# EXTRATROPICAL CYCLONES: THE ERIK PALMÉN MEMORIAL VOLUME

Edited by
Chester W. Newton and Eero O. Holopainen

American Meteorological Society

# EXTRATROPICAL CYCLONES

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Co-Edited by

Chester W. Newton
National Center for Atmospheric Research

Eero O. Holopainen
University of Helsinki

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*Chapter 1*

# *Erik Palmén's Contributions To The Development Of Cyclone Concepts*

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## 1.1 Palmén's Setting in the Evolution of Meteorology

Erik Palmén's scientific career encompassed the era during which theory and observations were brought together in a coherent conception of the global atmosphere. Earlier general circulation schemes mostly hypothesized meridional cells symmetrical about the earth, although some investigators, notably Dove and FitzRoy, emphasized air-mass exchanges by synoptic disturbances (Lorenz 1967, pp. 59–78). Contemporary studies of cyclones during the 19th and early 20th centuries, based on then-emerging thermodynamical-physical principles and fragmentary observations, established many of their significant features (Kutzbach 1979). Elements of the earlier investigations, together with new insights from observations and theory, were assimilated into the grand concept of the polar front theory of cyclones and the general circulation.

Palmén enthusiastically embraced this concept (introduced just before his entry into meteorology) and extended it through aerological studies outlined in Section 1.2. During this early part of his career, when he was affiliated with and became director of the Finnish Institute of Marine Research, he also engaged in oceanographic

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*Chapter 2*

# *General Circulation Studies in Chicago from the 1940s into the 1950s*

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## 2.1 Introduction

In the forty years that have passed since the time when Erik Palmén began his period of highest research productivity, the methods of general circulation research have changed drastically. Because of the technical aids that have become available through ever more sophisticated high-speed computers and satellites, nonlinear models of various forms can now be run and tested for time periods often of great length and even involving varying climate conditions over the earth.

In those early days, a concept of the actual general circulation was being pieced together gradually, at first mainly from surface observations, then from upper-air temperatures and pressures as these gradually became available, and finally using the upper winds which previously had been completely missing in cyclones with their cloud shields, just where they were needed most.

The expanding knowledge about the atmosphere and oceans was the subject of many research papers, also the objective of various expeditions into uncharted areas with a variety of aims. Theory, already a main method for attacking the cyclone problem in the Bergen school of Vilhelm Bjerknes, demanded almost visionary insight into the general circulation. The main theoretical tool was to linearize the basic equations, mostly already known from the physicists of the preceding century, and to integrate them with different objectives, of which the formulation of "conservation theorems" was perhaps the most far reaching and successful.

Probably there will be little disagreement in saying that among the researchers of those days Carl-Gustaf Rossby was one of the most outstanding personalities, certainly the best-known leader of such activity for a number of years. He had written an extensive monograph (Rossby 1941) on the general circulation just before the onset of the 1940s war. Like all authors following the original Hadley presentation, he aimed to show the then up-to-date three-cell ageostrophic flow (Fig. 2.1)—very similar to Bergeron's version (1928). In a later interpretation (Rossby 1949), however, a small fourth equatorial cell was included similar to Fletcher's (1945), to depict the widespread existence of double equatorial troughs. This interpretation was later rejected by the Indian meteorologist Asnani (1968) and replaced by him with a new model.

## 2.2 Rossby's General Circulation Concepts

Rossby seriously reacted to a suggestion by Albert Defant (1921) that a large-scale mixing coefficient should be

*Chapter 3*

# *Advances in Knowledge and Understanding of Extratropical Cyclones during the Past Quarter Century: An Overview*

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## 3.1 Introduction

The purpose of this chapter is to present an overview of the progress that has been made in knowledge and understanding of the extratropical cyclone in the roughly quarter-century that has elapsed since Palmén worked actively on the subject. It is recognized that other contributors to this volume will describe more fully Palmén's own contributions to the subject and will treat in greater detail various aspects of the subject that are only touched upon here.

With the purpose of keeping the overview to manageable size, it has been decided to focus on only certain aspects of the cyclone problem. Topics to be emphasized are the structures of fronts and cyclones and the processes of frontogenesis and cyclogenesis. Such important topics as the role of cyclones in the general circulation, orographic cyclogenesis and mesoscale precipitation features within cyclones will be left for others to discuss. With the purpose of putting the advances of the past quarter-century into perspective, the development of knowledge and understanding of the extratropical cyclone prior to 1960 will first be sketched.

## 3.2 Status of the Cyclone Problem Prior to 1960

As documented by Gisela Kutzbach (1979) in her treatise, *The Thermal Theory of Cyclones: A History of Meteorological Thought in the Nineteenth Century,* a considerable knowledge of cyclone structure and behavior existed prior to World War I and many relevant thermodynamic and dynamic principles were understood. Espy, Ferrel, Dove, Loomis, Buchan, Mohn, Ley, Köppen, Bigelow, Margules, von Ficker, Dines and Shaw are among the many early meteorologists whose substantial contributions are described in Kutzbach's book. The picture of cyclones gleaned from the efforts of these early investigators, however, seems fragmentary when viewed against the remarkable synthesis achieved by the Bergen school of meteorologists under V. and J. Bjerknes in the period following World War I. In the polar front theory of cyclones, which they put forth at that time (Bjerknes and Solberg 1922), the cyclone forms as a result of an instability of the polar front, a surface of discontinuity separating tropical and polar air masses. Beginning as a wave on the front, the cyclone undergoes a characteristic life cycle that terminates in the occluded stage in which the tropical air has

## *Chapter 4*

# *Role of Cyclone-Scale Eddies in the General Circulation of the Atmosphere: A Review of Recent Observational Studies*

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# Theory of Extratropical Cyclones

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*Chapter 6*

# *Processes Contributing to the Rapid Development of Extratropical Cyclones*

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## 6.1 Introduction: Historical Perspective

The study of extratropical cyclones has provided the basis for vigorous scientific debates within the meteorological community for at least the past 150 years. In her monograph entitled *The Thermal Theory of Cyclones: A History of Meteorological Thought in the Nineteenth Century,* Kutzbach (1979) documents the interest of the leading European and American meteorologists of the 19th and early 20th centuries in providing a description of the weather and airflow associated with cyclones and identifying the physical processes that contribute to their development. In the 19th century, the emergence of the so-called "thermal theory of cyclones" (see Fig. 6.1) was based, to a large degree, on the work of Espy, who believed that the decrease of surface pressure in storms is related primarily to the release of latent heat in the ascending air near the storm center. By the early 20th century, the theoretical work of Margules and V. Bjerknes and the observational studies by Dines (which indicated extratropical cyclones were cold core systems) led to a more dynamically based perspective on cyclogenesis. The energy conversions and low-level convergence associated with instabilities in regions marked by significant temperature gradients (especially in the lower troposphere) were recognized as important contributing factors in the development of extratropical storms.

The growing awareness of the importance of dynamical processes provided a basis for the polar front theory of cyclogenesis that was developed by the Bergen school in Norway (see, e.g., Bjerknes and Solberg 1922) and set the stage for vigorous discussions concerning the relative importance of dynamic and thermodynamic processes in extratropical storms. Kutzbach's (1979, pp. 125–128) discussion on the "controversial evidence" introduced through the synoptic studies of Hann and Loomis in the late 19th century, and Brunt's (1930) brief note on the origin of cyclones, in which he reviews the differences between the thermal (or "local heating") and dynamic (or

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# Chapter 7

# Orographic Cyclogenesis

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## 7.1 Introduction

The idea that extratropical atmospheric variability on time scales of the order of several days is due to an intrinsic instability of the atmospheric circulation is widely accepted in dynamic meteorology. The most evident manifestation of this variability is the development and movement of cyclones and anticyclones (Blackmon et al. 1984). The leading process has been identified, after Charney (1947) and Eady (1949), in the baroclinic instability of a vertically sheared current. The basic formulation of the theory has been substantially improved over the past thirty years. While the linear problem has been generalized to more "realistic" basic state flows, the nonlinear problem has been tackled with an increasing degree of complexity, including dynamical analysis of chaotic regimes (Malguzzi et al. 1988; Buzzi et al. 1990). Baroclinic instability depends in an essential way upon boundary conditions, and orography enters the problem as a lower boundary condition. We shall see that orographic cyclogenesis is a phenomenological manifestation of the sensitivity of the baroclinic atmosphere to surface relief.

That terrain characteristics are important in determining cyclogenesis and cyclone paths has long been recognized in synoptic meteorology (see, e.g., Ficker 1920), but progress in the understanding of the different processes associated with orography (flow blocking or diversion, roughness variations, elevated heat sources and sinks, etc.) has been rather slow. Mountains and ocean-continent contrasts induce quasi-stationary planetary waves that destroy the zonal symmetry of the time-averaged flow. This asymmetry, in turn, affects the spatial distribution of cyclogenesis frequency and of cyclone tracks (see, e.g., Manabe and Terpstra 1974). This is not, however, the sole effect of mountains on cyclonic scale disturbances. Mountains also have a strong direct influence on baroclinic transient eddies, in the sense that they locally affect, through flow diversion and blocking, the spatial structure, rate of growth and propagation of these synoptic scale disturbances (Hsu 1987; Buzzi and Tosi 1989) and these, in turn, affect the time-averaged flow (Speranza 1988; Malguzzi et al. 1988).

Forecasting orographic cyclogenesis has always been a difficult task probably due, among other causes, to lack

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# Chapter 8

# Organization of Clouds and Precipitation in Extratropical Cyclones

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## 8.1 Introduction

A number of models accounting for the distribution of cloud and precipitation in extratropical cyclones were proposed during the 19th and early 20th centuries. A history of these has been recounted by Bergeron (1959, abridged version in Bergeron 1981) and also by Ludlam (1966) in his inaugural lecture as professor of meteorology. These models culminated in the classical Norwegian polar-front cyclone model of the Bergen school (Bjerknes and Solberg 1922) in which the patterns of cloud and precipitation were related to vertical air motions resulting from the relative movement of different air masses along inclined frontal surfaces. This model is still widely used today. During the past quarter-century, however, the availability of imagery from satellites and radars has revolutionized the capability to observe cloud and precipitation. The imagery has drawn attention to many synoptic-scale and mesoscale features not explained by the classical model, as discussed by Reed in Section 3.3.3. It is now clear that the Norwegian model, de-

# Chapter 9

# Transverse Circulations in Frontal Zones

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## 9.1 Introduction

Today, seventy years after the concept of fronts was introduced by the Bergen school, the nature of fronts and their connection with cyclones are still under intense investigation and debate in the meteorological community. New sophisticated observation techniques developed during the past decades and elaborate model simulations have made it possible to analyze the three-dimensional structure of fronts in great detail. Numerous studies published in recent years have increased our knowledge of the formation of fronts and jet streams. The classic textbook by Palmén and Newton (1969) has formed a solid basis for this research and has been of immense importance for the recent theoretical advances.

The present paper does not aim at a complete review of this extensive research activity, but deals mainly with the development of the semi-geostrophic two-dimensional theory. For more complete reviews of the field, the reader is referred to recent papers by Hoskins (1982), Orlanski et al. (1985), Keyser and Shapiro (1986), Bluestein (1986) and Keyser (1986). Additional aspects, with emphasis on recently observed three-dimensional frontal structures in cyclones, are reviewed by Shapiro and Keyser in Chapter 10.

In the years after World War I, Jack Bjerknes and his coworkers had to rely on surface observations and what they could see in the sky. Bjerknes (1919) arrived at his model of the polar front cyclone through a study of convergence lines on the surface map. He inferred the existence of circulations in vertical planes normal to the front. Such transverse circulations were thus part of the frontal concept right from the beginning. Bjerknes assumed that the surface front would continue upward as a surface of discontinuity in velocity and temperature, sloping in accordance with Margules' formula.

As aerological observations became available in the late 1920s and 1930s, Jack Bjerknes could begin to study the three-dimensional structure of the frontal cyclones. Much of this work he did in close cooperation with Erik Palmén, and they wrote three joint papers on the subject. They dissected fronts in the troposphere and found that they were sloping baroclinic layers of transition, about a kilometer deep (Fig. 9.1).

In the early Bergen school, the polar front was considered the prime mover of weather systems in middle and high latitudes. Preexisting fronts were held responsible for the formation of new cyclones, and clouds and continuous precipitation were considered to be the result of warm air ascending over the sloping frontal surface. Two crucial questions, however, remained: How are fronts formed, and what causes the vertical motion that produces frontal clouds and precipitation?

Tor Bergeron (1928) gave at least a partial answer to the first question. He suggested that fronts could be formed as a result of advective concentration of isotherms along the dilatation axes in hyperbolic fields of horizontal flow. Such confluent advection, which is frequently seen to take place

# *Chapter 10*

# *Fronts, Jet Streams and the Tropopause*

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## 10.1 Introduction

The advent of kite and balloon-borne meteorograph soundings during the early 1900s and the subsequent deployment of regional rawinsonde networks provided the observational basis for the study of the spatial and temporal evolution of fronts, jet streams and the tropopause. During the mid-century years (1935–1965), researchers focused on the structural characteristics of fronts and their associated jet streams near the tropopause, and on the diagnosis of the frontogenetic processes and secondary circulations governing their life cycles. The pioneering observational study by J. Bjerknes and E. Palmén (1937) showed fronts to be transitional zones of finite width (~100 km) and depth (~1 km), rather than near zero-order discontinuities extending from the surface to the tropopause. Newton (1954) presented the most comprehensive diagnosis of all components of upper-level frontogenesis during this period, and Sawyer (1956) and Eliassen (1962) derived the diagnostic theory for geostrophically forced secondary circulations about fronts based on the semigeostrophic equations, which was later expanded to the temporal dimension by Hoskins (1971) and Hoskins and Bretherton (1972).

In contrast to their upper-level counterparts, surface fronts received less attention from researchers during the period, with the exception of the classic study by Sanders (1955). The conceptual model of surface fronts and their evolution during the life cycle of extratropical cyclones

*Chapter 11*

# *Advances in Numerical Prediction of the Atmospheric Circulation in the Extratropics*

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## Chapter 12

# Advances in the Understanding and Prediction of Cyclone Development with Limited-Area Fine-Mesh Models

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## 12.1 Introduction

Since the early scientific theories of the development of extratropical cyclones in the 19th century (Kutzbach 1979), meteorologists have sought a complete and quantitative description of the physics of these atmospheric systems that dominate weather in middle latitudes. The earliest studies were descriptive and based almost entirely on surface observations. With the advent of instrumented aircraft in the early 1930s, operational rawinsondes in the 1940s and satellites in the 1960s, a more complete three-dimensional picture of the structure of extratropical cyclones emerged, as described by others in this volume.

Professor Palmén contributed much to the early documentation of the three-dimensional structure of extratropical cyclones through his careful analyses of ra-

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