "the nice sketches in the papers of [Jacob Bjerknes and Halvor Solberg] were mostly based on surface observations and not accompanied by convincing case studies." As a result, analyses that adhered to Bergen methods were often prohibited at national forecasting agencies, against the wishes of some of the more open-minded analysts (e.g., Namias 1981, p. 493; Jewell 1983, p. 166).

In Vienna, Felix Exner downplayed these new ideas (e.g., Exner 1921, 1925, 1927), writing that the polar front "is to be regarded merely as a schematic hypothesis" (Exner 1925, p. 355). In Germany, Heinrich Ficker (1923) lauded the new analysis scheme, but disagreed that this model was both new and radical, criticizing the lack of referencing to previous work (e.g., Friedman 1989, p. 199; Davies 1997, section 4; Volkert 1999; Fleming 2016, 46–50). This slight was painful and confusing, especially because the Bjerkneses had previously lived and worked in Leipzig with Vilhelm founding the Geophysical Institute there (e.g., chapter 4 of Friedman 1989; Jewell 2017, 423–445). This anger was still apparent 60 years later when Schwerdtfeger (1981, p. 501) wrote,

> "in their publications in the first volumes of the scientific journal "GP" [*Geofysiske Publikasjoner*], the mature and highly respected scientist V. Bjerknes, as well as the two younger men, had shown a spectacular disregard for the work previously done by others, in particular the Austrian meteorologists in the Vienna School. To write in the 1920s about a polar front and its displacements on the rear side of cyclones without referring, for instance, to Ficker's (1910) highly relevant work about the spreading of cold air masses over Russia, or to discuss the observation that the center of a young mid-latitude depression tends to lie near the northernmost part of the warm air without ever mentioning Exner's textbook (1917), was not only an unnecessary and unprovoked lack of

courtesy toward the Austrian colleagues, but also a neglect of an unwritten rule for scientific writing, valid at this time...."

In contrast, Kutzbach (1979, 217–218) argued that their omission of citations was more arbitrary than intentional, pointing out that Jacob did not even cite his father's work despite its clear connections to his work. She concludes that "they were evidently preoccupied with the presentation of their own viewpoint."

Yet another point of conflict was that the Bergen School's emphasis on lower-tropospheric temperature gradients was at odds with Ficker's (1920) own theory on upper-tropospheric and lower-stratospheric influences on cyclogenesis, which was gaining adherents globally (e.g., Douglas 1924) and in conflict with those who believed that the pressure field, not the temperature field, was the primary field of interest (Davies 1997, 2010). Much later, Bergeron (1959, p. 457) wrote,

> "So compact was, in fact, the opposition ... from leading quarters in Europe, especially this Vienna School, ... that the ideas of the initiating Bergen School made very little headway to begin with outside Norway. Its adepts were severely discouraged and might even have given up using their ideas and findings in practice."

To win adherents, the Bergen School needed to rethink their strategy.

The 1928 article: Part I of an envisaged compendium and a PhD thesis en passant

Tor Bergeron (1891–1977; Fig. 1), the Swede, was always a bit different than the Norwegians: father and son, Vilhelm and Jacob Bjerknes, and Halvor Solberg. Bergeron [biographies in Liljequist (1981), Weickmann (1979), and Schultz and Friedman (2007)] was more thorough in his writing style, more willing to cite the previous work, and more willing to challenge existing models (including Jacob's own cyclone model). He was known "for his painstaking work in trying to account for as much detail as possible" (Jewell 2017, p. 485). Through two important papers in the 1920s (Bergeron and Swoboda 1924; Bergeron 1928) and his subsequent role as the Bergen School's greatest apostle (Liljequist 1981, p. 420; Friedman 1989, p. 197), he was able to explain the Bergen methods in a way that mollified many of the critics, producing a vigorous defense of the Norwegian approach. His articles cited numerous publications that showed the linkages between the earlier ideas and the Bergen model, evidencing the Bergen methods in a way that the J. Bjerknes papers did not. The evidence that Bergeron marshaled in these two papers was one approach that helped sell the Bergen methods to skeptical meteorologists.[1] Both of these papers were written in the German language, and, to our knowledge, neither has been available in English. Given the importance of these papers to the foundations of meteorology, this present article describes the first widely available translation of the second of these papers: "Über die dreidimensional verknüpfende Wetteranalyse" (Bergeron 1928), included with this article as an electronic supplement (Bergeron 2020). We also provide context for the history of its origin and its scientific impact to help guide the reader through this 118-page article (see also the sidebar "Translating the title").

"Über die dreidimensional verknüpfende Wetteranalyse" was Bergeron's PhD dissertation; it appeared in 1928 in the journal *Geofysiske Publikasjoner* [*Geophysical Publication*], published by the Norsk Geofysisk Forening [Norwegian Geophysical Society]. Although Bergeron often said that it was his most quoted article (Liljequist 1981, p. 420), it has not been cited as much as others by the Bergen School meteorologists. Specifically, at the time of

[1] To be fair, J. Bjerknes and the others were also taking their need to show the evidence of the Bergen methods more seriously. Bjerknes and Solberg (1921), Bjerknes and Giblett (1924), Rossby and Weightman (1926), and Bjerknes (1930) were attempts to contribute to this conversion effort as well. The middle two were directed specifically at the application of the Bergen methods to the United States.

writing of this article (March 2020), Bergeron (1928) had 294 citations according to Google Scholar, whereas Bjerknes (1919) had 422 citations and Bjerknes and Solberg (1922) had 590 citations. But, Bergeron (1928) was an integral contribution to the Bergen School's output and was one contribution that helped convince more skeptical meteorologists around the world of the value of the Bergen methods. "In his own way, [Bergeron] decisively helped his Norwegian colleagues to win worldwide recognition for the so-called polar front theory, not by theorizing a bit more, but rather by showing how and where the observed facts of the real weather could fit into the idealized conceptual picture" (Schwerdtfeger 1981, p. 501).

But, the importance of Bergeron (1928) went beyond just defending the Bergen methods. It also

Fig. 1. Tor Bergeron photograph around the time of writing his dissertation (Photographer: likely Elfriede Bergeron Schinze) (courtesy of oldimaginery.com).

- discussed the processes of frontogenesis and frontolysis (i.e., frontal strengthening and weakening, respectively) due to deformation, in a way that would later be quantified through the kinematic formulation by Petterssen (1936);
- extrapolated the frontogenesis and frontolysis fields globally to help explain the general circulation of the Earth's atmosphere;
- discussed the influence of aerosols on atmospheric visibility, including salt and Saharan dust into Europe; and
- presented an early version of the Wegener–Bergeron–Findeisen effect.

The variety of topics that Bergeron covered in his dissertation illustrated his breadth of knowledge and his ability to synthesize it in new and creative ways.

Prelude—A key decade: 1918–28

In 1918, Bergeron had been working as a junior meteorologist at the Swedish Meteorological and Hydrological Institute. A visit from Jacob Bjerknes and Halvor Solberg was influential in

Bergeron (and three other Swedes, including Rossby) going to Bergen in 1919 to learn the Bergen methods of analysis and forecasting and bring them back to Sweden (Liljequist 1981, 411–412). Bergeron began working at the Bergen School [*Værvarslingen på Vestlandet*; Forecasting Division of Western Norway] on 15 March 1919. By the end of 1919, he returned to Stockholm. But, having been exposed to the intellectual environment of Bergen, he found the institute stultifying (Jewell 1983, 166–167). The contrast between the two locations was stark. In Bergen, the two pioneering articles by Bjerknes and Solberg (1921, 1922) were being written without Bergeron (despite his discovery of the occlusion process, which was integral to the 1922 article). In Stockholm, however, Bergeron was burdened with work responsibilities and was unable to build a similar scientific milieu to undertake the same kind of scientific writing as his peers.

Translating the title

The title of Bergeron (1928) was one of the more interesting challenges facing the translating team, and it illustrates Bergeron's use of the German language to convey new meteorological knowledge. "Über die dreidimensional verknüpfende Wetteranalyse" translates literally to "On the Three-Dimensional Interlooping Weather Analysis." *Verknüpfende* does not have any meteorological meaning; it is the feminine form of the present participle of the verb *verknüpfen*, which in English translates as "link," "interloop," "interlace," or "combine," a term that is most commonly used in weaving to link threads together. As with many expressions in the text, this expression appears to be typical for Bergeron. He considers his analysis style not just as fully "three-dimensional" (as opposed to simpler one- or two-dimensional approaches) in geometrical dimensions, but also "interlooping" the various meteorological elements, in particular the mass field with the temperature distribution. [In a very strict linguistic sense, the analysis is regarded as interlooping, and interlooping is further qualified as three-dimensional.] The translating team believes that Bergeron had in mind a three-dimensional *and* an interlooping analysis, with both adjective terms in parallel, literally in German: "Über die dreidimensionale, verknüpfende Wetteranalyse." This belief is supported by the main title of chapter I (p. 16) "Allgemeine Prinzipe zur Ausnutzung der *inneren Verbindungen* zwischen den meteorologischen Elementen" or "General principles making use of the *inner links* between meteorological elements" [emphasis added].

In a further complication, Bergeron's close colleague Liljequist (1981, p. 420) wrote that Bergeron chose the translation as "Three-Dimensionally Combining Synoptic Analysis" (omitting the "on the" and choosing "combining synoptic"), a title consistent with Bergeron's translation of the Russian title of Bergeron (1934) in his reference list for Bergeron (1959, p. 471). Thus, we have adopted Bergeron's own translation of his title at a later time in his life.

In 1922, he returned to Bergen. By then, it was apparent that the external reception to the Bergen methods was not as successful as had been hoped. To counter this, Bergeron "believed that well-produced exemplars of synoptic charts that displayed the Bergen methods at work would at least help to stem the criticism based on avoidable misunderstanding or ignorance" (Jewell 1981, p. 167). By 1923, Bergeron decided to take time away from the regular forecasting duties in Bergen and concentrate solely on scientific research. He traveled to London and Paris to learn the forecasting techniques there and how to help convert them to the Bergen methods, then he would go to the Geophysical Institute at the University of Leipzig to earn his licentiate (equivalent to a master's degree) under Prof. Ludwig Weickmann Sr. (Liljequist 1981, 417–419; Jewell 1983, p. 167) (see sidebar "Leading scientists"). On his first-ever flight in a single-passenger plane from Croydon, England, to Rotterdam, Netherlands, in October 1923, he was fascinated by the distribution of clouds as he flew above a sloped, stationary front (Jewell 1983, 167–168). Arriving at Leipzig, Bergeron wrote back to Bergen asking for their maps and data of this case. Turns out that Czech Gustav Swoboda, who was visiting Bergen, had become interested in the same case. Swoboda brought the rolled-up maps to Leipzig, and the two meteorologists performed the analysis within a year. Originally designed to be just 5–10 pages long (Liljequist 1981, p. 417), "Wellen und Wirbel an einer quasistationären Grenzfläche über Europa" ["Waves and vortices at a quasistationary boundary surface over Europe"] (Bergeron and Swoboda 1924)[2] became a 91-page monograph published by the Geophysical Institute

[2] An English-language review of Bergeron and Swoboda (1924) was published in *Monthly Weather Review* by Willett (1926).

Leading scientists

Bergeron helped to maintain the link from Bergen to Leipzig, where he had stayed for an extended research during 1923 and 1924. An interesting, but little known, backcloth to this connection and the evolving international cooperation on a voluntary basis is provided by a group photograph taken at the tenth meeting of the International Aerological Commission in Leipzig in the summer of 1927; it features 32 scientists, 2 of them women, and 2 spouses (Fig. SB1). Ludwig Weickmann (#35) hosted the assembly and no less than 13 further persons were depicted whose research papers and books appeared in the list of references of Bergeron's thesis. Just eight years after the Treaty of Versailles, renowned scientists from the former Central and Allied Powers met in a workshop-type atmosphere, including a number of younger members of Weickmann's group. Bergeron's article appeared one year later and contained detailed references to more than 30 works of those depicted who belonged to the various schools of thought about air masses, cyclones, and fronts. Bergeron knew the then-current literature well indeed, paid due credit to the contribution of others, and vigorously defended the hypotheses put forward by the Bergen School and himself in particular—rendering his article of 1928 a PhD thesis *par excellence*.

01 Henryk ARCTOWSKI *(56)* *(Poland; 1871-1959)*
02 György MARCZELL *(56)* *(Hungary; 1871-1943)*
03 Elen E. AUSTIN *(32)* *(Great Britain; 1895-1987)*
04 Albert PEPPLER *(45)* *(Germany; 1882-1942)*
05 Luise LAMMERT *(40)* *(host team; Germany; 1887-1946)*
06 Rudolf LEMPFERT *(52)* *(Great Britain; 1875-1957)*
07 Spas VATSOV *(71)* *(Bulgaria; 1856-1928)*
08 Peregrin ZISTLER *(43)* *(Germany; 1883-1966)*
09 Pavel MOLCHANOV *(34)* *(Russia; 1893-1941)*
10 Erich BRUHNS *(27)* *(loc. host; Germany; 1900-1987)*
11 Felix Maria EXNER *(51)* *(Austria; 1876-1930)*
12 Eduard FONTSERÈ*(57)* *(Spain; 1870-1970)*
13 Hugo HERGESELL *(68)* *(Germany; 1859-1938)*
14 Theodor HESSELBERG *(42)* *(Norway; 1885-1966)*
15 Gilbert WALKER *(59)* *(Great Britain; 1868-1958)*
16 Elias MARIOLOPOULOS *(27)* *(Greece; 1900-1991)*
17 Lewis Fry RICHARDSON *(46)* *(Great Britain; 1881-1953)*
18 Enrique MESEGUER *(48)* *(Spain; 1879 - >1949)*
19 Mrs. WALLÉN *(Sweden)*
20 Napier SHAW *(73)* *(Great Britain; 1854-1945)*
21 Mrs. HESSELBERG *(Norway)*
22 Johannes ENGE *(23)* *(host team; Germany; 1904-1972)*
23 Paul MILDNER *(30)* *(host team; Germany; 1897-1976)*
24 Karl KEIL *(29)* *(Germany; 1898-1987)*
25 Dan La COUR *(51)* *(Denmark; 1876-1942)*
26 Filippo EREDIA *(50)* *(Italy; 1877-1948)*
27 August SCHMAUSS, *(50)* *(Germany; 1877-1954)*
28 Vilhelm BJERKNES *(66)* *(Norway; 1861-1952)*
29 Martin HERRMANN *(23)* *(host team; Germany; 1904-1958)*
30 Axel WALLÉN *(50)* *(Sweden; 1877-1935)*
31 Hendrik CANNEGIETER *(48)* *(Netherlands; 1879-1964)*
32 Franz LINKE *(49)* *(Germany; 1878-1944)*
33 Wasaburo OISHI *(53)* *(Japan; 1874-1950)*
34 Ewoud van EVERDINGEN *(54)* *(Netherlands; 1873-1955)*
35 Ludwig WEICKMANN *(45)* *(host; Germany; 1882-1961)*
36 Zsigmond RÓNA *(67)* *(Hungary; 1860-1941)*

Fig. SB1. Participants at the 11th meeting of the International Aerological Commission, Leipzig, 29 Aug to 3 Sep 1927. Numbering is in five columns, from left to right, with the following annotations for each person; number, first name, surname, (age at conference, country of work—not necessarily nationality—and lifespan). Underlined names are those authors who are cited in Bergeron (1928). The high-resolution scan of the photograph was kindly provided by Mirella Eredia (granddaughter of #26); surnames mostly follow Börngen et al. (2015; Fig. 3.12).

of the University of Leipzig. It was the first publication to thoroughly detail a weather situation using the Bergen methods, and "one of the most detailed case studies ever published in a western language" (Schewerdtfeger 1981, p. 502). However, because it was coauthored, Bergeron could not use it for his dissertation, so he had to start again on a new topic.

Back in Bergen in February 1925 (Liljequist 1981, p. 419), Bergeron decided that his new dissertation topic would provide further justification for the Bergen methods. It would describe indirect aerology, his method of obtaining the vertical structure of the atmosphere from limited upper-air data, and detailed evidence for the existence and formation of cold and warm air masses, as well as the narrow zones between the air masses constituting fronts. Bergeron began writing his dissertation in the winter of 1926/27, nearly completing it by the beginning of 1928 (Liljequist 1981, p. 420). After some delays at work that prohibited its timely completion, he was awarded a Doctor of Science degree from Oslo University on 20 September 1928 (Liljequist 1981, p. 431).

He was motivated to publish his thesis in German in *Geofysiske Publikasjoner* (co-founded by Vilhelm Bjerknes) because of the close cooperation between the Leipzig School and Vilhelm Bjerknes (who founded the Leipzig institute in 1913) (Schwerdtfeger 1981), the collaboration that resulted in the definition of the now-traditional frontal symbols in 1924 (Jewell 1981, 1983; Weickmann 1983), and the building upon his previous work with Swoboda (Schwerdtfeger 1981, p. 502). Bergeron (1928) also had extensive German referencing, in part because he was initially writing for acceptance in a German university, but also because his writings always had extensive citations, unlike the sparsely referenced works by J. Bjerknes and Solberg. But, Bergeron also recognized the close links with the past and viewed the Bergen methods as "part of a complex continuum, not a solitary revolution" (Vollset et al. 2018, p. 344), later writing, "Old knowledge will often be rediscovered and presented under new labels, causing much confusion and impeding progress" (Bergeron 1959, p. 443). However, Bergeron (1928) was written around the time when "the meteorological language change[d] from German to English" (Liljequist 1981, p. 418), which may explain why the paper has not received the level of attention of other Bergen School publications. Even still, at the time of its publication, at least one review of the article appeared in English (Björkdal 1931 in *Monthly Weather Review*).[3]

Style of writing

If one reads Bergeron's (1959) English-language chapter for the Rossby Memorial Volume, it is clear how engaging and meticulous a writer Bergeron could be. On Bergeron (1928), Bengtsson (1981, p. 515) wrote:

> "The paper is very typical of Tor's way of writing, with footnotes covering a substantial part of the paper and showing his immense, almost encyclopaedic, knowledge covering all fields of meteorology as well as his passionate interest and pride in the art and profession of meteorology."

For this reason, it has been a long-time goal of the first author to be able to read an English version of Bergeron (1928). Over the past three years, the translation was completed in pieces, finally being completed in late 2019 (see the acknowledgments). Proofreading, laying out, and annotating the initial translation was eye-opening in many ways. For example, Bergeron commonly employed emphasis such as italics in his writing style (e.g., Blanchard 1978, 389–390). Another way was through v a r i a b l e s p a c i n g b e t w e e n c h a r a c t e r s, termed *gesperrt gedruckt* [spaced out]. We tried to stay true to Bergeron's style by keeping that formatting within the present translation.

Bergeron was a perfectionist in his writing, as was Swoboda. To accommodate these exacting authors, Bergeron and Swoboda (1924) required eight proofs (Liljequist 1981, 418–419). Like Bergeron and Swoboda (1924), *Geofysiske Publikasjoner* issues were published and sold individually. Another anecdote pertains to Bergeron (1928): "[Bergeron] tried to hold the night-express [train], from Bergen to Oslo, in order to get some extra time for making the

[3] Misspelled as *Bjorkdal* in the journal.

very last corrections in the manuscript of his doctor's thesis before sending it to the printer in Oslo" (Liljequist 1981, p. 429).[4]

The structure of his thesis with three chapters and subdivided in sequentially numbered 28 sections (paragraphs) closely mimicked Exner's textbook *Dynamische Meteorologie* [*Dynamical Meteorology*] (1917, 1925, second edition with 13 sections composed of 96 paragraphs). Bergeron was obviously influenced by that, even if Exner did not originate that style. Both Bergeron (1937) and Chromow (1940) [a book based on Bergeron's notes, to be discussed later] had similar structures, and Chromow (1940) even was printed in the same or similar type faces.

Otherwise, Bergeron (1928) resembles a modern student's PhD thesis in many recognizable respects. The writing is at times bold, but at other times tedious. Lists of citations are provided with little context (e.g., pp. 5, 6, 11, 32, 82). The references are sometimes incomplete, lacking a consistent format (pp. 96–102). Another problem was highlighted in a translation of a German review of Bergeron (1928) by Björkdal (1928) that appeared in *Monthly Weather Review*, preceded by the translator Andrew Thomson: "Bergeron's extremely valuable and suggestive book which is marred for English readers by an involved style of sentence structure" (Björkdal 1931, p. 275). For example, a literal translation of one troublesome sentence reads: "On the other hand, as was shown, due to dissimilar histories, at least two types of air masses, WM [warm air mass] and KM [cold air mass], which have different properties, develop" (Bergeron 1928, p. 69). In an interview, C. C. Wallén, a student of Bergeron's said that Bergeron's dissertation "is really considered to be a bible of the Bergen School, and practically all of what had developed from 1918 to 1928 exists in that book, although … it is not easy reading" (Wallén 1995, p. 6).

A natural question is why such a careful writer and someone who knew seven languages would sometimes write in this convoluted manner, especially when other articles written by Bergeron in English were much more readable. We can only offer the following possible explanations. First, Bergeron was writing in the tradition of the old German style, which was to mimic the Latin tradition of long complex sentences. Second, Bergeron's own style of writing mirrored the complexity of nature, as opposed to the sanitized version found in other Bergen School articles such as Bjerknes and Solberg (1922). Third, Bergeron tended to include a lot of detail, abundant literature citations, qualifications, and side points that many others would probably omit in the spirit of a more streamlined and readable text, as Vilhelm Bjerknes wrote, "it is very difficult to make him finish a work, or to make him reduce a paper to its simplest possible form" (Fleming 2016, p. 69). Finally, Bergeron ambitiously envisioned his dissertation as a book, so he felt more comfortable expanding on the depth and length of argument. Clearly, his was not an ordinary PhD, having gone well beyond what was necessary to achieve a degree at the time. His dissertation was his way to put his personal mark on the field and distinguish himself from his Bergen colleagues.

A planned Part II of the 1928 article: Envisioned early on, realized across political and linguistic boundaries

At the time he wrote his dissertation, Bergeron viewed it as the first part in a two-part series—as suggested by the subtitle "Erster Teil: Prinzipielle Einführung in das Problem der Luftmassen- und Frontenbildung" ["Part I. Fundamental introduction to the problem of airmass and front formation"]—further indication he envisioned this as a contribution to an eventual textbook. The second part would discuss the dynamics of fronts, but would not be completed until 1934 after two extended visits to Russia (Schwerdtfeger 1981, p. 505). On his first day of work in

[4] In fact, Bergeron (1928) is a rare issue of *Geofysiske Publikasjoner* with published errata. (Of the 82 issues through the first 10 volumes, there were only 6 published errata, 3 of which were from Bergen School members.) The errata of Bergeron (1928) identified mostly minor errors, while missing at least one quite large error (i.e., paragraph being cut off abruptly in the middle on p. 18). During our translation, we also identified a few other minor errors (e.g., pp. 20, 28, 46, 90).

Moscow in 1930, he met a map analyst in the weather service, Vera Romanovskaya. They were married in February 1932, and she translated his lecture notes from German into Russian (Liljequist 1981, p. 421; Fleming 2016, 49–50). Both Part I and Part II would be published together in Russian (Bergeron 1934), although not be widely available. Bergeron (1937) wrote an outline for the *Bulletin of the American Meteorological Society*, picking up where the 28 sections of Part I ended, starting with sections 29–42 on fronts, occlusion, the dynamics of extratropical cyclones, and tropical cyclones, and which Editor Robert Stone, described as "a brief summary of Dr. Bergeron's eventual monograph in German in *Geofysiske Publ.*" (Bergeron 1937, p. 265). This monograph was never completed. Elements of Bergeron's planned monograph later appeared in Godske et al.'s (1957) *Dynamic Meteorology and Weather Forecasting*, what Bergeron referred to as "THE Book," and is a thorough compendium of the Bergen methods (Liljequist 1981, p. 424; Vollset et al. 2018, 249–252).

Based on the two Russian parts and Bergeron's lectures in Russia on the Bergen methods (Liljequist 1981, p. 423), one of Bergeron's students, Sergei Petrovich Chromow[5] published a textbook on synoptic meteorology drawing upon Bergeron's lectures (Chromow 1934); encouraged by Ficker, a revised 1937 version was translated into German by Swoboda and published in 1940 (Chromow 1940). Bergeron contributed to the German translation, commented on the text, and provided original drawings for the book. Also, Ficker made sure that the concepts from the Vienna School were properly credited (Fleming 2016, p. 50). Bergeron later wrote a review of the book entitled "a new era in teaching synoptic meteorology," calling the book "*the first, authoritative, complete and systematic text-book of Practical Synoptic Meteorology, based on strictly physical principles*" [emphasis in the original] (Bergeron 1941, p. 251). To our knowledge, Chromow's books have not been translated into English, although the *Bulletin of the American Meteorological Society* published a review and three summaries of Chromow's 88 rules for forecasting synoptic situations derived from his 1934 book (Schell 1934, 1935a,b,c).

[5] Sometimes spelled "Chromov" or "Khromov."

Immediate impact of Bergeron (1928) on atmospheric science and its continuing relevance

Bergeron (1928) was an important scientific document for the following key reasons.

1) It was the most thorough justification of the Bergen methods of synoptic analysis in which Bergeron articulated his principles of indirect aerology (p. 14). Nyberg (1981, 510–511) summarized Bergeron's dilemma:

   > "Bergeron had a very difficult task when he attempted to analyse three-dimensionally what happened in the atmosphere. He possessed only surface observations; no daily aerological observations existed then…. Using observations of clouds and other hydrometeors, such as rain, showers, hail, drizzle, haze, mist and fog[,] it was possible to obtain information about the three-dimensional structure of the troposphere."

   Specifically, the emphasis was on the air masses: "It was Bergeron who, in his 1928 paper, first took up a systematic study of air masses, their source regions, and transformations" (Eliassen 1978, p. 388). Bergeron argued that air masses could be classified by uniform properties of temperature, lapse rate, visibility (i.e., aerosol content), the type of precipitation (i.e., rain showers vs drizzle) (Bergeron 1928, p. 36, Table 1, appendix), and even electrical conductivity (p. 17). He incorporated his earlier 1918–19 work on quantifying subjectively the influence of aerosols on visibility for SMHI as an appendix, and this became integral to his airmass definition. He classified air masses as warm or cold, continental or marine, and the difference in temperature between the surface air and that of the Earth's surface (what Bergeron denoted Δ). Bergeron showed that the warm air masses were horizontally homogeneous, whereas the cold air masses had sloped isentropes [i.e., barotropic and baroclinic; both terms coined by Vilhelm Bjerknes (Bjerknes 1921)], and he explained how modification of those air masses occurred (Fig. 2). He also demonstrated the existence of the two air masses (three in the winter with the Arctic air mass) through airplane sounding data from the Netherlands (see sidebar "Evidencing air masses") indicating distinct temperature zones throughout the year that the air masses inhabited.

Bergeron called his analyzed weather maps (e.g., Fig. 3) "composite charts" rather than "surface charts" because they introduced more information from the indirect aerology than just surface data (e.g., Nyberg 1981, p. 511). "In those years, not all members of the Bergen School shared Bergeron's keen interest in aerology" (e.g., Bergeron 1978; Schwerdtfeger 1981, p. 503). Bergeron also set the Bergen School's advances in the context of the then-existing literature. The early Bergen papers were nearly devoid of references, but some of their ideas had been at least partially foreshadowed in the literature, as reviewed by Bergeron (1928, 11–12), Bergeron (1959), and Volkert (1999).

2) Bergeron advanced the concept of deformation-induced frontogenesis, considering and illustrating its effect in theoretical terms (Fig. 4), pinpointing the importance of its contribution, and demonstrating a link between the large-scale distribution of different types of air masses and the occurrence of sharp fronts. He presaged the eventual mathematical development of the frontogenesis function by Petterssen (1936), discussed more completely by Keyser et al. (1988) and Schultz (2015). In fact, Bergeron invented the terms frontogenesis and frontolysis (Bjerknes 1930, p. 11; Petterssen 1933, p. 50). In effect, the idea of fronts as undergoing strengthening and weakening opened an entirely new (and perhaps, at least initially, an unwelcome) vista for the Bergen School because hitherto they had regarded a frontal surface as a pre-existing entity and had focused on demonstrating how a front became distorted during cyclogenesis (Bergeron 1928, 12–13).

Specifically, Bergeron was concerned with the question:

"Is there really one polar front, with air of subtropical origin towards the equator and

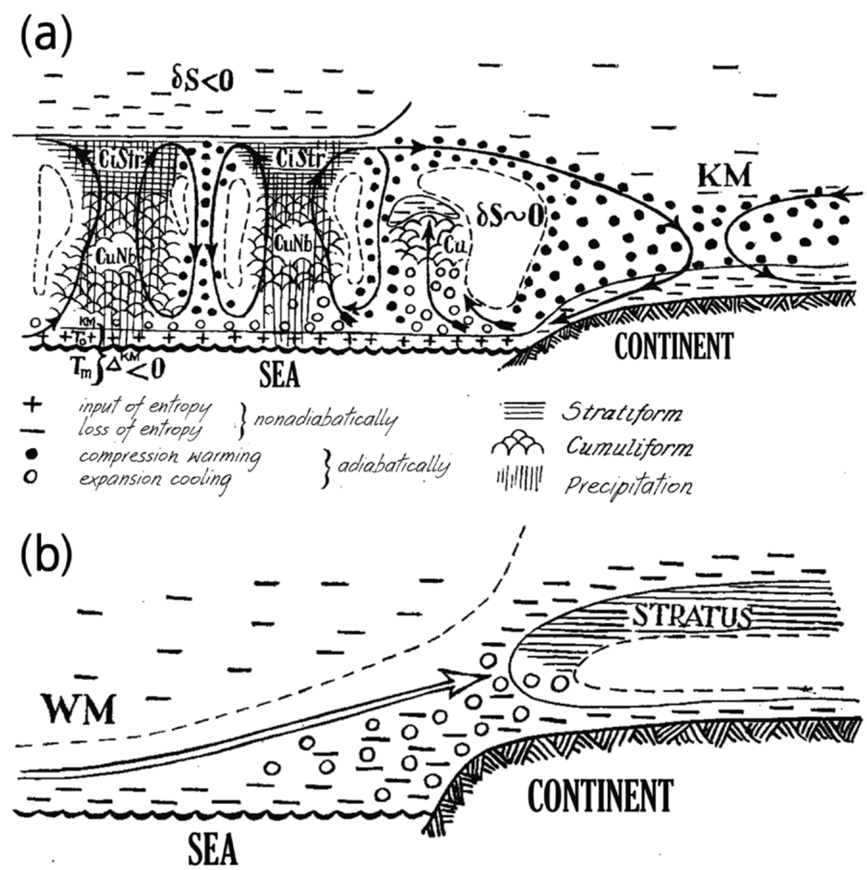

Fig. 2. (a) Schematic for diabatic influence in a cold air mass (KM) in winter and (b) schematic for diabatic influence in a warm air mass (WM) in winter (adapted from Bergeron 1928, Figs. 7 and 8).

Evidencing air masses

To demonstrate that there were discrete air masses in the Northern Hemisphere, Bergeron obtained upper-level potential temperature data at 3 km above mean sea level from Soesterberg, Netherlands (Fig. SB2). He argued that there were temperature regimes throughout the year, indicating the existence of discrete air masses with relatively uniform temperatures. Bergeron also recognized the existence of much colder air present in the winter (e.g., potential temperature of 8°–12°C), and named it *Arctic air*, the first to recognize the separate existence of this air mass.

To see if a similar graph constructed from modern data would yield a similar pattern, the potential temperature at 700 hPa from twice-daily upper-air data over De Bilt, Netherlands, from 1980 was plotted. De Bilt is about 9 km away from Soesterberg. The year 1980 was selected because it was the first year of the dataset that we had access to. Besides the general warming between 1922 and 1980, the separation between the air masses in 1980 was perhaps not quite so obvious as in 1922. Of course, there was considerable subjectivity in how Bergeron and we drew the curves, but it is easier to spot a gap between the cold and warm air in the 1922 data, in part because of the fewer airplane ascents.

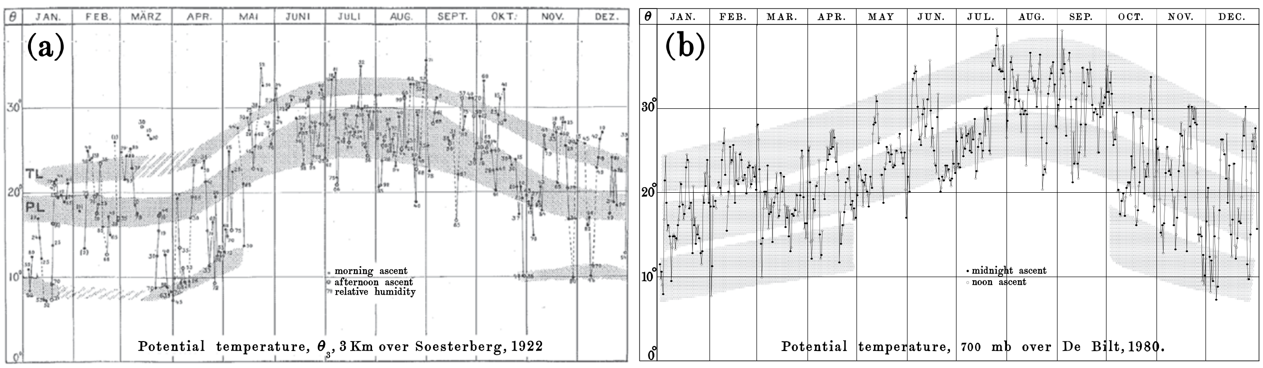

Fig. SB2. (a) Potential temperature at 3 km over Soesterberg, Netherlands, during 1922 (Bergeron 1928, Fig. 13). (b) Potential temperature at 3 km over De Bilt, Netherlands, during 1980.

subpolar cold air toward the poles…? Or are there more types of air masses and therefore other cyclogenetically active discontinuities as, for instance, an arctic front between subpolar air over the northern North Atlantic and true arctic air over the polar regions proper? …. [Bergeron (1928)] apparently postponed an answer to that question by referring directly to a cold mass (KM) and a warm mass (WM); he avoided the notation PL (polar air) and TL (tropical air) which the Bjerkneses (father and son) had used, and said that the two kinds of names have the same meaning 'under certain circumstances' (p. 33)" (Schwerdtfeger 1981, p. 506).

Frontogenesis and frontolysis led Bergeron to two conclusions. First, the idea of an uninterrupted circumpolar front cannot persist for more than a few days, and, second, that the types of air masses involved in cyclogenesis is irrelevant, as long as there is contrast between them (e.g., Schwerdtfeger 1981, p. 506).

Bergeron showed how deformation along the edges of air masses creates frontal zones, initially called *transition zones* (Bergeron 1928, p. 69). It is here that the order of magnitude differences in the characteristic properties of air masses are enhanced and the horizontal homogeneity condition in air masses is no longer met: "Thus, the combination of deformation field and entropy field … would always lead sooner or later … to an accentuation of a frontal zone." (Bergeron 1928, p. 78). In this way, Bergeron articulated a chain that crosses scales from the microscale to the planetary scale:

air modification through surface fluxes → air masses → fronts →
frontogenesis/frontolysis → general circulation.

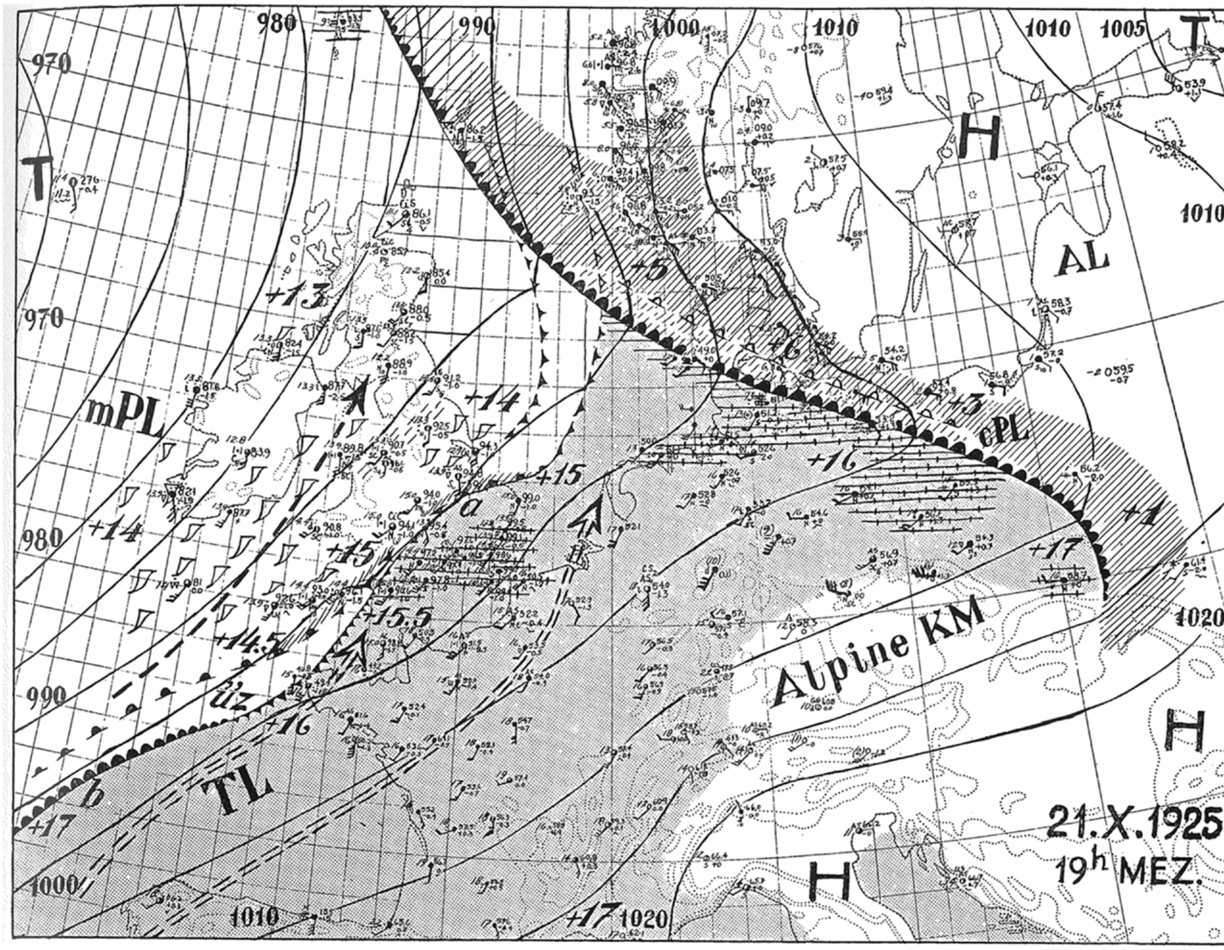

Fig. 3. Bergeron's composite chart for 0700 UTC 22 Oct 1925 (Bergeron 1928, Plate IV, Map 2).

Bergeron also argued for the equivalence between fronts and inversions. They formed in the same way, just depending on the orientation of the axis of deformation.

3) Bergeron contributed to a vigorous defense against a counterhypothesis to the Bergen School's identification of cyclogenesis as primarily a lower-tropospheric process. Around 1920, there were competing ideas about the "seat" of cyclogenesis. The Bergen School argued that cyclogenesis occurred on the lower-tropospheric polar front, but the Vienna School (including Exner and Ficker) called upper-level (stratospheric) effects on surface pressure *primary* and tropospheric effects *secondary* (e.g., Ficker 1920;[6] Reed 1921; Davies 1997, 2010; Schultz et al. 2019, p. 16.10). In the 1920s, the Bergen School sought to downplay the importance of these upper-level effects and contributions of the Vienna School (Liljequist 1981, p. 413; Schwerdtfeger 1981, p. 501; Friedman 1989, pp. 198–199) or not even acknowledge the controversy in some contexts. Bergeron was open to these ideas and cited many papers by Exner and Ficker within his dissertation, so acknowledging them was perhaps his guarded way of mentioning them without giving them too much credence. Whatever the cause, by the late 1930s, Jacob Bjerknes became more willing to admit that upper-level effects were more important (Bjerknes 1937; Bjerknes and Holmboe 1944).
4) A minor element of Bergeron (1928), but a significant one for the history of cloud microphysics, was his explanation of the role of the ambient conditions in the onset of drizzle as opposed to rain showers—a distinction that he continued to develop and led to the

[6] Ficker (1920) was translated by Volken and Brönnimann (2010) and placed in historical context by Davies (2010).

formulation of the Wegener–Bergeron–Findeisen process (e.g., Blanchard 1978; Weickmann 1981). Specifically, Bergeron (1928, p. 31) wrote, "The author recognizes in the interaction between dense and compact water clouds with layers of permanent ice nuclei a main source of ... all forms of precipitation except drizzle and its solid counterpart." Bergeron (1978, 391–392) wrote,

> "...when starting later in 1927 to write my doctor's thesis, these ideas came to form a short section (No. 9) of "Wetteranalyse, 1" (Bergeron 1928). It was written in German (and thus hardly read in the United States or England) and printed in September 1928. That year, therefore, is the real year of birth of that theory, and not 1933 or 1935 as generally quoted).... When later ... I ... [was] chosen to represent Norway at the UGGI meeting in Lisbon in 1933, I at last sat down trying to present the ice nucleus theory in a more complete, detailed, and convincing shape, with the known result (Bergeron 1935)."

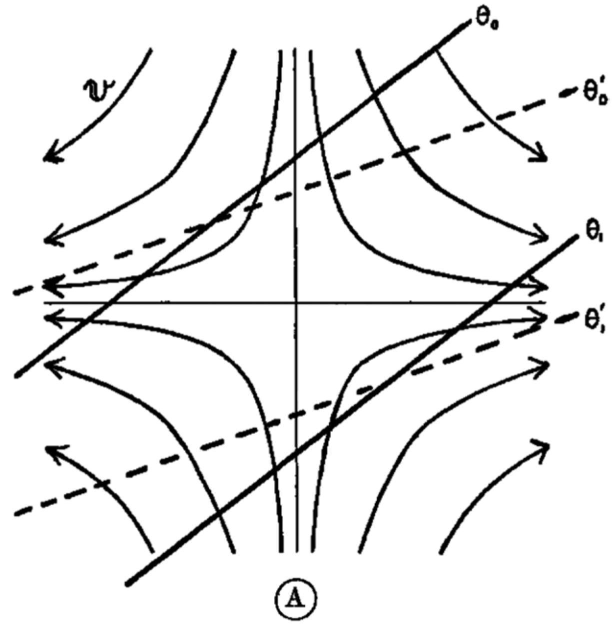

Fig. 4. Deformation field v vs entropy field Θ. Hyperbolic projection of a flat symmetrical v field (Bergeron 1928, Fig. 17a).

5) Bergeron classified the influence of aerosols on visibility (p. 23, 55, and appendix). This work largely followed up his earlier work for SMHI on visibility, but it also convinced him that the visibility of the atmosphere was set at the source regions of the air masses and was transported great distances. Thus, visibility could be used to distinguish different air masses.
6) Finally, Bergeron advanced a nuanced explanation of the assertion that meteorology constituted a distinct and special scientific discipline. As a comparatively less experienced scientist in the 1920s, Bergeron had developed a striking view on this particular topic, and it formed one of the underlying themes of his doctoral thesis. This was not entirely a surprise because Vilhelm Bjerknes had often expressed views on the scientific status of meteorology. Indeed, in the two-volume compendium that he and his colleagues had produced some years earlier (Bjerknes and Sandström 1910; Bjerknes et al. 1913) and in his essay on weather prediction (Bjerknes 1904), Vilhelm had sought to emphasize its physical and mathematical foundations. However, Bergeron went one step further in his thesis. He did not set out to defend the discipline's credentials by referring to its firm foundation, but rather he asserted its special character!

Bergeron first set out his view on the scientific method in the Preface (pp. 1–2). He regarded this method as the benchmark for assessing the Bergen School's research, his own work, and that of others. Thereafter, he often commented, when appropriate, upon the application of this method to the topic under consideration. He set out the ingredients of his scientific method through the following argument. First, the pre-eminence of *facts* (which he subsequently regarded as quality-controlled observations), and that they should "speak for themselves" (p. 1). Second, that facts alone are insufficient or inadequate because they could at least be superficially consistent with contrasting theories, and hence, on pure objective grounds, recourse to facts alone limits developments. Third, that "weather" has special characteristics. Specifically, that weather exhibits *the* greatest diversity of phenomena, and in essence it operates on the edge of instability so that "a seemingly great effect can arise from a small cause" (p. 2), later articulated under chaos theory (e.g., Lorenz 2004). Therefore, weather research itself is special, and in particular statistical methods can lead to contradictory or unfruitful results, and purely theoretical or purely empirical approaches are inappropriate. For meteorology, adopting a pure deductive approach would entail making oversimplified assumptions, and pure induction is not an option because "every case" is slightly different so that the standard approach of the natural sciences to classify phenomena is not an easy option. The key statement in his argument was that "The formation of concepts in our science is subject to an undesirable arbitrariness, which should not be understood as a deficit of objectivity, but rather as the lack of an atypical epistemological basis necessary for a fruitful dynamic meteorology" (p. 2). The answer was the Bergen methods. Except for this final step of referencing the Bergen methods, this argument is nuanced and subtle, and it remains relevant today.

In the main body of the thesis, he expanded on some of the foregoing points.

- Bergeron argued for hypothesis-driven research accompanied by observational verification (p. 6).
- He distinguished between mere interrelationships of variables as opposed to legitimate "cause and effect" linkages (p. 7).
- He celebrated successful "verification" as a prelude to further advances (p. 10).
- He argued, that in view of inadequate direct observational data, it is rational to adopt the approach of "indirect aerology" (p. 10).
- He argued (somewhat in contradiction to his earlier caveat) for the necessity of "induction" (but plus "insight") (p. 12).
- He indicated that beyond induction there must be an effective program of deduction (p. 16).
- He stressed the need for the researcher to adopt a detached view when examining contradictory ideas and hypotheses (p. 86).

All of this argumentation can be set against the prevailing background of the time when the philosophical foundations of science were being explored by others (e.g., Suppe 1977).

Conclusion

The first widely available English translation of Tor Bergeron's PhD dissertation and an examination of the history in which it was written allows us to emphasize the importance of this work in the history of atmospheric science. Its primary purpose was on advocating for the Bergen methods of synoptic analysis. Judging by the reception, it seems to have hit its target (e.g., Björkdal 1931), although other factors certainly helped secure its global dominance (Friedman 1989, 241–246). Indeed, Vilhelm Bjerknes remarked on Bergeron's contributions in a letter dated 26 January 1928: "It was also at this time [1919] T. Bergeron came as a fully equal collaborator, and as the one who perhaps more than others has the credit of the further development of the methodology" (reported in Jewell 2017, p. 490).

As Bergeron would later write about his role in the cold-rain process: "In order for an idea to be accepted, one must evidently believe in it and fight for it." (Bergeron 1978, p. 392), which would appear to be equally applicable for the Bergen methods. In a similar vein, he wrote, "the rediscoverers of these concepts and structure models, and the whole Bergen School, who fought for them and used them consistently in practice, deserve the main credit for them" (Bergeron 1959, p. 453). Besides defending the Bergen methods, there were other elements that were touched upon in this work, as well, including importance of soundings to understanding about stability and precipitation processes, early work on aerosols and visibility, and the first articulation of the Wegener–Bergeron–Findeisen process. As such, Bergeron (1928) was important for the coming developments in meteorology over the next century.

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Appendix: Reading Guide to Bergeron (1928)

Navigate to the most interesting and relevant parts of the article.

- Pages 5–11: The seat of cyclones is in the lower troposphere, not the upper troposphere and lower stratosphere. On pages 6–7, Bergeron criticizes those who use the hydrostatic equation to attribute cause-and-effect between large pressure changes in the upper troposphere and lower stratosphere to surface pressure changes, a topic that still generates considerable discussion today: Hirschberg and Fritsch (1991, 1993) versus Steenburgh and Holton (1993); Knippertz and Fink (2008) and Knippertz et al. (2009) versus Spengler and Egger (2009).
- Pages 11–14: History of frontal concepts before the Bergen School; overview of the Bergen methods.
- Page 19: Discussion of conserved variables. Surface temperatures are unreliable for frontal analysis; instead, use temperatures in the free atmosphere.
- Pages 21–25: Discussion of aerosols: observations, sources, transport, and contributions to visibility.
- Pages 27–28: Cold front being retarded by the Alps and formation of a lee cyclone.
- Pages 29–31: Wegener–Bergeron–Findeisen process discussed.
- Pages 32–38: The formation and types of air masses (cold and warm), including the diabatic influences on cold and warm air masses in winter (Fig. 3 of the present article).
- Page 39: Vacillation between warm and cold air masses at sites over the North Sea with abrupt changes in temperature.
- Pages 42–48: Analysis of the Berck soundings in drizzle and rain where Bergeron links the lapse rate of the air to the types of hydrometeors, providing evidence for the Wegener–Bergeron–Findeisen process. Data in appendix II.
- Pages 54–56: Linking the visibility of the air to the type of air mass.
- Pages 59–61: Cold air masses have sloping isentropes (baroclinic), and warm air masses have horizontal isentropes (barotropic).
- Pages 61–68: Evidence for the existence of two air masses, with narrow frontal zones in between.
- Page 68: Bergeron challenges the Lindenberg School on the topic of whether surface air temperatures can be used for analyzing fronts.
- Pages 69–73: Order of magnitudes of gradients within air masses and frontal zones.
- Pages 73–78: Kinematics of frontogenesis and frontolysis, including that frontogenesis occurs when the angle between the axis of dilatation and the isentropes is less than 45°, later shown mathematically by Petterssen (1936).
- Pages 78–80: Fronts and inversions have similar properties. Describes kinematic frontogenesis in this way: "The hyperbolic point is simply the 'Napoleon' of the air masses that due to the coming together of scattered "soldiers" increases their impact force" (p. 80).

- Pages 80–83: Describes the previous literature on frontogenesis.
- Pages 84–94: Links the local vertical circulations of frontogenesis to planetary-scale circulations.
- Pages 103–107: Bergeron's table and guidelines for manual visibility classification.

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