Reprint of
Hans Volkert, "Components of the Norwegian Cyclone Model: Observations and theoretical ideas in Europe prior to 1920".

The Life Cycles of Extratropical Cyclones

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Preface

This monograph contains expanded versions of the invited papers presented at the International Symposium on the Life Cycles of Extratropical Cyclones, held in Bergen, Norway, 27 June–1 July 1994. The symposium coincided with the 75th anniversary of the introduction of Jack Bjerknes's frontal-cyclone model presented in his seminal article, "On the Structure of Moving Cyclones." The event was attended by approximately 300 scientists and students from around the world and included 207 papers and poster presentations, of which 17 were invited lectures. The symposium provided a state-of-the-science account of advances in the research and forecasting of extratropical cyclones. The symposium was organized by Sigbjørn Grønås of the Geophysical Institute of the University of Bergen, Norway, and Melvyn Shapiro of the National Oceanic and Atmospheric Administration (NOAA)/Environmental Technology Laboratory, Boulder, Colorado, USA. Preprints of the invited and submitted presentations were published in three volumes and are available through the Geophysical Institute of the University of Bergen. A special issue of *Tellus* (1995), **47A**, 525 pp., was dedicated to the publication of 27 reviewed papers from the symposium.

This monograph should be of interest to historians of meteorology, researchers, and forecasters. It contains material appropriate for teaching courses in advanced undergraduate and graduate meteorology. The chapter bibliographies provide a valuable source for key references on many aspects of extratropical cyclones.

The symposium was hosted by the University of Bergen and cosponsored and generously supported by societies, universities, government organizations, private companies, and endowments from Norway and the United States. Norwegian support was provided by the Norwegian Geophysical Society; University of Bergen; Norwegian Meteorological Institute; Research Council of Norway; Norwegian Department of Church, Education and Research; Meltzers Høyskolefond; O. Kalvi og Knut Kalvi's Almennyttige Fond; Intel Supercomputer Systems; Cray Research; Silicon Graphics Inc.; Aanderaa Instruments; and Vesta Foriksring. United States support was provided by the NOAA/Environmental Research Laboratories; American Meteorological Society (AMS); National Science Foundation, Office of Naval Research; University Corporation for Atmospheric Research; and the National Center for Atmospheric Research.

The first nine chapters of the monograph present a historical overview of extratropical cyclone research and forecasting from the early 18th century into the mid-20th century. The first chapter presents Vilhelm Bjerknes's 1904 paper, which outlined a rational approach to weather forecasting through the synthesis of classical hydrodynamics and thermodynamics with meteorological observations. Bjerknes envisioned weather forecasting as a problem in mechanics and physics in which the dynamical equations for atmospheric motion were integrated through numerical methods. Arnt Eliassen highlights the early studies of Vilhelm Bjerknes and their connection to Jack Bjerknes's Bergen school cyclone model. Hans Volkert discusses observations, theories, and conceptual models prior to 1920 that reaffirm the international scope of the scientific milieu that sowed the seeds for the subsequent Norwegian conceptual models of extratropical cyclones. Science historian Robert Marc Friedman chronicles the political, societal, and economic factors that contributed to the development of scientific thought leading to the capstone of the Bergen school contributions: The Life Cycles of Extratropical Cyclones and the Polar Front Theory of Atmospheric Circulation, published in 1922 by Jack Bjerknes and Halvor Solberg. Chester Newton and Harriet Rodebush Newton review the advances in American meteorology before 1919 and how the Bergen school polar-front and cyclone concepts came to be adopted into daily weather forecasting by the U.S. Weather Bureau. Peter Lynch critiques the numerical methods applied by L. F. Richardson in his historic attempt at dynamical weather forecasting. Lynch repeats Richardson's forecast, with more successful results, using modern computational initialization methods. The next chapter presents a transcript of a tape-recorded informal lecture by Erik Palmén delivered in Helsinki, Finland, in 1979. Palmén spoke about the contributions of the Bergen school and the period when he worked with Jack Bjerknes on the analysis of the northern European serial thermograph sounding experiment, reported on in their classical 1930s papers on the three-dimensional structure of extratropical cyclones. Brian Hoskins recaps the career of Reginald Sutcliffe and his contributions to the formulation to quasigeostrophic theory and its application to the theoretical understanding of cyclone development. The historical chapters are concluded with a commemorative photograph album, compiled by Melvyn Shapiro, which portrays some of the key contributors to the advancement of meteorology.

The succeeding chapters present an overview of contemporary research on the theory, observations, analysis, diagnosis, and prediction of extratropical cyclones. The sequence of presentations transcends the planetary-scale to mesoscale scales of motion. Eero Holopainen presents an overview of recent observational studies of extratropical cyclone climatology and their relation to planetary-scale waves. Isaac Held explores selected aspects of planetary wave dynamics and their interactions with smaller scales. Brian Farrell presents a historical review of advances in the theory of cyclone development and introduces a contemporary approach toward a generalized theory of baroclinic development. Adrian Simmons discusses numerical simulations of idealized and actual cyclone life cycles with an emphasis on the larger scales of motion, including downstream and upstream baroclinic development, and recent results from predictions produced at the European Centre for Medium-Range Weather Forecasts (ECMWF). Melvyn Shapiro and collaborators present a planetary-scale to mesoscale perspective of cyclone life cycles which aspires to build a conceptual bridge between theoretically idealized cyclone life cycles and those observed in nature. Lance Bosart provides an overview of observed cyclone and anticyclone life cycles and discusses current and future directions in extratropical cyclone and anticyclone research. Huw Davies reviews the theoretical studies of frontogenesis within the framework of quasi- and semigeostrophic dynamics. Daniel Keyser reviews classical and contemporary perspectives on the representation and diagnosis of frontal circulations in two and three dimensions. Keith Browning documents observed mesoscale aspects of extratropical cyclones, which include frontal fracture, air streams, dry intrusions, and mesoscale substructures associated with surface cold fronts. Alan Thorpe addresses the dynamics of extratropical cyclones associated with mesoscale structures and includes discussions of potential vorticity "thinking," frontal-wave cyclones, and the role of conditional symmetric instability in the formation of frontal rain bands. Thor Erik Nordeng presents an overview of numerical simulations of mesoscale substructures and physical processes within extratropical cyclones, addressing topics such as frontal structures and dynamics, surface friction and fluxes of heat and moisture, latent heating, and nonclassical mesoscale cyclone development. Louis Uccellini, Paul Kochin, and Joseph Sienkiewicz describe forecasting advances at the U.S. National Meteorological Center, with an emphasis on the performance of models and forecasters in predicting oceanic cyclogenesis. Michael McIntyre discusses, among other topics, his "vision of the future" for the potential for humans to interact usefully and efficiently with computer-based systems in advancing the accuracy of numerical weather predictions. The monograph concludes with a collection of photographs taken at the Bergen Symposium by Carlye Calvin and Nadine Lindzen (lead photographers), with additional contributions provided by David Schultz, Howie Bluestein, and Melvyn Shapiro.

The editors acknowledge and thank the authors and reviewers for their contributions to the monograph. We express our appreciation to NOAA's Environmental Research Laboratories (ERL), James Rasmussen, Director; ERL/Environmental Technology Laboratory, Stephen Clifford, Director; and the Faculty of Natural Sciences, University of Bergen, Kjell Saelen, Director, for providing the resources essential for carrying the monograph to completion. We acknowledge and give special thanks to Sandra Rush for her exemplary contribution as technical editor of the monograph and for her preparation of the camera-ready versions of the chapters for publication. Our appreciation to Keith Seitter of the American Meteorological Society for his encouragement of this project and for his preparation of the monograph subject index. Special acknowledgments are due to Carlye Calvin for preparing the Bergen symposium photo album, and to Frank Cleveland for his assistance in obtaining many of the photographs appearing in the historical photo album, and to Paul Neiman for his help in constructing the historical photo album.

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Components of the Norwegian Cyclone Model: Observations and Theoretical Ideas in Europe Prior to 1920

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1. Introduction

The publication of a scientific article is occasionally used to mark, in retrospect, the beginning of a new era for a scientific discipline. For meteorology, Jacob Bjerknes's article of 1919, "On the structure of moving cyclones" (referred to as JB19 in the following), provides such a landmark, as it first introduced the model of the *ideal cyclone*, which greatly influenced research and practical weather forecasting for many years to come. The achievement made by the Bergen school of meteorology at the end of World War I can, it is thought, be esteemed especially well if related observations and theoretical considerations, published before 1920 are recalled.

At the beginning of JB19, J. Bjerknes gave the following "characteristic traits" of the surface flow of a moving cyclone (Fig. 1): (a) a spiraling inflow toward the cyclone center; (b) two lines of convergence (*steering line* and *squall line*, which were later called warm and cold fronts, respectively[1]); and (c) the pronounced warm sector to the south of the cyclone center, signifying a pronounced asymmetry in the temperature distribution. In this chapter, we look for evidence as to what extent these components of the Norwegian cyclone model were individually described in the European literature during the period 1880 to 1920.

The Bergen school's visualization of their concepts through skillfully crafted conceptual sketches and later also by detailed weather maps appears to be one of the foundations of its success. This was in contrast to the general practice for fewer figures to appear in journal articles before 1920 than nowadays. But figures have been published earlier and some of these, which are to date probably not widely known, are reproduced here. Thus, we can obtain a quite direct impression of the way extratropical cyclones and their components were viewed in Europe during the four decades around the turn of the century.

A very thorough historical investigation of the much wider topic, the thermal theory of cyclones, was carried out by Gisela Kutzbach (1979; K79 in the following). It includes 49 historical diagrams, and mentions, in its later chapters, the majority of the works quoted here. However, most of the figures reproduced here were not included. A special feature of Kutzbach's book is its appendix, which contains short biographies of scientists who had made important contributions during the early phase of cyclone research. We also make some biographical remarks in footnotes to stimulate interest in the acting persons.

This chapter is organized as follows: Section 2 deals with investigations regarding cyclones as a whole, some of them indicating an asymmetric temperature field. Section 3 presents observations, a laboratory experiment, and theoretical ideas regarding squall lines as examples of discontinuities in the atmosphere. Section 4 mentions descriptions of pronounced warm sectors. Section 5 briefly outlines the reception and tradition of these early studies, together with the Norwegian cyclone model after 1920. Finally, conclusions are drawn concerning the value of such a retrospective investigation.

2. Asymmetric Cyclones

The terms *depression, barometric minimum*, or *cyclone* have been used for larger-scale regions of lower surface pressure and significant weather since the early nineteenth century. Mostly thermodynamic concepts were used in the numerous attempts to explain the internal structure and the development and progression of cyclones (K79).

1. The now familiar terms were introduced by Bjerknes and Solberg (1921), where the change in nomenclature is briefly commented in a footnote (on p. 25).

M. A. Shapiro et al. (eds.), *The Life Cycles of Extratropical Cyclones*

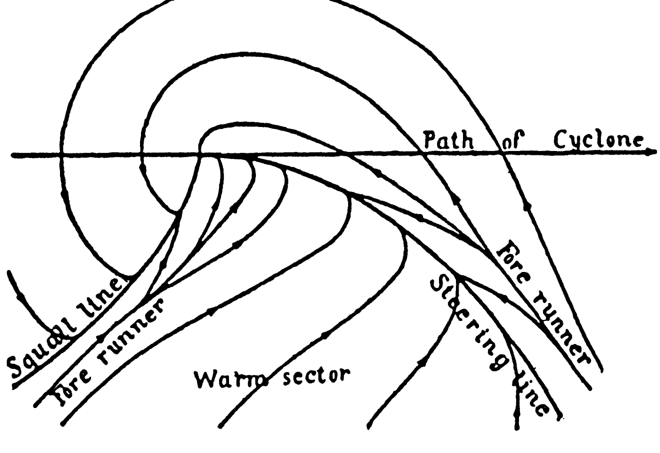


FIG. 1. First appearance of the Norwegian cyclone model and its flow structure. The components are an asymmetric cyclone moving from left to right, a sector of warm air in the south, and two separation lines ahead of and behind the warm sector (JB19, Fig. 1).

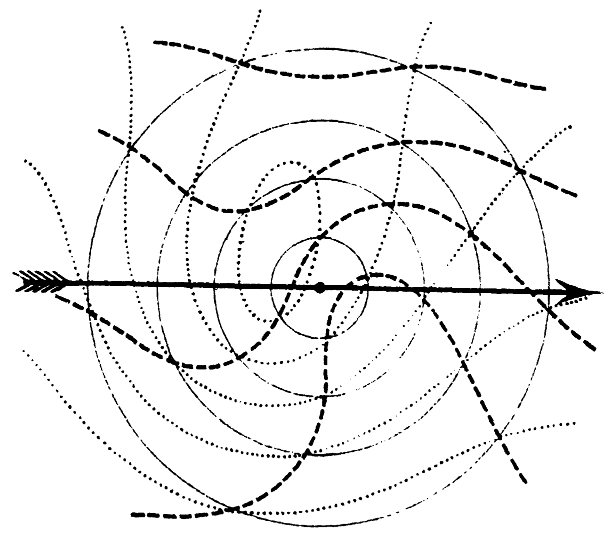


FIG. 2. Interrelationship among idealized circular surface isobars (solid lines), cirrus-level isobars (dotted lines), and mean isotherms of the air mass between (dashed lines) (Köppen 1882a, Fig. 2a on plate 23).

There have also been attempts to link the effects of dynamics and thermodynamics in a consistent manner. Köppen[2] (1882a), when reviewing empirical rules put forward by Ley (1872), introduced a consistent conceptual model, which related a circular surface low, a slightly westward shifted upper-level trough, and a highly asymmetric mean temperature distribution of the intermediate layer (Fig. 2). The temperature field was obtained by graphical subtraction, that is, by joining points of equal pressure differences. The upper level pressure field was constructed from observations of cirrus cloud motion provided by Ley. This method of *indirect aerology*[3] was later used during the early years of the Bergen school. Köppen's schematic and its background were also discussed in the widely read German textbook on meteorology by Sprung (1885).

The meteorological services established in many European countries during the second half of the last century thoroughly investigated cases of strong depressions passing over their areas of interest. A very revealing example is the case study by Shaw[4] et al. (1903), when "the British Isles were visited by a storm of unusual severity." They stressed the value of time series from self-recording instruments (see Fig. 3) as a supplement to synoptic charts. They discussed the coincidence of pressure fall and temperature rise (during the night!) at stations south of the storm's center (Valencia, Southport, and Stonyhurst) and contrasted it with the development at places which were "under the path of the storm" (Glasgow and Aberdeen). In their concluding paragraph, Shaw et al. (1903) mentioned the role of the "strong and warm Southerly wind . . . independent of any local action within the storm area" for the development of this particular event. As an aside we note Shaw's remark in the discussion that "he had no wish to add another to the theories of storms—there are too many of these already," but he wanted to increase the knowledge of the facts and to deal with their classification.

In 1906, Shaw and Lempfert published the pioneering monograph, *The Life History of Surface Air Currents*, in which they applied their concept of air trajectories to show that cyclones comprise air masses from very different source regions. One of the many diagrams is reproduced in Fig. 4, depicting a mature cyclone over the Atlantic with a polar airstream in its rear and a subtropical one ahead of it. The methodology, originally developed for more mesoscale studies over the British Isles, had been applied to a "historic" data set, which covered 13 months in 1882 and 1883, in an attempt to describe the complete *life history* of surface air currents in

2. Wladimir Peter Köppen (1846–1940) was appointed director of the department of storm warnings and forecasting in the newly founded Deutsche Seewarte (literally, German sea observatory) in Hamburg in 1875, and worked as chief scientist and director of the research department of this institution from 1879 to 1919. Köppen is best known for his later work regarding climatology, for example, for his classification of climates, although he also made important contributions to synoptic and mesoscale meteorology during the earlier years of his career (cf. K79, 237–238).

3. The term *aerology* was suggested by Köppen before the Commission on Scientific Aeronautics in 1906 to distinguish the study of the free atmosphere, throughout its vertical extent, from investigations confined to the atmospheric layer near the earth's surface.

4. Sir William Napier Shaw (1854–1945) was director of the Meteorological Office in England from 1905 to 1920, knighted in 1915, and was first professor of meteorology at Imperial College until 1924. He introduced trained scientific staff at the Meteorological Office, emphasized studies of the physics of the atmosphere, and produced the four volume *Manual of Meteorology* (cf. K79, 243–244).

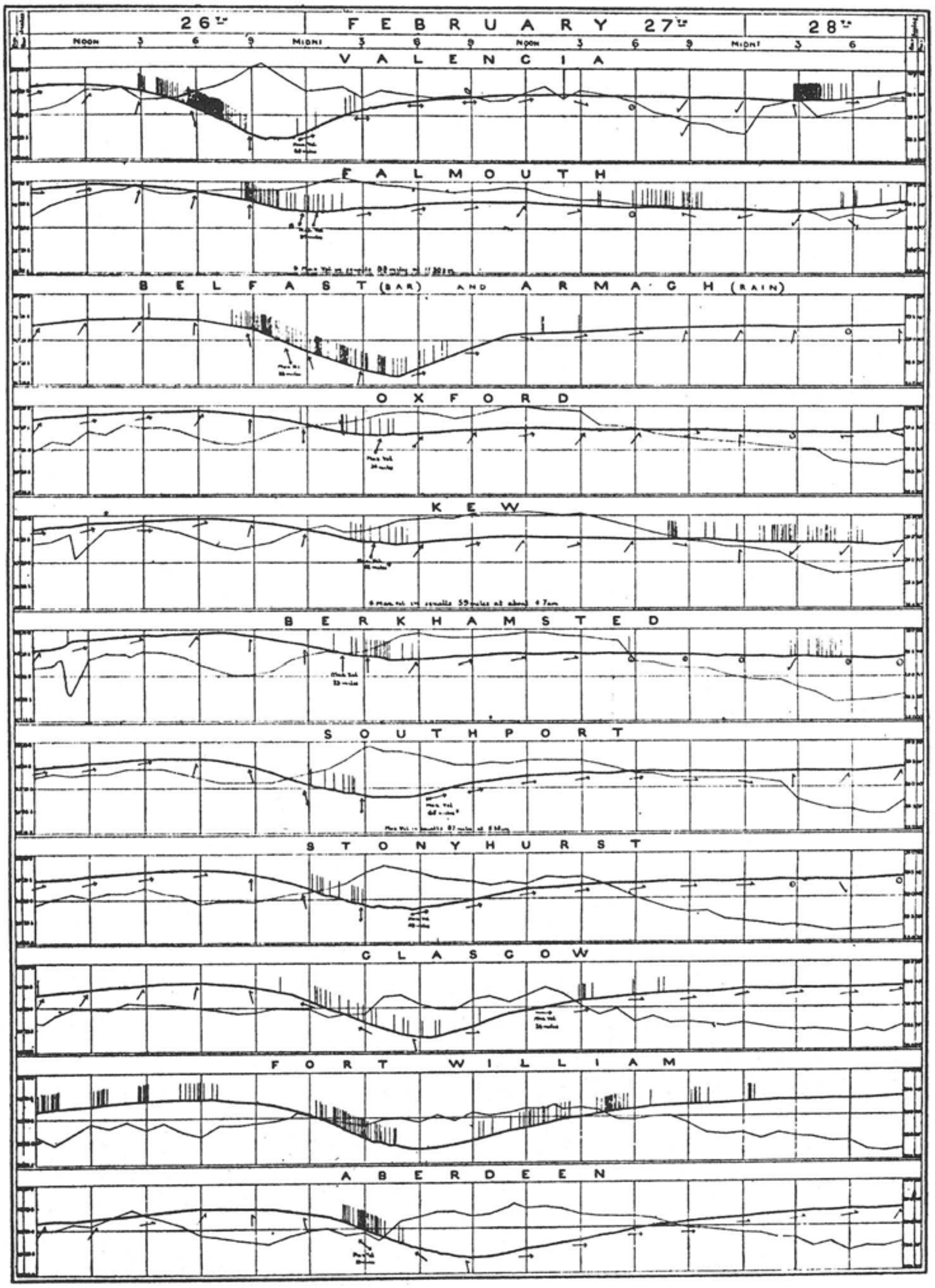
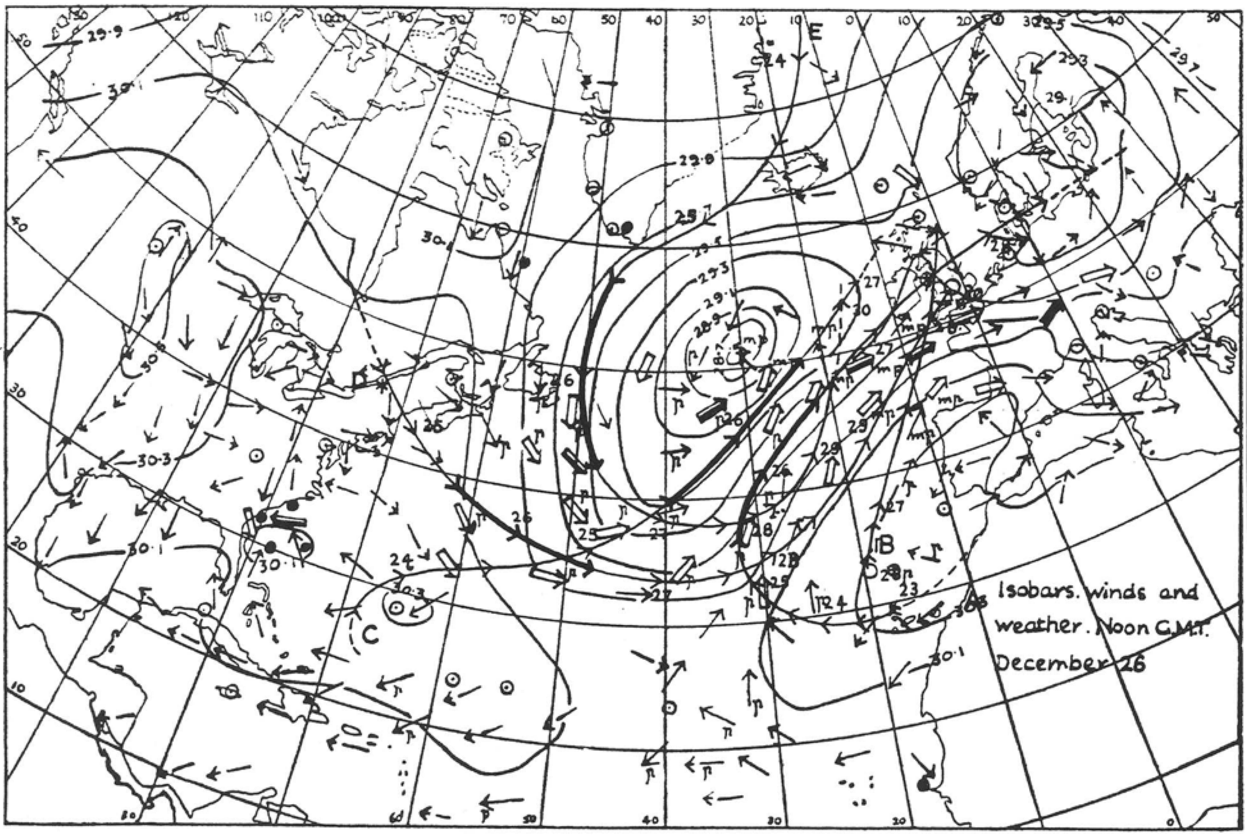


FIG. 3. The passage of a strong depression over the British Isles documented by time series of pressure (thick line), temperature (thin line), horizontal wind, and rainfall (short vertical lines on pressure trace; each line marks 0.01 inch = 0.25 mm) for the period 0900 GMT 26 February 1903 until 0900 GMT 28 February 1903 at eleven stations. The horizontal line in the middle of each series represents 29 inch Hg (980 hPa) and 40°F (4.4°C) with ranges of 1 inch Hg (33.8 hPa) and 10°F (5.6 K) above and below; 3-hour periods are separated by vertical lines (Shaw et al. 1903).

the vicinity of cyclones. In their conclusions, the authors admitted uncertainties in the database and suggested that "observations must be extended on the one hand by enlarging the area and on the other by including measurements made in the upper air."

Techniques of obtaining upper air data from ascents of manned and unmanned balloons and of kites began to be developed before the turn of the century (cf. the very recent account by Hoinka (1997)). Soon coordinated ascents from several European stations were organized. A paper by Hergesell[5] (1900) collected results of these international

5. Hugo Hergesell (1859–1938) was founding president of the International Aerological Commission from 1896 to 1914, then director of the aerological observatory in Lindenberg. He developed instruments, improved observation procedures for the free atmosphere, and encouraged close cooperations between meteorology and aeronautics.



NOTES.—In the Synoptic Charts on Plates XXIV, XXV and XXVI direction and force of wind have been indicated

thus: ⊙ calm, - → 1–3, ⟶ 4–6, ⟹ 7 & 8, ⟹ 9 & 10, ➡ 11 & 12, the numbers referring to the Beaufort wind-scale.

Weather is indicated thus: • rain, p showers, m mist, f fog

FIG. 4. Synoptic surface chart of 1200 GMT 26 December 1882 with superimposed trajectories for the period 23–30 December. The synoptic information is in light gray (blue in the original print) and contains pressure (increment 0.2 inch Hg = 6.8 hPa), wind and weather (see legend). The trajectories are in black (labeled A-E); small arrows along them mark 12-hourly intervals (the day numbers are given at the noon positions); the 24-hour period centered on the synoptic map time is thickened (Shaw and Lempfert 1906, Fig. 2 of plate xxiv).

ascents. Besides many technical details it contained approximated upper air charts such as the distribution of isotherms at a height of 10 km for 13 May 1897 (Fig. 5). Today's practice to construct upper air charts on constant pressure surfaces had not yet been adopted. The cold core over central Europe was put in relation to the extended cold period at the ground, which was classified as a good example of the quasi-regular weather anomaly in mid-May known as *Eisheiligen* in German.

3. Squall Lines

Elongated, narrow regions of rapid or quasi-discontinuous change in meteorological parameters were investigated throughout the last century. Most frequently, meteorologists described passages "of a sudden strong wind or turbulent storm" (dictionary definition of *squall*), which were found to progress over extended areas as organized lines separating a warmer air mass from an advancing colder one (cf. K79, Section 6.7).

In a very detailed account in two parts, Köppen (1882b) documented the event of 9 August 1881. The bulk of this study dealt with the description of the impact that this fierce cold front had in various places on its way across Germany. An account was also given of how the data collection was gradually extended after Köppen had realized that the event was not just a local thunderstorm, as he had first suspected. The pressure and temperature analyses during the peak phase are of particular interest (Fig. 6). They show a distinct mesoscale trough-ridge system; an isolated area of low pressure to the east of 12°E and south of 48°N, probably due to Föhn in the Alpine lee; and a narrow band of distinct

FIG. 5. Isotherms at a height of 10 km (lowest value in the center: –80°C; increment: 5 K) constructed from simultaneous balloon ascents on 13 May 1897 (Hergesell 1900, plate i).

temperature contrast all the way from the Baltic coast (at the northern edge of the panel) to the Black Forest (in the southwest), which was partly collocated with storm force winds. All these features, incidentally, are remarkably similar to recent analyses of a cold front observed during the Fronts Experiment 1987 (see Volkert et al. 1992).

The few other diagrams in Köppen's monograph include barograms from eight stations—some with distinct pressure jumps—and qualitative isochrons of the leading edges of thunderstorms associated with the squall line. Köppen mentioned as mechanisms conducive for the strong temperature contrast: airflow from different source regions ahead of and behind the front, strong insolation in the east, and evaporative cooling in areas experiencing heavy rain and even hail in the west.

Ten years later, Durand-Gréville[6] (1894) systematically investigated thunderstorms and their relation to squall lines, many of which progressed from France into the eastern parts of Europe. Hourly isochrons and a mesoscale pressure analysis (Fig. 7) document the "particularly severe squall line of 27 August 1890." The general conclusions of the investigation comprised, inter alia: (1) squall lines can be detected by the bulged form of the isobars, (2) significant weather is triggered by the highly disturbed flow field, and (3) there are only a few depressions without an area of squalls where precipitation is likely to be produced. He suggested a combination of self-registering instruments in the western parts of France with the telegraph transmission of data to the east as a tool for timely warnings.

Beginning in 1895, Margules[7] used a mesoscale network of four barographs around Vienna in an attempt to relate high winds at the central location with the pressure gradient in its neighborhood, especially for thunderstorm situations. Although the number of stations proved to be insufficient for general conclusions, Margules (1897) discussed, among other cases, the pressure traces during the passage of a "devastating storm of short duration" on 26 August 1896 (Fig. 8). Westerly surface winds of 90 km h^{-1} coincided with the onset of a steep pressure rise (about 10 hPa over 2 h) in Vienna. Comparisons with stations farther to the west and from Sonnblick mountain observatory (3106 m) revealed that the cold (i.e., denser) air advanced eastbound north of the Alps, but was confined to a layer below the Alpine crest height. Special mention was made of the quasi-instantaneous (i.e., within less than 12 min) pressure jump of about 10 hPa in Gmunden, situated at the Alpine baseline about 200 km to the west of Vienna. At the end, Margules considered his work as meager compared to Köppen's study. During the following years, he thoroughly investigated temperature steps in thermograms from mountain and nearby valley stations for three-dimensional analyses of the progression of air masses. This observational evidence eventually served as the background for Margules's celebrated theoretical studies on the energetics of storms and surfaces of discontinuity (cf. K79, Section 6.6). We note that highly resolved pressure traces continue to be relevant for the investigation of frontal modification by the Alps (e.g., Hoinka et al. 1990; Volkert et al. 1991).

Line-squalls constituted a topic of detailed research at the Meteorological Office in England during the first decade of this century. Lempfert[8] (1906) and Lempfert and Corless

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6. Emile-Alix Durand-Gréville (1838–1914) was a French writer and independent scientist who translated works by novelists such as Turgenev into French and taught for a long time in St. Petersburg before returning to Paris in 1872. From 1890 onward he carried out highly resolved analyses of squall lines, thunderstorms, and hail storms. He contributed mathematical, physical, and climatological articles to several encyclopedic works, was in charge of all meteorological aspects for the publisher of the *Grande Encyclopédie*, and served as vice-president of the Société Astronomique.

7. Max Margules (1856–1920), a physicist and chemist of outstanding calibre, but of rather introverted and partly eccentric personality, worked at the Zentralanstalt für Meteorologie in Vienna from 1882 to 1906. After the turn of the century he published the first thorough theoretical analyses of atmospheric energy processes using thought experiments derived from his earlier observational studies (cf. K79, 239–240).

8. Rudolf Gustav Karl Lempfert (1875–1957) was a university assistant to Shaw in Cambridge (1898–1900) and held various positions at the Meteorological Office between 1902 and 1938, ranging from personal scientific assistant of the director (Shaw) to assistant director. He drew all charts of the 1906 memoir on surface air currents and later thoroughly investigated line-squalls (cf. K79, 238–239).

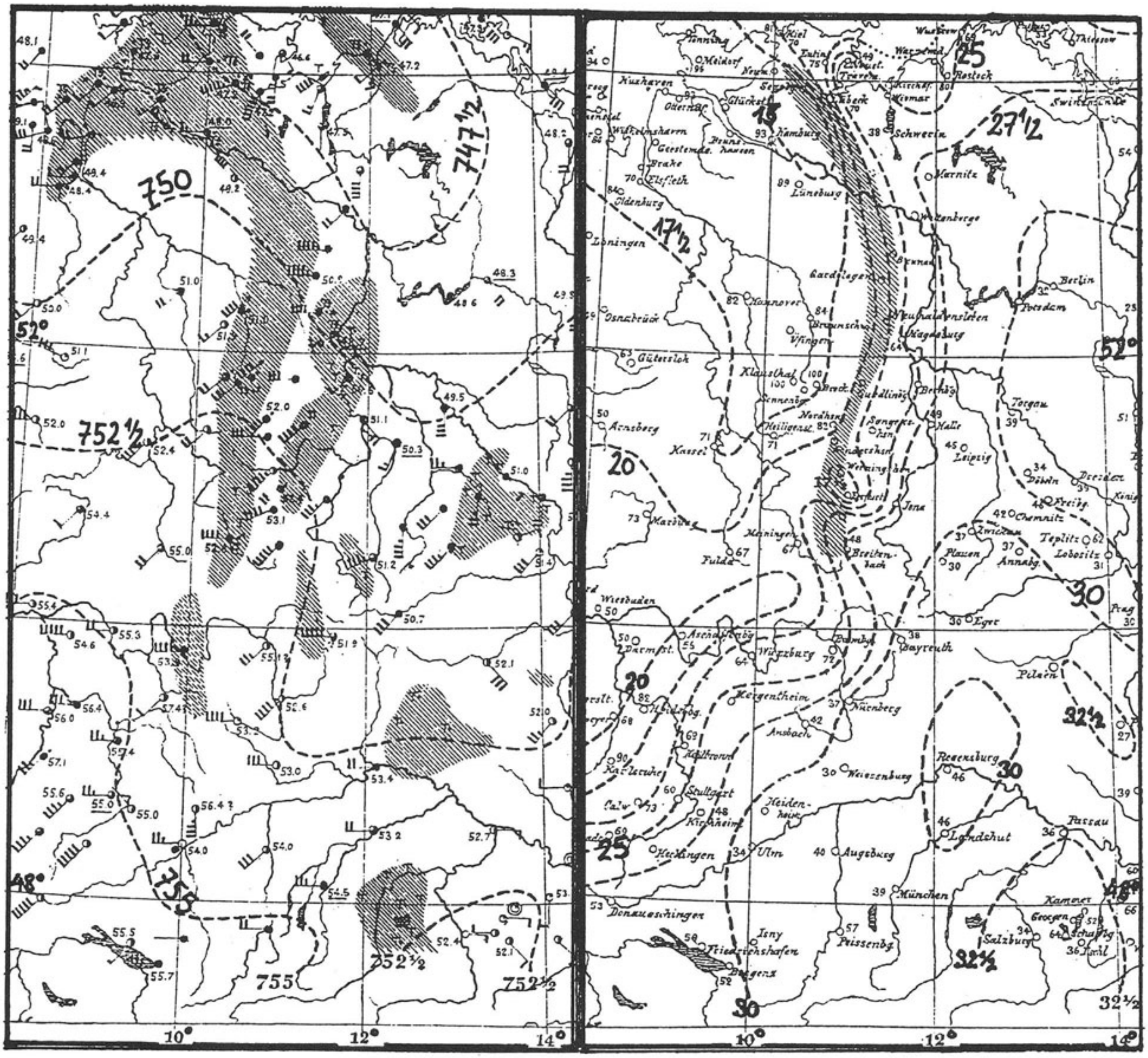

FIG. 6. Mesoscale surface charts over central Germany for 9 August 1881, 2 p.m. The left chart shows station reports of wind (long and short flags, respectively, for single and double Beaufort grades), cloud cover (octa), sea level pressure (mm Hg above 700), pressure analysis with 2.5 mm Hg (3.3 hPa) increment, and areas with thunderstorms (hatched). The right chart displays station reports of relative humidity, a temperature analysis (reduced to sea level with a 2.5 K interval), and area of stormforce winds (hatched) (Köppen 1882b; central portions of plates 20 and 21).

(1910) presented several detailed case studies containing a number of synoptic weather maps, isochron charts, and careful mesoscale analyses of the pressure field. Of special interest is the practice of identifying the squall line with a fault in the pressure analysis (Fig. 9) to achieve consistency with the jumps in the barograph traces at fixed stations. Lempfert (1906) stated that "line-squalls tend to arrange themselves with regard to depressions, and to rotate round their centres, like the spokes of a wheel." Lempfert and Corless (1910) described four cases and culminated in a discussion of "the wind vector changes" across the discontinuities. Conceptual vertical sections (see K79, Fig. 46) depicted the flow in a fixed frame of reference and in one steadily moving with an idealized backward-sloping "linear front," clearly indicating "upward motion in front of the line and downward motion behind it."

At approximately that same time, the intrusion of a denser fluid under a lighter one was investigated in the laboratory by Schmidt[9] (1911) with explicit reference to

9. Wilhelm Schmidt (1883–1936) was a research scientist at the Zentralanstalt für Meteorologie in Vienna from 1905 to 1919, then professor of physics of the earth in Vienna and, from 1930 until his sudden death, successor of F.M. Exner as director of the Zentralanstalt. He was renowned for his laboratory experiments with gravity currents, and he constructed a variograph to register atmospheric pressure differences at squall lines. Around 1920 he coined the term "*Austausch*" for the description of a whole range of geophysical exchange processes for which coefficients can be determined empirically.

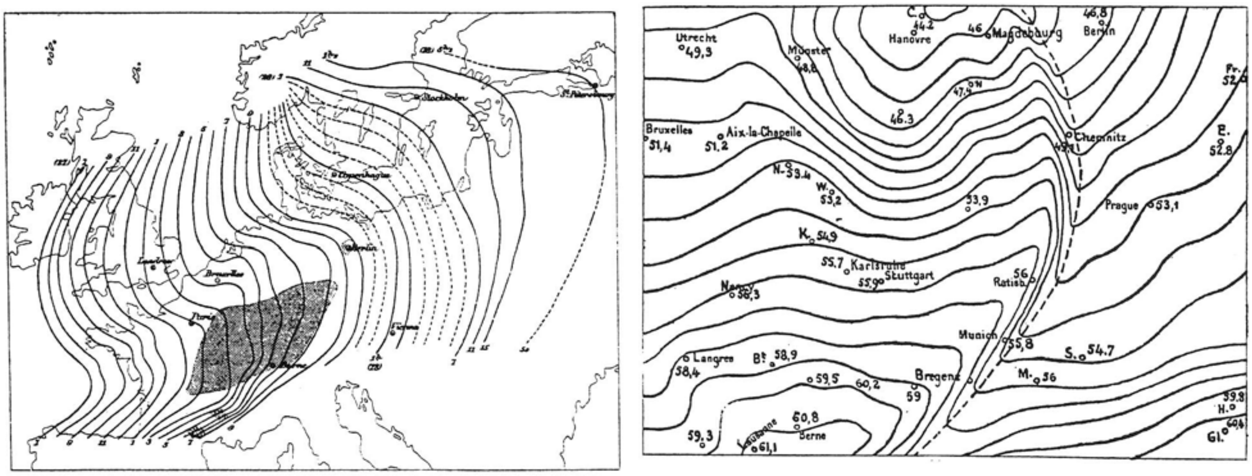

FIG. 7. The squall line of 27 August 1890. Left: hourly isochrons of pressure jump (longer intervals in the east) and areas with thunderstorms (hatched); locations are from west to east: London, Paris, Brussels, Berne, Copenhagen, Berlin, Vienna, Stockholm, St. Petersburg. Right: pressure observations (reduced, mm Hg above 700) and analysis over central Europe for 27 August 1890, 9 pm (increment: 1 mm Hg = 1.33 hPa) (Durand-Greville 1894, Figs. 1 and 2).

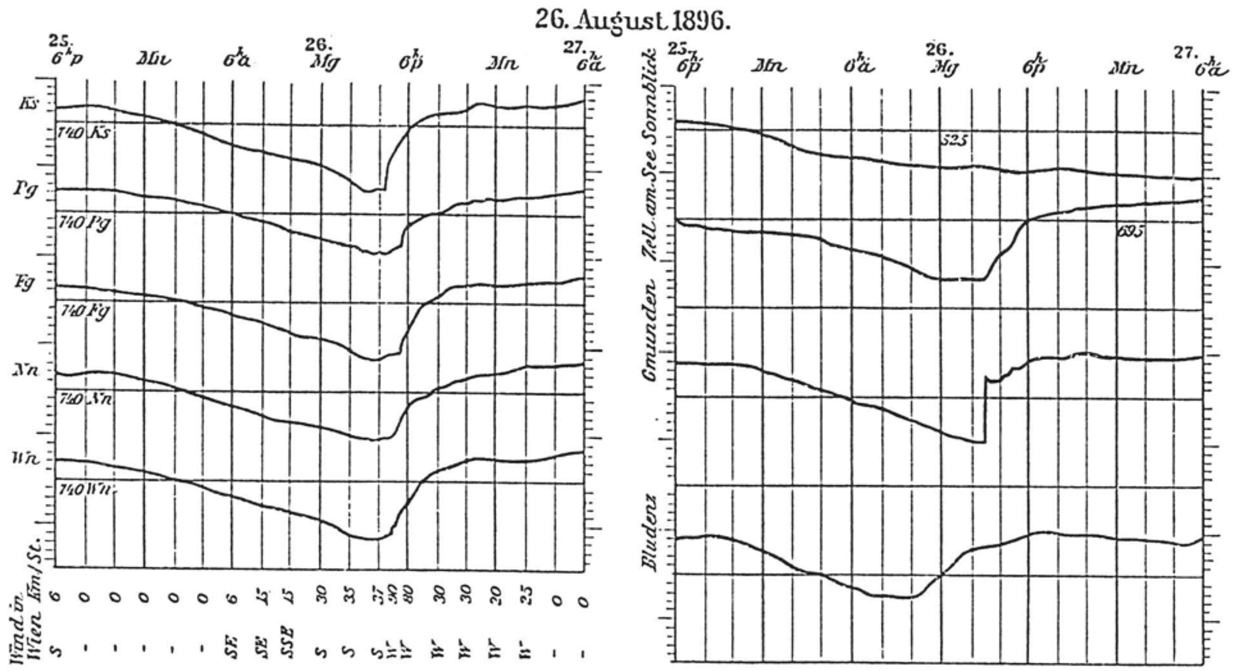

FIG. 8. Surface pressure traces for the period 25 August, 6 p.m., until 27 August 1896, 6 a.m., for a mesoscale network of stations around Vienna (left) and other stations in the west of Austria (right). Vertical lines every two hours; Mn: midnight; Mg: noon; tick marks every 1 mm Hg (= 1.33 hPa); horizontal lines designate reference pressure of 740 mm Hg, except for Zell am See (695 mm Hg) and Sonnblick (525 mm Hg). Station codes: Ks - Krems, Pg - Bratislava, Fg - Feldsberg, Nn - Neunkirchen, Wn - Vienna. Wind speed (km h^{-1}) and direction for Vienna are given every 2 hours under the left diagram (Margules 1897, Fig. 5).

squall lines. Such a *gravity current* was used as a prototype for the interaction of warm and cold air masses. Schmidt worked with an elongated, two chambered tank bounded by glass walls. Salt water was used as the denser fluid. Inclination angles varying between 0.5° and 35° resulted in different flow speeds once the separation between the chambers was lifted. Time exposure (2 s) photographs of illuminated suspended particles (sawdust) were produced to infer the instantaneous velocity distribution (Fig. 10). Characteristic was the elevated head of the denser fluid with some turbulent motion above and recirculation behind it. Schmidt translated the results of his experiments to temperature differences and propagation speeds of squall lines and found good agreement with Köppen's case. At the same time he regretted the

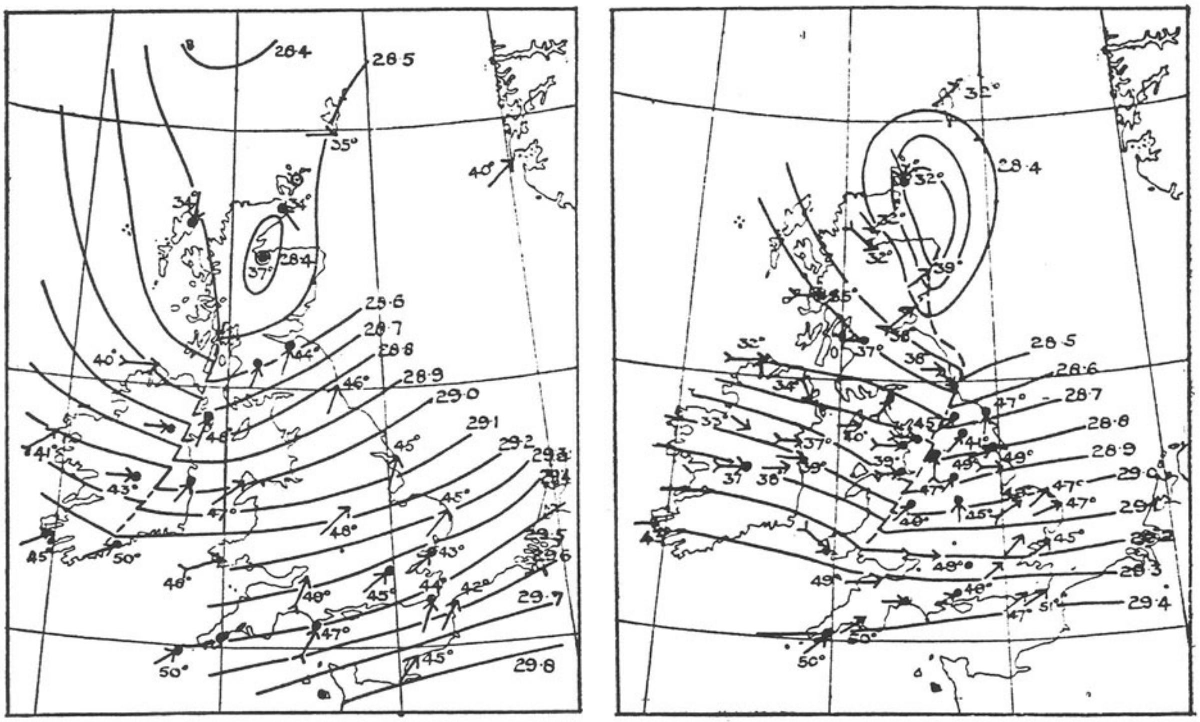

FIG. 9. Synoptic surface charts with wind and temperature (°F) observations as well as a mesoscale pressure analysis (increment: 0.1 inch Hg = 3.4 hPa) with a line-squall (dashed) extending southward from a surface low for 1800 GMT 19 February 1907 (left) and 2100 GMT 19 February 1907 (right) (Lempfert and Corless 1910, Figs. 7 and 8).

insufficiency of observational data to evaluate the analogy between laboratory and atmosphere in a more rigorous fashion, without mentioning the detailed case studies by Lempfert.

Köppen (1914) reviewed his earlier studies, the work of Durand-Gréville and Schmidt, and he presented observations of the severe squall line that passed over the German Bight on 9 September 1913 where it caused the crash of the airship L1. Quickly alternating upward and downward motions of considerable strength forced the airship down to 100 m above the sea, up to 1400 m and down onto the sea. When it touched the water with some 20 m s^{-1}, it broke apart and sank after a short while. The close proximity of updrafts and downdrafts was said to have been directly observed earlier and was considered characteristic for squalls connected with thunderstorms.

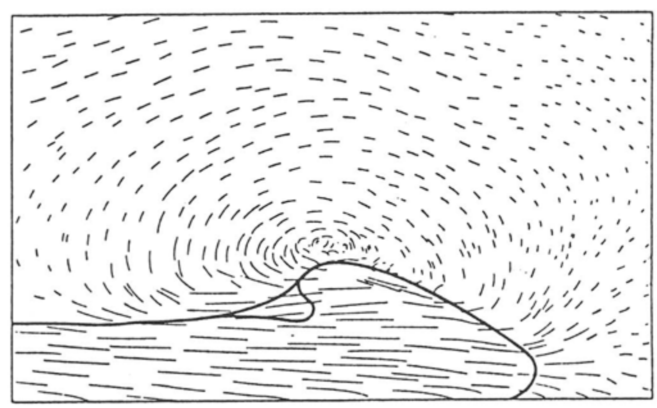

FIG. 10. Instantaneous velocity distribution during the intrusion of dense fluid (thin lines show the movement during 2 sec). Flow direction is from left to right. The approximate outline of the "head" is marked by the bold line (Schmidt 1911, Fig. 2).

During the second half of the last century, theoretical considerations based on physical principles were gradually applied to meteorological problems, beginning with *thermodynamics*, for example, the effects of variable temperature and moisture in the atmosphere (typically at rest); and then also leading to *dynamics*, that is, the role of various forces for the movement of the atmospheric fluid. The latter topic included the investigation of different air masses separated by a surface of discontinuity and the stability of such an arrangement subject to small perturbations.

The renowned physician and physicist Hermann von Helmholtz[10] (1888) was probably the first to consider math-

10. Hermann Ludwig Ferdinand von Helmholtz (1821–1894) was the most influential scientist during the late nineteenth century in Germany as was his contemporary and friend Lord Kelvin in England. He received his basic training as an army surgeon, and later was professor of physiology. From 1871 he was professor of physics at a newly created institute in Berlin. He gave a mathematical treatment of the energy conservation principle in 1847. In fluid dynamics he investigated discontinuous motions and the condition of dynamic equilibrium along surfaces of discontinuity (see K79, 235–236).

ematically the equilibrium condition of the surface between different air masses on the rotating globe, specifically of an idealized (axisymmetric and inviscid) atmosphere, by juxtaposing two homogeneous layers of different angular momentum (i.e., wind speed) and potential temperature (i.e., density). He found that a dynamically stable equilibrium can exist if the two layers are separated by an *inclined* surface of discontinuity. The derivation of the stability condition is followed by a detailed qualitative discussion including frictional effects and the role of typical cyclones and anticyclones for mixing processes at the postulated prototype discontinuity.

Later, Margules (1905) introduced thought experiments dealing with the available potential energy, which is stored in adjacent air masses of different mean temperatures and which may be converted to kinetic energy (of a storm) when the colder air mass moves under the warmer one. Explicit mention is made of the better known motion fields along squall lines and the lesser understood ones within complete cyclones, when a warmer air mass is often followed by a cold air outbreak in the rear. Interestingly, JB19 quoted this passage as supporting evidence for his new conceptual model, although Margules concluded his paper with the frank remark: "The source of the storms lies, as far as I can see, entirely in the potential energy. . . . The horizontal pressure distribution appears as a kind of transmission within the storm's motion, by which a fraction of the air mass can aquire high velocities. . . . This leads to problems which cannot be solved by considering solely energetics."

One year later, Margules (1906) transformed Helmholtz's frontal-equilibrium condition to a constantly rotating Cartesian coordinate system. He wrote in the introduction: "I am trying to derive Helmholtz's equation in a way, that may well offer easier applications to meteorological problems." The simple model of a steady-state front involved an inclination angle α, which can be determined as a function of the velocity and temperature differences across the front. This well-known textbook formula was also quoted in JB19 (but erroneously from the 1905 paper) during the discussion of the squall line (cold front) together with Schmidt's laboratory study. Margules checked his idealized model using distinctly differing registrations of temperature and wind of stations not far from each other (Vienna and Bratislava). He also considered a temperature gradient zone in relation to vertical changes in wind speed rather than a sharp discontinuity. Finally, he followed Helmholtz's discussion on mixing processes acting on separated air masses or fluids and introduced simple thought experiments, for which he derived formulas for the energy conversion through mixing.

4. Warm Sector

Asymmetries in the temperature distribution within cyclones were hinted at in the literature before 1920. We have mentioned Köppen (1882a), Shaw et al. (1903), and Margules (1905) as examples. Detailed case studies of extended regions of anomalous warm air progressing over the whole of northern Asia were available by 1911.

Ficker[11] (1911) analyzed 11 episodes of about 10 days each from the years 1898 to 1902 when *warm waves* (as he called them) had traveled all the way from 40°E to at least 110°E. He confined his analyses mostly to isochron charts of the daily positions of the leading edge of the wave of warm air, but also presented some synoptic temperature analyses (Fig. 11). A massive warm sector spanned as much as 20 degrees of longitude over Siberia and was bordered by a zone of warming ahead of it and cooling behind it. Ficker also gave a conceptual scheme (Fig. 12) as a summary of this study and its companion (Ficker 1910), which dealt with the progression of *cold waves*. The scheme emphasized the thermal structure and did not give a characteristic length scale. But if one associates the bounding isotherm with what the Bergen school later called the *polar front*, similarities become obvious.

In Vienna, an intermediate position between the theoretician Margules and the data analyst Ficker was occupied by Exner[12]. For many of the present meteorological community, the factor to convert temperature to potential temperature (Exner's function) appears to be the only association with his name, although he was among the leading figures of European meteorology of his day, besides, for example, N. Shaw and V. Bjerknes.

Exner's textbook on dynamical meteorology (completed 1915, published 1917) was to a large extent based on concepts first developed by Margules. In chapter 74 on "the genesis of cold air outbreaks," for instance, a Margulean type front was introduced separating a cap of cold polar air, which

11. Heinrich von Ficker (1881–1957) was a research assistant at the Zentralanstalt in Vienna in 1906, held university positions in Innsbruck and Graz from 1909 to 1914, was a professor in Berlin from 1923 to 1937, and director of the Zentralanstalt as successor of W. Schmidt from 1937 to 1953. Fisker made many balloon ascents in Föhn flows for his dissertation, scrutinized the large body of surface data from Russia, and explored the interactions of troposphere and stratosphere in the development of cyclones (see K79, p. 233).

12. Felix Maria Exner (1876-1930) worked at the Zentralanstalt in Vienna from 1900 to 1910 with a leave of one year (1904–1905) for a world tour with extended stays in India and the United States. He was a professor in Innsbruck from 1910 to 1917 and then director of the Zentralanstalt and professor of physics of the earth in Vienna. He pioneered numerical weather forecasting by evaluating the surface pressure tendency for a geostrophically balanced flow with a climatologically determined thermal forcing before 1908, published a textbook on dynamical meteorology in 1917, undertook rotating tank experiments to study analogies of tornados as well as the general circulation with embedded cyclones, and attempted to explain cyclogenesis by the interaction between the westerlies and cold air outbreaks from polar regions (see Shields 1995, 1–3).

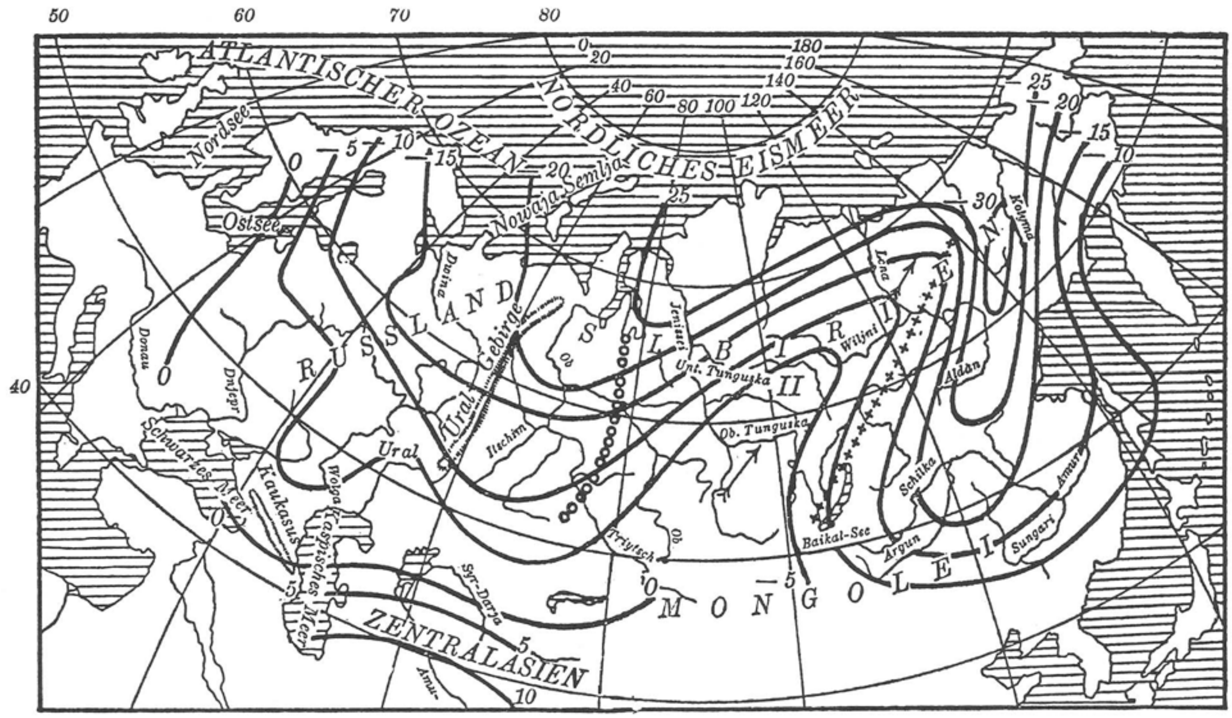

FIG. 11. Surface isotherms on 3 December 1901. Along the line ++++, quick warming is in progress; along the line oooo, fast cooling. Labels in °C; interval: 5 K. (First published by Ficker (1911, Fig. 11), taken from Exner (1917, Fig. 56)).

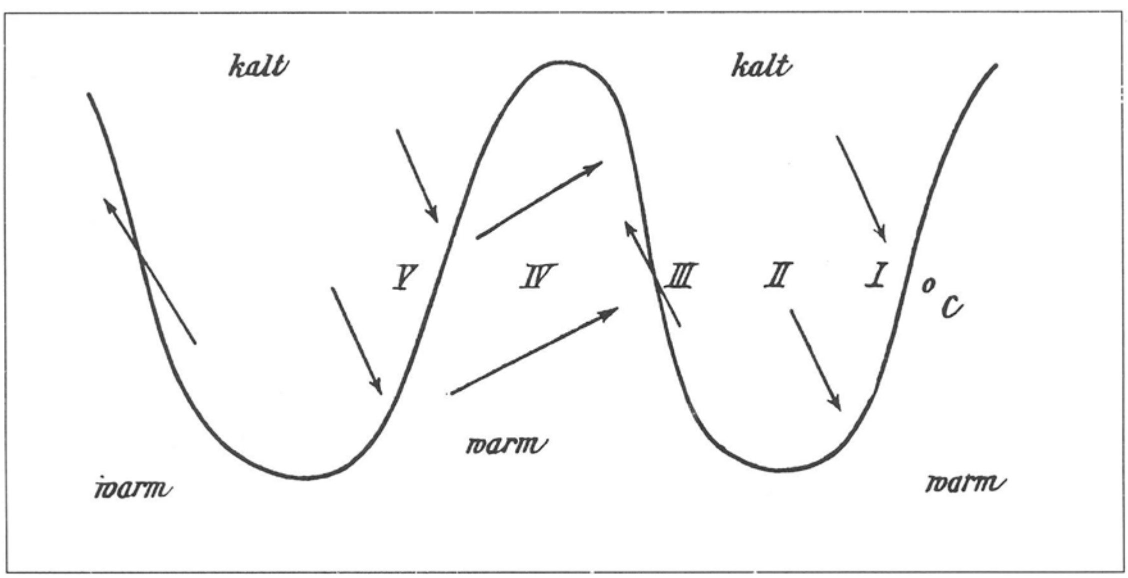

FIG. 12. Scheme of warm and cold waves over Asia depicting a bounding isotherm (wavy line) between cold air to the north and warm air to the south as well as predominant wind directions. The roman numerals designate different states at different places at the same time as well as the sequence of events at a location, say C, when the complete system passes from west to east. I: onset of cold wave with NW winds; II: lowest temperatures; III: gradual warming with winds from S to SE; IV: extremely warm SW winds; V: as I; phases III to V resemble the passage of a depression (Ficker 1911, Fig. 13).

is in steady westward motion relative to the warmer air aloft and farther south (Fig. 13). This may be viewed as a cross section through the *polar front*, a term introduced by the Bergen school some years later. Exner investigated how the frontal inclination α changes when the cold air gets retarded, for example, by frictional processes. He found a shallowing of the front equivalent to a gain of potential energy, which in part might be responsible for the strong winds observed during outbreaks of cold air toward the south.

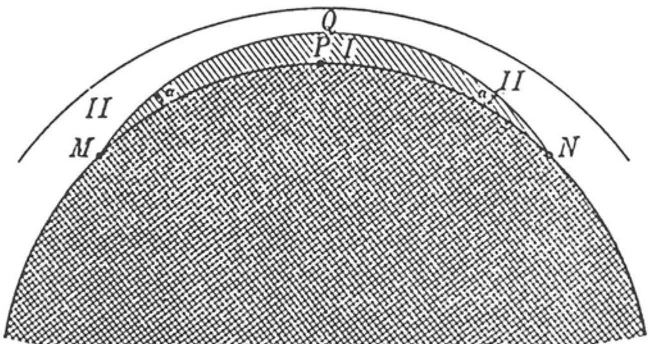

FIG. 13. Polar cap of a cold air mass (I) underneath a warm air mass (II). *O*, center of the earth; *P*, north pole; *M O P N*, span of the solid earth (Exner 1917, Fig. 58).

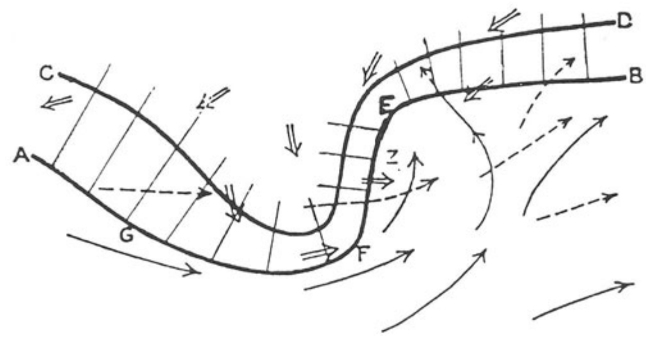

FIG. 14. Form and position of the separation surface between cold and warm air in a cold-tongue region. Full single arrows: warm airflow at the surface; dashed arrows: warm airflow aloft; double arrows: cold surface airflow (Exner 1920, Fig. 6).

One year after JB19 had been published, V. Bjerknes organized a meteorologists' conference in Bergen to better acquaint colleagues from abroad with his recent findings. For political reasons it took place in two sittings (Friedman 1989, 196). The German-speaking scientists gathered during the second part, when Exner (1920) presented his view of cold and warm airflow, in a lecture that Davies (1990) called "seminal but comprehensively unacknowledged." Having started with the general circulation including a Margulean type of polar front, and having presented observational evidence of cold air outbreaks, Exner developed a "hypothetical picture of the shape and position of the boundary between cold and warm air in the region of a cold-air-tongue, which progressed eastwards" (Fig. 14). The section EB of the surface front line AB was identified with the steering line (warm front) and EF with the squall line (cold front). CD gave the front position at a higher level; so the cold front was considered to be steeper than the warm front. It was noted that the scheme described best the development of shallow (i.e., only tropospheric) cyclones, which occurred often over North America and could be seen as early stages of mature cyclones, which extended into the stratosphere and were more frequent in the Atlantic sector. In a footnote, Exner stated that he became acquainted with the Norwegian cyclone model and the new *polar front theory* at the conference after he had written down his lecture (dated Vienna, 7 July 1920). He found the correspondence between both concepts encouraging and mentioned possible extensions of the theory of asymmetric cyclones.

5. Reception in the Secondary Literature

The preceding sections document the availability prior to 1920 of a variety of studies that dealt with components of the Norwegian cyclone model (first published in JB19). Today it appears to be impossible—and somewhat irrelevant—to exactly reconstruct which of these studies were known to J. Bjerknes, his father, and their co-workers in Bergen.[13] A comparison of all the papers quoted in the preceding sections with JB19 reveals the special quality of the latter: on only a few pages a quite elaborate conceptual model was introduced ("I have been led to some general results concerning the structure of cyclones"), which had been inspired by detailed analyses from meteorological archives and a daily weather forecasting practice, and which outstandingly combined earlier findings. This section attempts to back this view by looking at some pieces of secondary literature about the Norwegian cyclone model and its evolution.

The immediate impact exerted by Norwegian cyclone model and the polar front theory, not only on practical aspects of weather analysis but also on the scientific meteorological community, must have been considerable. Invited by the editors of *Meteorologische Zeitschrift* (one of them Exner), Ficker (1923) compiled a detailed review article about the "polarfront and the lifecycle of cyclones." In essence, he congratulated V. Bjerknes and collaborators for the introduction of a new compact scheme with clear and memorable diagrams and for coining short and characteristic names for the various phenomena. Ficker considered the description of the life cycle of cyclones as the most novel finding of the

13. A detailed account of the situation in Bergen during the summer of 1918, when J. Bjerknes wrote JB19, is given by Friedman (1989, chapter 6). In his (mainly personal) bibliography with historical remarks, V. Bjerknes (1933, 783–787) mentions Ficker's (1910) and Helmhotz's (1888) papers as sources of inspiration for empirical data analyses and theoretical investigations, respectively, during the few years at Leipzig University (1913–1917). Note that the research program of this new institute could not be pursued continuously during the course of World War I. The move to Bergen in 1917 proved to provide "lucky circumstances, which made it possible to continue the work, though in a much different way, namely as practical rather than theoretical weather predicition."

Bergen school, which also had implications for practical forecasting. On the other hand, he strongly disagreed with the claim that a radically new theory had been presented, and related the components of the Norwegian concept to earlier findings of others, especially from the Viennese school.

Textbooks for students may be used as indicators of how the development of concepts is generally seen in a scientific discipline. Raethjen (1953) presented a detailed monograph about extratropical cyclones and their dynamics some 30 years after the origin of the Norwegian cyclone model. He put strong emphasis on the historical development of concepts and compiled a detailed bibliography of 840 titles published between 1830 and 1950, including the studies of Köppen, Helmholtz, Margules, Ficker, Exner, Shaw, and Vilhelm and Jacob Bjerknes. In his conclusions, Raethjen emphasized two main cyclogenetic mechanisms: the thermal contrast between pole and equator, which can induce upper-level cyclogenesis in the jet stream regime, and gradient zones of latent or sensible heat at lower levels. Within frontal zones, both effects tend to be combined and most effective. He also noted that this kind of duality had already been advocated by the Viennese school of meteorology whereas the Bergen school had emphasized processes at lower levels.

More contemporary textbooks, such as Wallace and Hobbs (1978), tend to introduce just the Norwegian cyclone model as the standard—although idealized—conceptual model for extratropical cyclones. In their biographical footnotes about scientists who were claimed to have made major contributions to the atmospheric sciences, Jacob and Vilhelm Bjerknes, Helmholtz, Margules, and Shaw were mentioned.

There are also reviews that concentrate on the development of concepts from various points of view. Bergeron (1959), one of the Bergen school scientists, gave a wide and balanced historical review of the development of synoptic meteorology, putting into perspective the early case studies mentioned above in relation to the work of the Bergen school. One of his conclusions was that apparent rediscoveries were frequent in meteorology because of the complexity of the subject, an inefficiency in international bibliography and terminology and, very often, due to insufficient data to validate new hypotheses. He saw an essential difference between the case studies of, say, Köppen or Durand-Gréville and the Bergen school findings in the fact that the latter used "a rationally introduced concept on a routine basis on the daily synoptic charts."

The Bergen school period served as the terminus in Kutzbach's admirable book (K79), which discusses all primary sources on cyclone research between 1840 and 1920. Its conclusion states that "the polar front theory of cyclones is seen as an outstanding synthesis reconciling new insights and findings with important earlier results in meteorological theory" (p. 219), rather than representing a sharp break with older theories.

Schwerdtfeger (1981) criticized the indifferent attitude of the Bergen school scientists toward referencing older studies that had relevance to the cyclone model. Furthermore, he considered Bergeron's influence as essential for the acceptance of the new concepts in the synoptic practice in Europe, because, as Schwerdtfeger put it, Bergeron showed how to analyze the observations, whereas the Bergen papers (as JB19) mostly presented model sketches.

Friedman's (1989) scientific biography of V. Bjerknes discusses in depth the development of the cyclone and polar front models. Yet, both concepts feature as just two components of the elder Bjerknes's astonishingly dense curriculum vitae in an epoch of dramatic political, social, and technological change. Friedman's psychologizing attitude to rationalize in hindsight the sequence of events may be debatable, but he certainly presents a wealth of detailed background material, for example, from exchanges of correspondence.

A considerable amount of consciousness about the development of current research from quite old roots is apparent in the Atmospheric Science group at ETH Zurich. In the first chapter of his treatise on extratropical cyclogenesis, Schär (1989) sketched the development of ideas from the nineteenth century to the present time and juxtaposed the concepts of the Viennese and Bergen schools around 1920. Davies (1990) presented a masterpiece in historical condensation at the centenary of the meteorological institute in Innsbruck—150 years and nearly 100 citations on less than 10 pages of skillfully crafted text. He loosely grouped the theoretical concepts into three categories: (1) cyclogenesis attributed to an instability of a quasi two-dimensional sharp front to three-dimensional perturbations, (2) formation of lows linked to the passage of an upper-level trough over a band of low-level baroclinicity, and (3) cyclones regarded as outcome of a wave growing within a broad, but deep baroclinic zone with frontal features as some embroidery. The achievements of the Bergen school were considered as a milestone in the first group, "a masterful crystallisation of the prime observed features . . . and sandwiched in time between contributions of Exner." A more detailed account recently became available in Davies (1997).

6. Concluding Remarks

This chapter illustrates that the history of extratropical cyclone research in general and of the Bergen school in particular is well documented, perhaps better than for any other branch of the atmospheric sciences. The achievements made in Norway, starting with JB19, were recognized from the beginning and are highly valued to the present day. But there are also quite a number of important roots of the Norwegian cyclone model that deserve to be remembered and should be touched upon in courses of synoptic meteorology. Closer looks at the development of ideas regarding extratropical cyclones clearly reveal what it has in common with the subject itself: *Rich structures that are fascinating to explore.*

The question of why the Bergen ideas feature so prominently up to the present time cannot be answered in our context. Hints may be that especially V. Bjerknes devoted considerable energy to the widespread promotion of their concepts. Examples for this effort are a lecture before the congress of Scandinavian geophysicists and its double publication in *Monthly Weather Review* (1919) and *Meteorologische Zeitschrift* (1919), a letter to *Nature* (1920b) and *Monthly Weather Review* (1921), a lecture before the Royal Meteorological Society that was published in detail in its *Quarterly Journal* (1920a), and a keynote lecture in the physics section during the centenary conference of German scientists and physicians (1922 in Leipzig with about 10,000 participants; Kölzer, 1922). This was in contrast to other scientists, many of whom used academy transactions as their main medium for publication.

In more recent years, the Norwegian model has been mentioned as an example for a static conceptual model that led to an "unhealthy" situation for the present development of research (Hoskins 1983). The contributions in this volume certainly document how fit meteorology is at present, especially in the important field of extratropical cyclones and their life cycles. A good understanding of the development of various ideas and their interdependence is thought to be conducive to progress, especially if interchanges are achieved across political boundaries and language barriers. Overlooking longer periods of time will also create some modesty about the most recent achievements, as Köppen (1932) remarked with direct reference to both Bjerkneses when, at the age of 86 years, he reminisced:

> I happily acknowledge that meteorology has made great advances compared to the situation in . . . 1880, especially through V. and J. Bjerknes. . . . We also had seen air masses of different character within the general airflow, but we could not make much of our observations.

And he continued:

> For the present generation of researchers it is perhaps interesting to learn that an earlier generation tackled the same problems, partly with some success and partly without.

This was 66 years ago. It certainly is still interesting—and still true—today.

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