Antecedents for the Shapiro–Keyser Cyclone Model in the Bergen School Literature

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ABSTRACT: Two widely accepted conceptual models of extratropical cyclone structure and evolution exist: the Norwegian and Shapiro–Keyser cyclone models. The Norwegian cyclone model was developed around 1920 by the Bergen School meteorologists. This model has come to feature an acute angle between the cold and warm fronts, with the reduction in the area of the warm sector during the evolution of the cyclone corresponding to the formation of an occluded front. The Shapiro–Keyser cyclone model was developed around 1990 and was motivated by the recognition of alternative frontal structures depicted in model simulations and observations of rapidly developing extratropical cyclones. This model features a right angle between the cold and warm fronts (T-bone), a weakening of the poleward portion of the cold front (frontal fracture), an extension of the warm or occluded front to the rear of and around the cyclone (bent-back front), and the wrapping around of the bent-back front to form a warm-core seclusion of post-cold-frontal air. Although the Norwegian cyclone model preceded the Shapiro–Keyser cyclone model by 70 years, antecedents of features of the Shapiro–Keyser cyclone model were apparent in observations, analyses, and conceptual models presented by the Bergen School meteorologists, their adherents, and their progeny. These “lost” antecedents are collected here for the first time to show that the Bergen School meteorologists were aware of them, although not all of the antecedents survived until their reintroduction into the Shapiro–Keyser cyclone model in 1990. Thus, the Shapiro–Keyser cyclone model can be viewed as a synthesis of various elements of cyclone structure and evolution recognized by the Bergen School meteorologists.

KEYWORDS: Extratropical cyclones; Fronts; Frontogenesis/frontolysis; History

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In Norway in the late 1910s, a mesoscale observing network was assembled with the goal of improving weather prediction to protect the Norwegian fishing fleet and increase agricultural output during the First World War. The network was assembled by the group at the Geophysical Institute in Bergen who would be called the Bergen School of Meteorology (e.g., Friedman 1989; Fleming 2016, his chapter 2; Jewell 2017; Vollset et al. 2018; Schultz et al. 2019, their section 6). The network was dense, consisting of 90 stations (Beck 1922, p. 398). A similarly dense network in the United States was estimated to require 3,300 stations, a far cry from the then-existing network of 300 telegraphic stations reporting weather conditions at the time of the First World War (V. Bjerknes 1919). The Norwegian observing network also allowed for the collection and analysis of surface data on extratropical cyclone structure and evolution, culminating in a conceptual model that became widely accepted (e.g., J. Bjerknes 1919; Bjerknes and Solberg 1921, 1922), albeit with some historical roots in previous literature (e.g., Davies 1997; Volkert 1999). This conceptual model, known as the *Norwegian cyclone model*, starts with the familiar open-wave cyclone with a warm front and a cold front (phase I in Fig. 1a). As the cyclone matures, the warm sector closes up (phases II and III), and the cold front catches up to and merges with the warm front, forming an occluded front (phase IV). The model has been remarkably durable over the past hundred years, and, despite having undergone several modifications [e.g., including catch-up being recast as wrap-up in Schultz and Vaughan (2011)], much of its essence survives intact to the present day.

By the 1980s, it was becoming clear that not all extratropical cyclones evolved in a manner similar to that of the Norwegian cyclone model. Fueled by intense interest in understanding rapidly developing cyclones (i.e., “bombs”; Sanders and Gyakum 1980), investigators flocked to the field of extratropical cyclones (e.g., Bosart 1999, his section 7). Idealized simulations of extratropical cyclones produced “unusual frontal configurations which the authors were hesitant to equate with those in the ‘real’ atmosphere, since similar frontal structures had not yet been documented by synoptic meteorologists” [Shapiro and Keyser 1990, p. 178; evidence in support of this quote is discussed in section 1 of Neiman and Shapiro (1993)]. Another contemporaneous tool was also showing similar structures: mesoscale model simulations of real-world cyclones with newly emerging community mesoscale models (e.g., Keyser and Uccellini 1987). Because horizontal grid spacings in these simulations were as small as 30 km, fronts could be better resolved than in the past, helping to reveal these new structures.

Field campaigns were conducted to study rapidly developing extratropical cyclones and their structures over the oceans: the Alaskan Storm Program in 1987 and the Experiment on Rapidly Intensifying Cyclones over the Atlantic (ERICA; Hadlock and Kreitzberg 1988) in 1988–89 (e.g., Neiman and Shapiro 1993, their section 1). Cognizant of the discrepancies in the frontal structures between the simulations and the Norwegian cyclone model, Melvyn Shapiro targeted specific locations within cyclones for intensive interrogation with airborne instrumentation during ERICA. Observations confirmed the structures and evolutions in the real and idealized simulations, leading Shapiro and collaborator Daniel Keyser to craft a new conceptual model of cyclone structure and evolution. What became known as the *Shapiro–Keyser cyclone model* (Fig. 1b) initially appeared in the Erik Palmén memorial volume chapter published by the American Meteorological Society (Shapiro and Keyser 1990), and was later followed by analysis of the first extratropical cyclone to be interpreted in the context of the Shapiro–Keyser cyclone model: ERICA Intensive Observing Period (IOP) 4 (Wakimoto et al. 1992; Neiman and Shapiro 1993; Neiman et al. 1993).

Although similar to the Norwegian cyclone model in phase I (cf. Figs. 1a and 1b), the Shapiro–Keyser cyclone model begins to deviate in phase II as the poleward portion of the cold front weakens near its intersection with the warm front in what is termed the *frontal fracture*. Also

starting to form in phase II, but better developed in phase III, is the bent-back front and the frontal T-bone. The *bent-back front* forms when the warm-frontal zone extends cyclonically around the low center in the strong winds of the cold conveyor belt, which is the low-level airstream within and poleward of the warm-frontal zone (e.g., Carlson 1980; Browning 1990; Schultz 2001). The *frontal T-bone* refers to the right angle between the cold front and the warm front. By virtue of a right angle between these fronts, the traditional occlusion process of the cold front catching up to and merging with the warm front and narrowing the warm sector cannot occur. In phase IV, the bent-back front wraps fully around the cyclone, enclosing the *warm-core seclusion*—a pool of warm post-cold-frontal air near the low center. The formation of the warm-core seclusion stands in contrast to a narrow ridge of warm air along the occluded front in the Norwegian cyclone model (cf. phase IV in Figs. 1a and 1b). Thus, the Shapiro–Keyser cyclone model is distinguished from the Norwegian cyclone model by four key features: frontal fracture, bent-back front, frontal T-bone, and warm-core seclusion.

The Shapiro–Keyser cyclone model was described as “an alternative conceptualization of frontal-cyclone evolution” by Neiman et al. (1993, p. 2177). Neiman and Shapiro (1993, p. 2174) reiterated,

the frontal-cyclone life cycle described here is not characteristic of all marine cyclogenetic events and has not been described for continental cyclones. The conceptualization of this evolution...should be considered a companion to, rather than a replacement of, the classical Norwegian frontal-cyclone occlusion life cycle.

None of the articles presenting the Shapiro–Keyser cyclone model indicated

Fig. 1. Conceptual models of cyclone evolution showing lower-tropospheric (e.g., 850-hPa) geopotential height and fronts (top), and lower-tropospheric potential temperature (bottom). (a) Norwegian cyclone model: (I) incipient frontal cyclone, (II) and (III) narrowing warm sector, (IV) occlusion (Schultz and Vaughan 2011, their Fig. 2); (b) Shapiro–Keyser cyclone model: (I) incipient frontal cyclone, (II) frontal fracture, (III) frontal T-bone and bent-back front, (IV) frontal T-bone and warm-core seclusion (Shapiro and Keyser 1990, their Fig. 10.27). The stages in the respective cyclone evolutions are separated by approximately 6–24 h and the frontal symbols are conventional. The characteristic scale of the cyclones based on the distance from the geopotential height minimum, denoted by L, to the outermost geopotential contour in stage IV is 1,000 km.

that any of the four key features of the Shapiro–Keyser cyclone model had any historical precedent in the scientific literature (except for the warm-core seclusion, for reasons to be discussed later).

Research by the first author of this article on the history of the Norwegian cyclone model has uncovered a number of sources that indicate the frontal fracture, the bent-back front, and the warm-core seclusion were known to the Bergen School meteorologists, whereas, as best as we can determine, the frontal T-bone does not appear to have concerned them, or at least it was not a feature that they wrote about. The frontal fracture, the bent-back front, and the warm-core seclusion were not restricted to isolated analyses. Consistent and repeated occurrences of these features in their articles, particularly in conceptual model diagrams of idealized cyclones, indicated that the Bergen School meteorologists had recognized these features and incorporated them into their analyses and scientific papers over many years before they were omitted in various incarnations of the Norwegian cyclone model since the 1950s. We do not believe that these features (alternatively referred to as *antecedents* in this article) are widely recognized or appreciated by present-day meteorologists. Thus, the purpose of this article is to showcase some of these antecedents that preceded the formal introduction of the Shapiro–Keyser cyclone model by as much as 70 years. In providing this historical perspective, we aim to establish a pedigree for the Shapiro–Keyser cyclone model prior to its initial appearance in 1990. In the remainder of this article, we focus on the three antecedents that were known to the Bergen School meteorologists—the frontal fracture, the bent-back front, and the warm-core seclusion—and we do not consider the frontal T-bone further. Figure 2 presents a timeline for the appearances of the three antecedents of the Shapiro–Keyser cyclone model in the Bergen School literature.

Frontal fracture

Shapiro and Keyser (1990, p. 186) introduced the term *frontal fracture*, a term that was defined, based on analyses of real and idealized model simulations, as the “loss of cold frontal baroclinicity (frontolysis) near the cyclone center during the early stages of cyclogenesis”

Fig. 2. Timeline of the three antecedent features of the Shapiro–Keyser cyclone model in the Bergen School literature: frontal fracture, bent-back front, and warm-core seclusion. Small icon graphics are representative rather than comprehensive illustrations of these antecedent features, represented in full by the figures in this article. Citations in italics for the bent-back front indicate that these sources expressed skepticism as to the importance of the bent-back front. Citations in italics for the warm-core seclusion in the 1920s indicate that the feature they identified as a seclusion differed from the warm-core seclusion of the Shapiro–Keyser cyclone model. The line under Godske et al. (1957) denotes the time interval from the completion of the writing of this source in 1948 to its publication in 1957.

(p. 178) and as “cold-front contraction south of, but not in the vicinity of, the cyclone center” (p. 178). The frontal fracture was featured in synoptic analyses of data from extratropical cyclones collected during field campaigns appearing in Shapiro and Keyser (1990, their Figs. 10.16, 10.20, and 10.23). Neiman and Shapiro (1993, p. 2160) used the frontal-fracture terminology of the Shapiro–Keyser cyclone model shortly after its introduction, writing that

the warm-frontal and polar-cold-frontal gradients of temperature distinctly separated (i.e., fractured) south of the cyclone triple point (junction of the cyclone’s warm and cold fronts). Horizontal frontogenesis diagnostics from a numerical simulation of this storm...show weak frontolysis...in this fracture region, and distinctly separated regions of warm and cold frontogenesis to the north and south.

The Bergen School meteorologists were aware that the poleward part of the cold front would be weaker relative to its more equatorward part as early as 1924 (Fig. 3a). In Bergeron and Swoboda (1924, Plate II, Maps 5 and 6), the poleward part of the cold front was analyzed as weaker near its intersection with the warm/occluded front (i.e., smaller triangles indicated a weaker cold front in their notation) (Fig. 3a, which shows their Map 6).

Later, Petterssen (1933) depicted the frontal fracture (Fig. 3b), writing, “Most frequently the northern part of the cold front and the southern part of the warm front are exposed to frontolysis. It is a common experience that cold fronts increase, and warm fronts decrease in intensity with distance from the cyclonic center.” A diagram by Godske et al. (1957) also showed the weaker northern end of the cold front where the flow is less frontogenetic than farther equatorward where the cold front lies parallel to the axis of dilatation of the flow field (Fig. 3c).

Eventually, depictions of the frontal fracture appear to have been dropped from conceptual models of cyclones. However, this feature would be seen again, in idealized baroclinic wave simulations showing the weakness along the poleward part of the cold front. For example, Hoskins and West (1979, their Figs. 6, 10b, 11b) showed a secondary maximum of relative vorticity along the cold front (the maximum being at the center of the low) and a minimum in frontogenesis at the poleward end of the cold front (their Fig. 15), indicative of a frontal fracture. Takayabu (1986, his Figs. 10 and 11) recognized that maximum frontogenesis occurred at a midpoint along the cold front, allowing for a weaker poleward portion of the cold front. Doswell (1984, 1985) and Keyser et al. (1988, their Fig. 10b2) showed that, due to the zero wind speed in the center of an idealized stationary vortex, where the potential temperature field is treated as a passive tracer, frontogenesis would be zero at the center of the vortex, implying that the poleward portion of the cold front would be weaker than farther equatorward (as discussed more fully by Schultz et al. 1998, p. 1782). The frontal fracture would finally reappear as a full-fledged feature of the Shapiro–Keyser cyclone model in 1990.

Bent-back front

The best-documented feature of the Shapiro–Keyser cyclone model in the Bergen School literature is the bent-back front, formed from the extension of the warm or occluded front rearward to the west of the cyclone center (Shapiro and Keyser 1990, their Figs. 10.16, 10.20, and 10.23). Schematics drawn by Refsdal (1929) and Bjerknes (1930) showed this evolution, with the bent-back front eventually developing into a secondary cold front (Figs. 4a,c). Refsdal’s (1929) schematic (Fig. 4a) even showed the bent-back front forming more than once (not that we authors can recall seeing an observational example of such an occurrence in the literature). The Bjerknes (1930) schematic (Fig. 4c) was supported by two case studies with enough surface data to justify the analyses (his maps A2–A5, C5–C6) (e.g., Fig. 4b, which shows map C5). The bent-back front may have been recognized even before 1929. For example, in a description prescient of Refsdal’s schematic, Bergeron [1928, p. 14; translated as Bergeron (2020) and discussed by Schultz et al. (2020)] wrote:

Already after [the analysis of] the big cyclogenesis on 22–24 October 1921, I had noticed that the numerous secondary cold fronts within the final cold-air outbreak were bent back – while the first cyclone of the following series had advanced sufficiently close – became retrograde and crowded together before the new perturbation.

(a) Bergeron and Swoboda (1924)

(b) Petterssen (1933)

(c) Godske et al. (1957)

Fig. 3. Examples of the frontal fracture in the Bergen School literature: (a) portion of Bergeron and Swoboda (1924, their Plate II, Map 6), reproduced within Godske et al. (1957, their Fig. 17.47.5 on p. 678), (b) Petterssen (1933, his Fig. 19j on p. 55), and (c) Godske et al. (1957, their Fig. 18.31.1 on p. 740).

(a) Refsdal (1929)

(c) Bjerknes (1930)

(b) Bjerknes (1930)

(d) Schinze (1932)

Fig. 4 (Continued on next page). Examples of the bent-back front in the Bergen School literature: (a) Refsdal (1929, his Fig. 33 on p. 61), (b) Bjerknes (1930, his Fig. C5), (c) Bjerknes (1930, his Fig. 10 on p. 13), and (d) Schinze (1932), appearing in Chromov (1940, his Fig. 213 on p. 432).

(e) Bergeron (1935)

(f) Godske et al. (1957)

Fig. 4 (Continued). Examples of the bent-back front in the Bergen School literature: (e) Bergeron's (1935) analysis, appearing in Friedman (1989, his Fig. 17 on p. 171), and (f) Godske et al. (1957, their Fig. 17.48.1 on the plate opposite p. 678).

This quotation appears to be the earliest reference to bent-back fronts in the Bergen School literature. Other Bergen School literature just before 1928 does not show analyses with bent-back fronts formed from the extension of the warm or occluded front (e.g., Bergeron and Swoboda 1924; Bjerknes 1924; Calwagen 1926). Thus, it may have been during 1927–28 that Bergeron first recognized the existence of bent-back fronts in extratropical cyclones.

After 1930, Bergeron continued to present the bent-back front in his publications. For example, Bergeron (1937, p. 269 and his Fig. 4) included a short bent-back front in his conceptual model of an extratropical cyclone and referred to it as “the comparatively new idea of the recurving [bent-back] occlusion.” (The bent-back occlusion of Bergeron and the bent-back front of the Shapiro–Keyser cyclone model are different terms for the same feature.) Chromov’s (1940) textbook, which draws heavily from Bergeron’s lectures in Russia (Liljequist 1981, 422–423; Schwerdtfeger 1981, p. 505), showed examples of bent-back fronts [e.g., p. 344, which comes from Bergeron (1935); p. 409; p. 432, which comes from Schinze (1932) and is presented in our Fig. 4d].

In 1959, Bergeron would reflect on re-analyses that he performed of historical cyclones, recognizing that his re-analyses allowed for the possibility of bent-back occlusions. For example, his re-analysis of the 14–15 November 1875 storm showed a bent-back occlusion (analyzed as a cold front) with a temperature drop from 9.4° to 7.2°C across it (Bergeron 1935; appearing in Bergeron 1959, his Fig. 5a on p. 449, and in Friedman 1989, his Fig. 17 on p. 171) (Fig. 4e). About another example, Bergeron (1959, p. 454) wrote:

the original version of the Bergen School model [15 August 1918; Bergeron 1959, p. 457]...contained also a feature that may be interpreted as the trough of the (backbent) occlusion.... [This] circumstance has probably never been emphasized, and it has only of late occurred to the present author.

In opposition to Bergeron who strongly believed in the existence of bent-back occlusions, Sverre Petterssen appears to have held different views. In the first edition of his graduate-level textbook, Petterssen (1940, 338–339) discussed bent-back occlusions quite extensively. He recognized that occluded fronts may be wrapped around the cyclone, forming bent-back occlusions, but most bent-back occlusions “are not real fronts,” consisting instead of surface pressure troughs. Petterssen’s claim that bent-back occlusions “are not real fronts” was based on the observation that the surface pressure trough associated with a bent-back occlusion moves more slowly than the wind component normal to the surface pressure trough, and that the surface pressure trough is a reflection of the upper-level trough associated with the cyclone.

In contrast to bent-back occlusions that were not considered “real fronts,” the bent-back occlusions that Petterssen (1940, 338–339) did consider to be “real fronts” formed when a secondary cyclone developed at the triple point (i.e., the intersection of the warm, cold, and occluded fronts), allowing for the occluded front to reverse its direction of motion and form the bent-back occlusion. Petterssen (1940, 338–339) conceded, however, that such a development was “not a frequent occurrence.” Saucier (1955, p. 302) offered a similar perspective as to whether bent-back occlusions possessed frontal characteristics or could be better described as surface pressure troughs, arguing that “a detailed cross-section analysis...would be in order” to aid in distinguishing between bent-back occlusions and surface pressure troughs. That Petterssen did not consider most bent-back occlusions to be real fronts in his 1940 graduate-level textbook is supported by their omission in his introductory textbook (Petterssen 1941, chapter 10).

Despite the emphasis on bent-back occlusions in the first edition of his graduate-level textbook, in the second edition, Petterssen’s (1956, p. 219) discussion of bent-back occlusions was much reduced, and he seemed to have only considered the situation where surface pressure troughs associated with a bent-back occlusion or a secondary cold front did not have a strong

temperature gradient, writing that such troughs were “usually a misuse of the concept of fronts.”

Bent-back fronts continued to appear in some sources until the late 1950s. Godske et al. (1957, their Fig. 17.48.1 on the plate opposite p. 678) presented the cyclone from Bergeron and Swoboda (1924), but now modified with a short bent-back front, albeit with no data to support it (solid blue line in Fig. 4f). The conceptual model in Bergeron (1937, p. 269 and his Fig. 4) was also revised and continued to include a bent-back front (Godske et al. 1957, their Fig. 14.4.1 on p. 532). [What date to attribute the figures in Godske et al. (1957) is worth a brief mention; the manuscript for the book was completed in 1948, but not published until 9 years later, as discussed in Godske et al. (1957, p. 3).]

At some point, bent-back fronts appear to have been dropped from conceptual models of cyclones, and analyses similar to that in Fig. 1a became common (e.g., Bjerknes 1951; Palmén 1951; Raethjen 1953, 17–18; Petterssen 1958, his chapter 14; Palmén and Newton 1969, their chapter 11; Byers 1974, his chapter 10; Wallace and Hobbs 1977, their chapter 3). The reasons remain unclear. Was the reason that bent-back

(a) Bjerknes and Solberg (1922)

(b) Bjerknes and Solberg (1922)

(c) Chromov (1940)

(d) Chromov (1940), enlarged and annotated

Fig. 5. Examples of various types of seclusions in the Bergen School literature: (a) the seclusion of Bjerknes and Solberg (1922, their Fig. 6 on p. 10), (b) the orographic seclusion of Bjerknes and Solberg (1922, their Fig. 7 on p. 10), (c) a possible warm-core seclusion of Chromov (1940, his Fig. 233 on p. 491), and (d) an enlargement of the cyclone center in (c) annotated to show the temperatures of the possible warm-core seclusion (selected temperatures are circled: red circles represent the warm air inside the warm-core seclusion; dark blue circles represent the cold conveyor belt air, mostly at stations over land; the cyan circle represents relatively warmer air, possibly because the station is over water, which may explain why it is not as cold as the rest of the cold conveyor belt air).

fronts were not being observed and analyzed, especially over the United States? Were bent-back fronts being reinterpreted as secondary cold fronts instead, without the extension of the warm/occluded front back through the cyclone? Were bent-back fronts inconsistent with the catch-up model of the occlusion process? Was dropping the bent-back front an expression of nostalgia for, and a desire to return to, the simplicity of the J. Bjerknes (1919) and Bjerknes and Solberg (1922) conceptual models? Perhaps all of these possible reasons are valid.

Pertinent to the above possible reasons, the Bergen School meteorologists often disagreed among themselves about the most important features among the variety of frontal analyses they produced, often based upon sparse data (e.g., Friedman 1989, 199–200). The bent-back occlusion or secondary cold front was one of those flashpoints:

Asked by foreign meteorologists about the possibility of such secondary cold fronts, Jacob [Bjerknes] categorically denied their existence. Bergeron went around at the same time delineating such structures on weather maps. Even when some members (Ernst Calwagen and Anfinn Refsdal) published maps showing secondary [c]old fronts, Jacob continued to deny their existence. According to Bergeron, Vilhelm [Bjerknes] and Jacob “prohibited ‘the rest of us’ to pretend to the outer world that something like that [secondary cold fronts] exists, because it might prejudice the hegemony of the one and unitary, grace-saving polar front” (Friedman 1989, p. 200).

Because the Bjerknes’s prohibited discussion of these alternative features (e.g., secondary cold fronts, bent-back occlusions), perhaps such features eventually were dropped from depictions of extratropical cyclones by other authors.

Before reappearing in its final form in the Shapiro–Keyser cyclone model in 1990, we authors are aware of one other study that considered the bent-back front. Takayabu (1986) diagnosed the formation of the bent-back front in an idealized baroclinic-wave cyclone, although he did not refer to the front as a bent-back front. Takayabu concluded from his diagnosis that horizontal advection was responsible for lengthening the front to the rear of the cyclone and that frontogenesis was responsible for maintaining the intensity of the front as the front wrapped around the center of the cyclone. Thus, the evidence presented in this section shows that the bent-back front was recognized originally by the Bergen School meteorologists, and later by Takayabu (1986), before its reappearance in and incorporation into the Shapiro–Keyser cyclone model.

Warm-core seclusion

Our chronicle of the warm-core seclusion begins with a letter from Vilhelm Bjerknes to Sir Napier Shaw, dated 25 January 1921, which read:

Mr. Bergeron asks for my opinion concerning words to be translated from Swedish to English.... Instead of taking place simultaneously along a finite length of the cold front and the warm front section, the occlusion may begin locally at a definite point, leading to the formation of a closed curve surrounding an encircled mass of warm air. Can we call this a process of *seclusion*? Speak of a *secluded* mass of warm air? Could we go further and speak of a *secluding* cyclone? (as reported in Jewell 1983, p. 167).

Shaw responded that these terms would be appropriate. A different term appears to have been used at the time, as well, suggesting some uncertainty over when the terminology for the seclusion was settled on by the Bergen School. Anne Louise Beck, an American who spent September 1920 to May 1921 in Bergen on a fellowship (e.g., Fleming 2016, 52–59), wrote that Bergeron referred to the seclusion as “*seclusia*”—this alternative terminology “arising from discussions in the laboratory” (Beck 1922, p. 395).

Regardless of the informal terms used within the Bergen School, the first appearance of the term *seclusion* in the published literature was in Bjerknes and Solberg (1922, their Fig. 2), in which the catch-up of the warm front by the cold front occurred not at the center of the cyclone but at some distance away from the center (Fig. 5a). Although Bjerknes and Solberg (1922) acknowledged that this catch-up may have been due to the retardation of the eastward advance of the warm front by the Norwegian mountains, allowing the cold front to catch up [i.e., with the formation of the so-called “Skagerak cyclone” to the south; see the third plate in Jewell (1981, between pages 488 and 489); Fig. 5b], the concept of seclusion was still presented in Bjerknes and Solberg (1922) as a general feature of extratropical cyclone evolution (Fig. 5a). Nevertheless, the concept of seclusion as a general feature of extratropical cyclone evolution did not last long, and the concept of the occluded front originating from the center of the cyclone and lengthening outward became orthodoxy. Bergeron (1959, p. 457) would later write, the seclusion was “a hypothesis that later had to be retracted.” Simply stated, there was no evidence at the time of the development of the Norwegian cyclone model—and no evidence at the present time that we authors are aware of—that true warm-sector air becomes secluded from the cyclone in the manner depicted by Bjerknes and Solberg (1922) in the absence of orography (Fig. 5a). The presence of orography is necessary to explain the “pinching off” of the warm sector in what is referred to as an *orographic seclusion* (Bergeron 1937, p. 267; Huschke 1959). In contrast to the warm-core seclusion process of the Shapiro–Keyser cyclone model, orographic seclusions have appeared in analyses and discussions by, for example, Bjerknes (1924, p. 35), Staff of the Hydrometeorological Section (1941, p. 275), Lu (1945, p. 314), and Mass and Schultz (1993, their Figs. 2a and 5).

Shapiro and Keyser (1990, their section 10.4) recognized the historical use of the seclusion process in the Bergen School literature, as did Neiman and Shapiro (1993, their Fig. 1 and the accompanying text). In contrast to the orographic-seclusion process of that early Bergen School literature, however, the warm-core seclusion process described in the Shapiro–Keyser cyclone model is characterized by the seclusion of post-cold-frontal air, not true warm-sector air (Shapiro and Keyser 1990, their Figs. 10.18 and 10.25). Was such a warm-core seclusion process envisioned by the Bergen School and their progeny? The answer appears to be yes. The Bergen School and their progeny recognized that the bent-back front could eventually wrap around the cyclone center, enclosing post-cold-frontal air (colder than had the air originated from the warm sector, but warmer than the air deeper within the cold sector). The Bergen School and their progeny did not give this process a name, but it is the essence of the warm-core seclusion process described in the Shapiro–Keyser cyclone model. The warm-core seclusion was evident in analyses by Chromov (1940, 491–493), which were derived from Bergeron’s lectures in Russia (Liljequist 1981, 422–423; Schwerdtfeger 1981, p. 505). For example, Chromov (1940, his Fig. 233) showed that a long occluded front could wrap around the cyclone center, enclosing relatively warm air; in the case presented in our Fig. 5c and enlarged in our Fig. 5d, air of 1°–3°C was pinched off by air of –5° to 0°C on the southeastern, eastern, northern, and western quadrants.

The warm-core seclusion was never formally depicted as a common evolutionary step for extratropical cyclones in the Bergen School literature. If bent-back fronts were not standard in most analyses in the literature, then the wrapping around of the bent-back front into a warm-core seclusion would not have occurred either, possibly explaining the absence of analyses of warm-core seclusions in the Bergen School literature. During the 1940s and 1950s, the term *seclusion* was used for the middle- and upper-tropospheric cutoff cyclones that form during the process that is now referred to as Rossby-wave breaking (e.g., Palmén and Nagler 1949; Simpson 1952; McQueen and Thiel 1956); the use of the term seclusion as a tropospheric-deep cutoff cyclone is clearly not related to warm-core seclusions in the lower troposphere in extratropical cyclones. The lower-tropospheric

warm-core seclusion would appear in its present form in the Shapiro–Keyser cyclone model.

It is of some interest that the warm-core seclusion of the Shapiro–Keyser cyclone model was not always depicted in its present form. In a summer school at the National Center for Atmospheric Research, Shapiro (1988, p. 165) presented a preliminary analysis of aircraft and dropsonde data from an extratropical cyclone during a pre-ERICA test flight on 28 January 1988 (Fig. 6). In the absence of any supporting data near the cyclone center, he drew his

Fig. 6. The 850-hPa temperature analysis (°C) of a warm-core seclusion at 0000 UTC 28 Jan 1988 (Shapiro 1988, his Fig. 7). The original caption listed the date incorrectly as 27 Jan, as can be determined by comparing this figure to Fig. 10.20 in Shapiro and Keyser (1990), which is an analysis for an earlier time in the cyclone's evolution.

analysis with the 850-hPa isotherms spaced evenly across the cyclone center (Fig. 6). With the benefit of further insight provided by additional ERICA analyses and model simulations of frontal structures in maritime extratropical cyclones, the Shapiro–Keyser cyclone model assumed its present form with the isotherms concentrated in the baroclinic zone surrounding the warm-core seclusion, as depicted in Fig. 1b.

Conclusion

The Norwegian cyclone model originated during an era in which a dense surface observing network revealed heretofore undiscovered frontal structures to the Bergen School meteorologists. Seventy years later, high-resolution model simulations and new observations within extratropical cyclones revealed alternative frontal structures to Melvyn Shapiro and Daniel Keyser, culminating in the development of the Shapiro–Keyser cyclone model. The present article showed how features of the Shapiro–Keyser cyclone model were preceded by studies published by the Bergen School. Starting in the 1950s, these features appear to have been dropped from classic depictions of the Norwegian cyclone model presented in textbooks (e.g., Bjerknes 1951; Palmén 1951; Raethjen 1953, 17–18; Petterssen 1958, his chapter 14; Palmén and Newton 1969, their chapter 11; Byers 1974, his chapter 10; Wallace and Hobbs 1977, their chapter 3), resulting in structures and evolutions similar to that in Fig. 1a.

Melvyn Shapiro was aware of many of the antecedents to the Shapiro–Keyser cyclone model, remarking in a 2006 interview on the development of the Shapiro–Keyser cyclone model that, “we discovered, as Bergeron had suggested before, ...the bent-back frontal structure and the warm-core seclusion” (2:06:53 in <https://opensky.ucar.edu/islandora/object/archives:7748>). Shapiro continued, “We weren’t clever. We had faith in the governing equations [i.e., the depictions of the frontal structures from the idealized and real cyclone model simulations] and didn’t go out and discover it [the Shapiro–Keyser cyclone model] by accident.” In the same interview, Shapiro also referred to “the origin of the Norwegian cyclone model and how there were analyses and datasets that went into Jack’s [Jacob’s] paper [J. Bjerknes 1919] and conceptual model that never appeared” and remain in unpublished archives in Bergen (2:33:00). Shapiro concluded: “There is a very rich history to what we do today that may be of value” (2:34:00). No doubt further investigation into the early Bergen School analyses and their correspondence would shed more light on the development of the terminology and concepts in our present models of cyclone structure and evolution. In this way, the antecedents to the Shapiro–Keyser cyclone model considered in this article remind us of Daniel Keyser’s question to Chester Newton about why existing ideas in meteorology continue to be rediscovered. Newton’s reply was “That’s why they call it *re-search*, rather than *search*.” Thus, the Shapiro–Keyser cyclone model can be viewed as a synthesis of various elements of cyclone structure and evolution recognized by the Bergen School meteorologists.

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