

# *A review of extratropical cyclones: observations and conceptual models over the past 100 years*

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# A review of extratropical cyclones: observations and conceptual models over the past 100 years

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## Introduction

It is now 100 years since the publication of Jacob Bjerknæs 1919 paper 'On the structure of moving cyclones' so it seems an appropriate time to celebrate this work and the research into extratropical cyclones that followed. The synoptic analysis methods developed by Bjerknæs (1919) were applied by national operational weather services worldwide, and their theoretical interpretation of cyclogenesis led to much scientific research over the following century.

In this article, I will provide a brief overview of the major scientific advances that have been made in synoptic extratropical cyclone research since 1919. I have restricted my review to a brief description of eight papers or book chapters that I think highlight the major discoveries and why they were important. All of these papers contain excellent figures that summarise and communicate the new scientific understanding in a way that is easy to understand way. Others, no doubt, would have chosen a different set of papers, so while you might disagree with my choices, at the very least, I hope this article stimulates some debate.

## Review of synoptic extratropical cyclone research

### *The 1920s: cyclone lifecycles*

The Bergen meteorologists in Norway set out to understand and describe the structure and evolution of extratropical cyclones. They made use of the extensive telegraph network across Europe to track observations of air pressure, temperature and wind and thus to describe the evolution and movement of surface weather systems on a continental scale for the first time. Bjerknæs (1919) paper contains a description of the cold and warm fronts with which we are so familiar today (shown in red and blue in Figure 1), although he

used different terms ('steering line' and 'squall line' for warm and cold fronts, respectively). He also used the observations to describe the evolution of clouds and precipitation along the frontal zones (grey shading in Figure 1).

While it might be argued that the Bergen school was not the first to describe such features, its scientists' skilfully crafted conceptual diagram demonstrates an outstand-

ing synthesis, enabling them to efficiently communicate their ideas. With only small adjustments, the Bjerknæs (1919) conceptual model has survived 100 years as an effective tool in weather forecasting and analysis. Both observational and theoretical descriptions of extratropical cyclones have been greatly expanded and enriched in the many decades since Bjerknæs (1919) was first published.

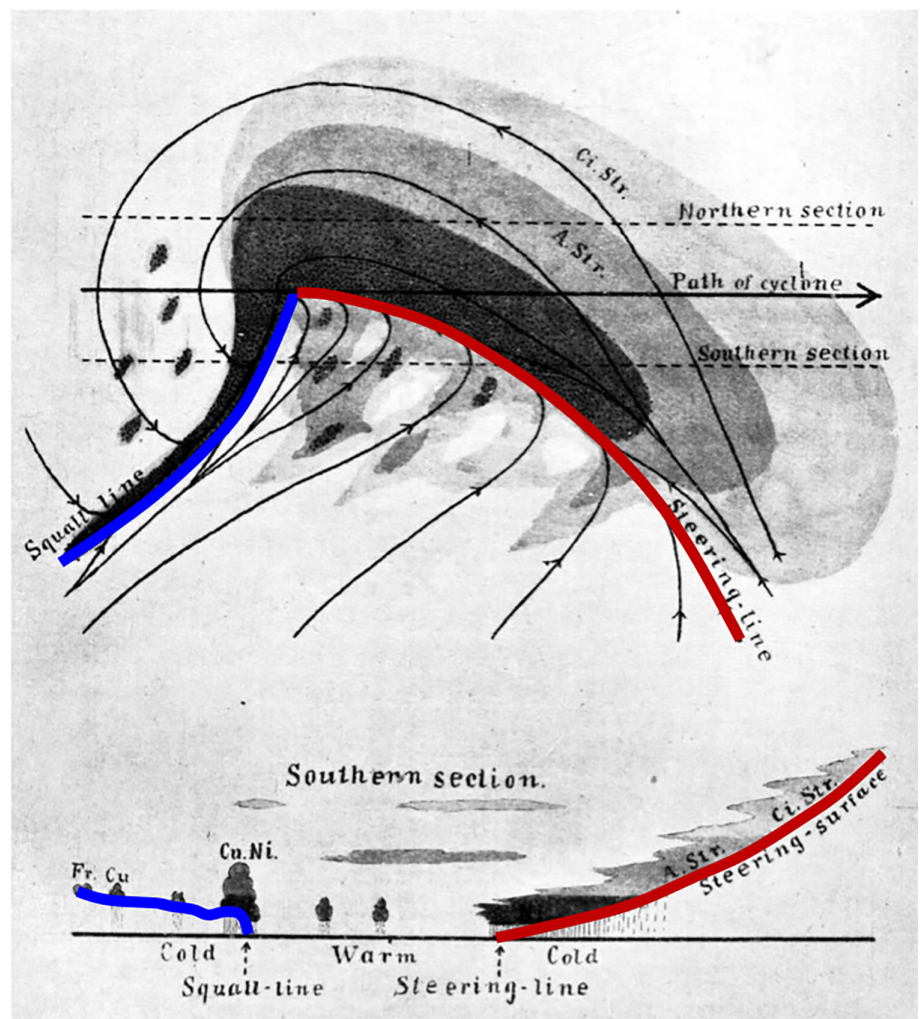


Figure 1. Adapted from Bjerknæs (1919), showing extratropical cyclone surface features (top) and above-surface features (bottom). The cold front (blue) and warm front (red) were originally termed the 'squall line' and 'steering line', respectively. Light grey shading indicates the position of clouds along the frontal zones and dark grey shading the location of precipitating clouds. © American Meteorological Society. Used with permission.)

### The 1930s: 3D cyclone structure

Although the original Norwegian frontal cyclone model was, in principle, three-dimensional (3D), it was based largely on surface observations. Studies in the 1930s started to make use of kite and balloon-borne instruments, which confirmed the 3D structure of cyclones. Therefore, my next choice of seminal paper is Palmén (1931), who created a conceptual model of the vertical structure of extratropical cyclones. This paper quantified the sloped nature of the cold and warm fronts (shown in blue and red in Figure 2), which were qualitatively inferred by Bjerknes (1919). It also described the characteristic shape of the tropopause for the first time with a low warm tropopause (or trough) behind the cold front (shown in yellow in Figure 2) and a high cold tropopause (or ridge) ahead of the cyclone (shown in cyan in Figure 2). Figure 2 provides an excellent summary of the previously unknown thermally asymmetric structure of extratropical cyclones.

### The 1940s: cyclone development mechanisms

The invention of radiosondes in the 1940s led to a range of studies on cyclone development mechanisms, which were poorly understood at the time. In Bjerknes and Holmboe (1944), they explain, in a simple way, the features common to all extratropical cyclones, such as an upper-level trough (shown in yellow in Figure 3), with associated divergence ahead. Also shown is a low-level cyclone (shown in orange in Figure 3) with convergence ahead and the characteristic westward tilt with height between the surface cyclone and the upper-level trough (shown in green in Figure 3). What was so new about Bjerknes and Holmboe (1944) was that they explained that the divergence, and hence vertical motion, was greatest in

high vertical wind shear and strong horizontal thermal gradient environments, which are conducive to cyclone development. Thus, they changed the view of cyclone development from that of a growing perturbation on a surface front to the interaction of upper- and lower-level features.

### The 1950s: cyclone climatologies

The next major development in the understanding of cyclones was due to increased access to worldwide observations after the war, which is still one of the greatest strengths of meteorology today. By collecting data from across the world, manual observations of mean sea-level pressure analysis could be prepared on a daily basis. One scientist who made use of these data was Petterssen (1956) who compiled one of the first climatologies of extratropical cyclones for the Northern Hemisphere. Petterssen (1956) showed that cyclogenesis was not distributed uniformly but occurred in preferred locations. They identified the major Northern Hemisphere storm tracks in the North Atlantic, Pacific and Mediterranean (shown in Figure 4) and continental cyclogenesis regions.

### The 1960s: descending airflows

In the 1960s, the study of extratropical cyclones received an unexpected boost due to an increased number of upper-air observations. Concerns about radioactive debris, initially deposited in the upper atmosphere above atomic test sites, descending to ground level led to a number of research aircraft observational campaigns, particularly in the USA. These new observations were used by Danielsen (1964) to produce the beautiful conceptual diagram in Figure 5. Danielsen (1964) showed that air parcels originating in the upper troposphere and lower stratosphere could descend behind

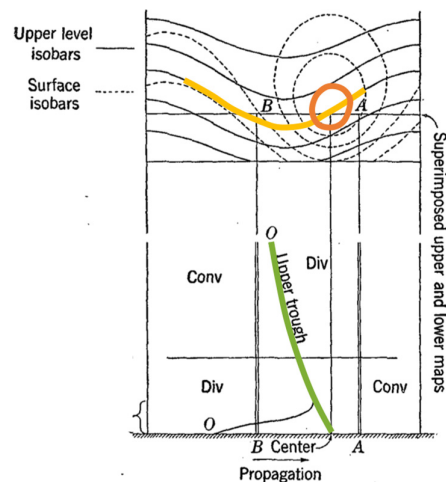


Figure 3. Adapted from Bjerknes and Holmboe (1944). The top panel shows a plan (map) view of the superimposed upper-level trough (yellow) and surface cyclone (orange). The bottom panel shows a vertical longitudinal cross section through the cyclone, depicting the characteristic vertical tilt with height (green), plus divergence at upper levels ahead of the trough and convergence at low levels ahead of the surface cyclone.

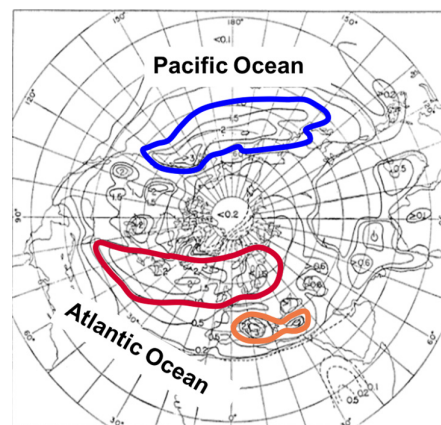


Figure 4. Adapted from Petterssen (1956). Northern Hemisphere DJF extratropical cyclone frequency per 100 000 km<sup>2</sup>. The three major oceanic storm tracks are highlighted in the Atlantic (red), Pacific (blue) and Mediterranean (orange).

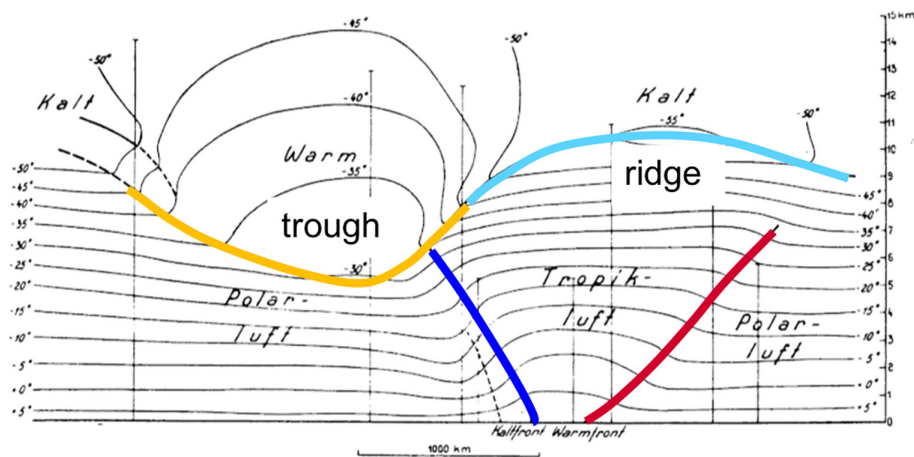


Figure 2. Adapted from Palmén (1931), showing a vertical latitudinal cross section through a cyclone from west to east. Cold front (blue) and warm front (red), upper-level trough behind the cyclone (yellow) and ridge ahead of the cyclone (cyan). Black contours are isotherms showing the thermally asymmetric structure of cyclones. Image from Newton (1990).

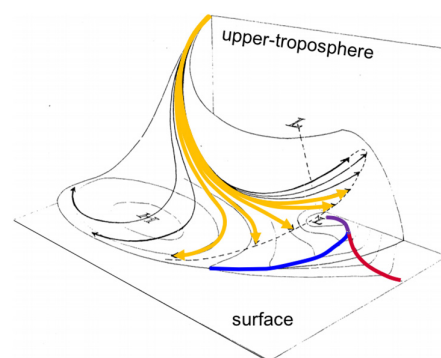


Figure 5. Adapted from Danielsen (1964). Surface cold, warm and occluded fronts (blue, red and purple respectively). The dry intrusion airflow (yellow) descends from the upper troposphere to the surface behind the cold front bringing dry air into the cyclone centre.

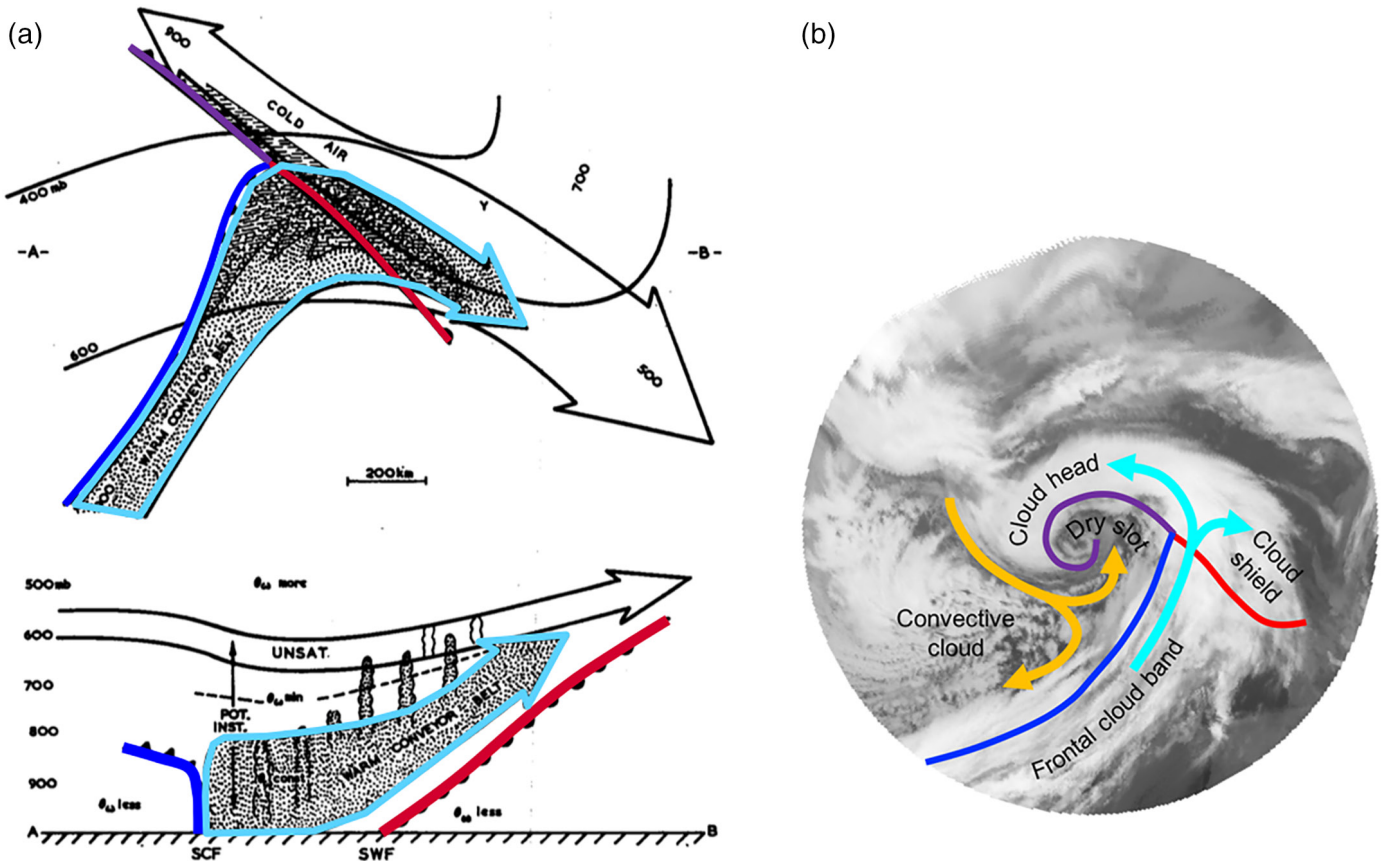


Figure 6. Left: Adapted from Browning (1971). The top panel shows a plan view of the surface cyclone and cyclone airflows and the bottom panel shows a vertical cross section through the cyclone. Surface cold, warm and occluded fronts (blue, red and purple respectively). The cyclone-relative warm conveyor belt airflow (cyan arrow) is located ahead of the cold front in the cyclone's warm sector (top) and ascends out of the boundary layer rising above the sloped warm front (bottom). Right: Adapted from Dacre et al. (2015). Cyclone-centred infrared satellite image from EUMETSAT (available from [www.met.rdg.ac.uk/~storms](http://www.met.rdg.ac.uk/~storms)), overlaid with surface frontal positions, dry intrusion airflow (yellow arrows) and warm conveyor belt airflow (cyan arrows).

the cyclone, reaching down to the surface (shown in yellow in Figure 5). This descending dry airflow is commonly referred to as the dry intrusion and was shown to be responsible for the formation of the characteristic cloud-free part of the comma-shaped cloud features, known as the dry slot, later confirmed by satellite images (Figure 6b).

### The 1970s: ascending airflows

The increasing data available from meteorological satellites and weather radars in the 1970s led to research into other cyclone-relative airstreams. These new technologies enabled observations of cyclone cloud and precipitation features to become more routine. At the forefront of this work was Keith Browning, with whom I was fortunate enough to work at the University of Reading for some years. In Browning (1971), he identified an ascending front-relative airflow, which rises up from the boundary layer in the warm sector over the warm front. This ascending airstream is known as the warm conveyor belt (shown as cyan arrow in Figure 6a) and was shown to lead to the formation of the cyclonic cloud head and anticyclonic outward flowing cloud shield

observed in the newly available satellite images (Figure 6b).

### The 1980s: moist processes

Renewed interest in cyclogenesis was sparked by a paper by Sanders and Gyakum (1980), who compiled a climatology of explosive cyclogenesis that came to be known colloquially as 'bombs'. Bombs are defined as cyclones that deepen by more than 24mb (corrected to a latitude of 60°N) in 24 hours. They observed a difference in deepening rates between continental and marine cyclones. In the Northern Hemisphere, explosively developing cyclones were found to occur preferentially over the Pacific and Atlantic Oceans (shown in Figure 7). This raised questions about the degree of importance of moist processes within extratropical cyclones which is still an active research topic today.

### The 1990s: cyclone mesoscale structure

Inconsistencies between the frontal structures observed in some cyclones and the Bjerknes (1919) conceptual model led to refinements of the model and to the

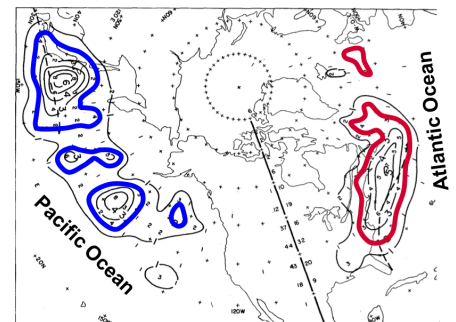


Figure 7. Adapted from Sanders and Gyakum (1980). Frequency of bomb cyclones per 5° x 5° lat/lon. The location of explosively developing cyclones was found to occur preferentially over the Pacific (blue) and Atlantic oceans (red), raising questions about the importance of moist processes in cyclone development. (© American Meteorological Society. Used with permission.)

development of new conceptual models such as that proposed by Shapiro and Keyser (1990). In Shapiro and Keyser (1990), they observed that, for many cyclones, particularly explosive cyclones, instead of the cold and warm front merging to form an occlusion, a cold frontal fracture takes place (shown in Figure 8). The cold front then moves perpendicular to the warm front,

and the gap between the cold and warm front is filled by warm air from the warm sector, creating a warm seclusion (shown in orange in Figure 8). In this type of cyclone, the cloud head is formed by the bent-back front rather than an occluded front. This work demonstrates that cyclone structure and evolution covers a broad spectrum that no single conceptual model can capture.

### The 2000s: numerical modelling

In the last 20 years, huge advances in numerical modelling has led to a situation where observations have been outpaced

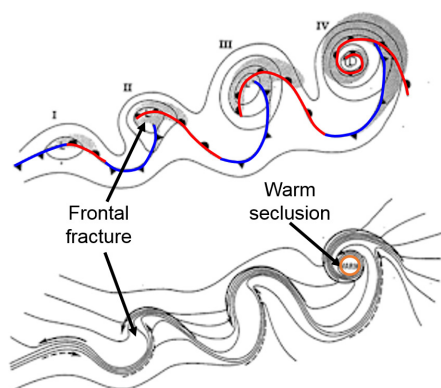


Figure 8. Adapted from Shapiro and Keyser (1990). Evolution of a Shapiro-Keiser-type cyclone. Top: cold and warm fronts (blue and red, respectively), isobars (black) and frontal precipitation (grey shading). Bottom: Isotherms. Frontal fracture occurs in stage II of the cyclone development when cold and warm fronts become separated. The warm seclusion occurs in the mature stage of cyclone development when warm air from the warm sector is cut off by the bent-back front.

by theory. Today, daily high-resolution NWP models show that mesoscale structures within extratropical cyclones can play a role in their development but observations of these structures are expensive to obtain as they require extensive field campaigns. Numerical modelling and observational advances have led to a continuum of new conceptual models, such as sting jets, tropopause folds, cyclone clustering, atmospheric rivers, polar lows and diabatic Rossby waves among others (Figure 9), too numerous to describe in detail in this brief article. However, all of these conceptual models fit nicely together like a jigsaw and continue to enhance our understanding. At the same time, sometimes, it can be difficult to reconcile the ever-broadening species of conceptual models, so care must be taken to link new understanding to existing models and to continue to make detailed observations to clarify which features of the model analyses are valid representations of actual mesoscale events.

### Summary

Since the seminal work of the Bergen meteorologists, we now understand much more about cyclone structure and evolution. However, there are still gaps in our knowledge, particularly regarding synoptic and mesoscale features associated with moist processes and their influence on predictability. Most modelling analyses to date have been performed with atmosphere-only models, but we are starting to explore how the atmosphere and ocean; and atmosphere and chemistry interact to influence cyclone evolution. Finally, there are ongoing

efforts to understand how climate change is likely to affect cyclones. Despite celebrating 100 years since the publication of Bjerknes (1919), there remains much exciting research on extratropical cyclones still to do in the future. For further reading on the research in the last 100 years, see Schultz *et al.* (2019).

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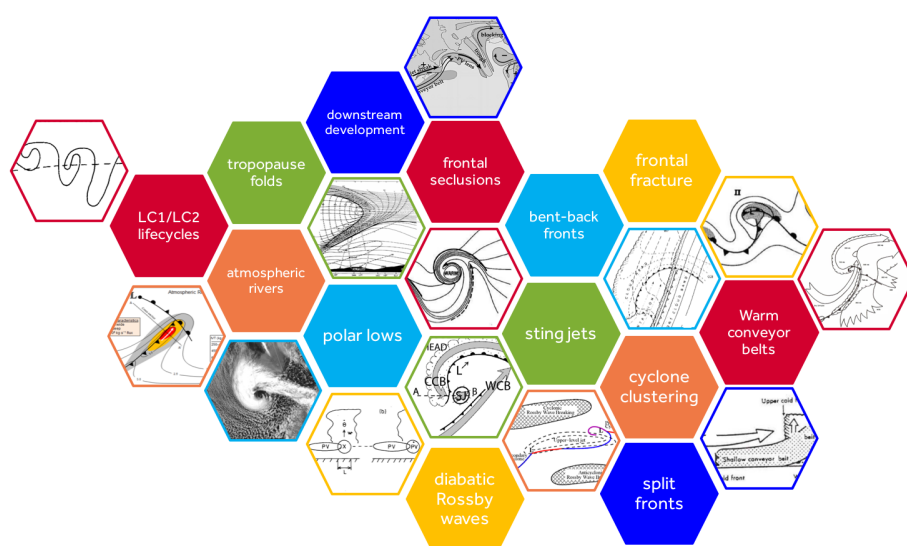


Figure 9. 'New' conceptual models describing the variety of structures and cyclone development mechanisms in observed and simulated cyclones.

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