EXTRATROPICAL CYCLONES

THE ERIK PALMÉN MEMORIAL VOLUME

Erik Herbert Palmén, 1898-1985

EXTRATROPICAL CYCLONES

THE ERIK PALMÉN MEMORIAL VOLUME

Co-Edited by

Chester W. Newton
National Center for Atmospheric Research

Eero O. Holopainen
University of Helsinki

American Meteorological Society
Boston
1990

© Copyright 1990 by the American Meteorological Society. Permission to use figures, tables, and *brief* excerpts from this monograph in scientific and educational works is hereby granted provided the source is acknowledged. All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording, or otherwise, without the prior written permission of the publisher.

ISBN 978-1-944970-33-8 (eBook)

Library of Congress catalog card number 90-81189

Published by the American Meteorological Society, 45 Beacon St.,
Boston, MA 02108

Richard E. Hallgren, Executive Director
Kenneth C. Spengler, Executive Director Emeritus
Evelyn Mazur, Assistant Executive Director
Arlyn S. Powell, Jr., Publications Manager
Jonathan Feld, Publications Production Manager

Editorial services for this book were contributed by Kim Dolphin, Linda Esche,
Brenda Gray, and Leslie Keros.

Contents

Preface	vii		
Introduction	ix		
1. Erik Palmén's Contributions to the Development of Cyclone Concepts			
C. W. Newton, National Center for Atmospheric Research			
1.1 Palmén's Setting in the Evolution of Meteorology	1		
1.2 Early Aerological Studies	2		
1.3 Large-Amplitude Upper-Level Disturbances	4		
1.4 Cyclone Development and Air-Mass Exchange	6		
1.5 Cooperative Roles of Extratropical Disturbances and Meridional Cells in the General Circulation	9		
1.6 Energy Conversions in Extratropical Disturbances	10		
1.7 Role of Extratropical Disturbances in Hemispheric Energy Processes	14		
1.8 An Appreciation	17		
References	17		
2. General Circulation Studies in Chicago from the 1940s into the 1950s			
H. Riehl, Denver, Colorado			
2.1 Introduction	19		
2.2 Rossby's General Circulation Concepts	19		
2.3 The Milieu at Chicago	21		
2.4 Palmén's and Other Views on Jet Streams	21		
2.5 Lateral Mixing and Meridional Circulations	22		
2.6 Meridional vs. Jet Stream-Relative Circulations	24		
2.7 Conclusion	25		
References	26		
3. Advances in Knowledge and Understanding of Extratropical Cyclones During the Past Quarter Century: An Overview			
R. J. Reed, University of Washington			
3.1 Introduction	27		
3.2 Status of the Cyclone Problem Prior to 1960	27		
3.3 Advances of the Past Quarter Century	30		
3.4 Concluding Remarks	41		
References	42		
4. Role of Cyclone-Scale Eddies in the General Circulation of the Atmosphere: A Review of Recent Observational Studies			
E. O. Holopainen, University of Helsinki			
4.1 Introduction	48		
4.2 Background Information on Cyclone-Scale Eddies	48		
4.3 Methods of Illustrating the Forcing Effect of Transient Eddies on the Time-Mean Flow	50		
4.4 Forcing Effect of Cyclone-Scale Transient Eddies on the Wintertime Climatological Circulation in the Northern Hemisphere	52		
4.5 Effect of Cyclone-Scale Eddies on the Low-Frequency Variability of the Atmospheric Circulation	57		
4.6 Remarks on Parameterization of the Cyclone-Scale Eddies	59		
4.7 Summary and Final Remarks	59		
References	60		
5. Theory of Extratropical Cyclones			
B. J. Hoskins, University of Reading			
5.1 Introduction	64		
5.2 Parcel Theory for Slantwise Displacements	64		
5.3 The Omega Equation View	65		
5.4 The Potential Vorticity Perspective	67		
5.5 Spherical, Primitive Equation Studies	70		
5.6 Diabatic Processes	74		
5.7 A Case Study	76		
5.8 Concluding Remarks	78		
References	79		
6. Processes Contributing to the Rapid Development of Extratropical Cyclones			
L. W. Uccellini, NASA/Goddard Space Flight Center			
6.1 Introduction: Historical Perspective	81		
6.2 Recent Interest in Rapid Cyclogenesis	83		
6.3 Characteristics of Rapid Cyclogenesis	84		
6.4 Feedback between Diabatic and Dynamical Processes During Rapid Cyclogenesis	95		
6.5 Summary and Issues	99		
References	102		
7. Orographic Cyclogenesis			
S. Tibaldi, A. Buzzi and A. Speranza, University of Bologna			
7.1 Introduction	107		

7.2	The Basic Phenomenology of Alpine Cyclogenesis	109	10. Fronts, Jet Streams, and the Tropopause	
7.3	A Theory of Lee Cyclogenesis	111	M. A. Shapiro and D. A. Keyser,	
7.4	Discussion of Recent Observational Results	116	State University of New York at Albany	
7.5	Results of Numerical Modeling	120	10.1	Introduction 167
7.6	Other Types of Lee Cyclogenesis	122	10.2	The Structure and Dynamics of Upper-Level Fronts, Jet Streams and the Tropopause 168
7.7	Summary and Conclusions	125	10.3	The Scale Contraction of Surface Fronts and its Role in the Initiation of Mesoconvective Precipitation Systems 173
	References	125	10.4	The Life Cycle of the Marine Extratropical Cyclone and its Fronts 177
8. Organization of Clouds and Precipitation in Extratropical Cyclones			10.5	Future Directions 186
	K. A. Browning, U.K. Meteorological Office			References 189
8.1	Introduction	129	11. Advances in Numerical Prediction of the Atmospheric Circulation in the Extra-Tropics	
8.2	The Warm Conveyor Belt and its Associated Cloud System	130	L. Bengtsson, European Centre for Medium-Range Weather Forecasts	
8.3	Rearward-Sloping and Forward-Sloping Configurations of the Warm Conveyor Belt and the Associated Patterns of Cloud and Precipitation	133	11.1	Introduction 194
8.4	The Cold Conveyor Belt and its Associated Cloud System	135	11.2	The Physical and Mathematical Basis for Numerical Weather Prediction 194
8.5	Instant Occlusion and the Associated Cloud and Precipitation	136	11.3	Numerical Methods and Modeling Techniques 195
8.6	The Classical Occlusion	139	11.4	Use and Importance of Observations 199
8.7	The Dry Intrusion and its Influence on Cloud Patterns During Cyclogenesis	140	11.5	Operational Achievements 202
8.8	Wide Mesoscale Rainbands	142	11.6	Prediction of Intense Cyclonic Developments 205
8.9	Narrow Mesoscale Rainbands Associated with Line Convection	144	11.7	Systematic Errors in Numerical Weather Prediction 210
8.10	The Mesoscale Structure and Mechanisms of Ana-Cold Fronts	146	11.8	Concluding remarks 215
8.11	Conclusions	150		References 217
	References	151	12. Advances in the Understanding and Prediction of Cyclone Development with Limited-Area Fine-Mesh Models	
9. Transverse Circulations in Frontal Zones			R. A. Anthes, National Center for Atmospheric Research	
	A. Eliassen, University of Oslo		12.1	Introduction 221
9.1	Introduction	155	12.2	Limited-Area Models 224
9.2	Sawyer's Analysis	156	12.3	Application of Models to the Study of Cyclones 227
9.3	Forcing by Confluence and Shear	158	12.4	The Metamorphosis of Hurricane Hazel Revisited 240
9.4	Modifications in Frontal Clouds	159	12.5	Summary 249
9.5	Forcing by Ekman-layer Convergence	160		References 251
9.6	"Symmetric" Inertial Stability	160	List of Symbols	255
9.7	Geostrophic Momentum as Coordinate	161	Index	257
9.8	Temporal Development of Frontal Structure	162		
9.9	Frontogenesis as a Three-Dimensional Process	163		
	References	164		

Preface

This monograph comprises the twelve invited/lead papers presented at the Palmén Memorial Symposium on Extratropical Cyclones. The Symposium was held at the University of Helsinki, Finland, from 29 August to 2 September 1988. It was organized by the Geophysical Society of Finland and the American Meteorological Society in cooperation with the Danish, Norwegian and Swedish Geophysical Societies.

The initiative for the symposium came from Dr. Joseph Smagorinsky, President of the AMS in 1986. A motivation for holding the symposium during the last week of August in Finland was the fact that 31 August 1988 was the 90th anniversary of the birth of Professor Erik Palmén. The objective of the symposium was to give, on the basis of recent observational and modeling studies, a state-of-the-art picture of research on the structure and dynamics of extratropical cyclones, a topic which Palmén pioneered during the era of advances in aerological analysis.

While Palmén was primarily an ingenious “observationalist,” he also closely followed developments of the theory of large-scale atmospheric circulation systems. Interested in weather forecasting since childhood, he was happy to acknowledge the rapid advances made in this area in recent decades with the aid of numerical modeling. It was therefore fully in accordance with his scientific attitude that the Palmén Memorial Symposium would include not only observational but also theoretical and numerical modeling studies of extratropical cyclones. As the content of the present monograph illustrates, the distinction between observational and modeling studies is becoming diffuse: Observationalists nowadays may use models and modelers may be conducting observational studies.

Ultimately, 62 full papers and 40 posters were presented at the symposium. A meeting review has been published in the *Bulletin of the American Meteorological Society*, Vol. 70, pp. 632–641 and, with some photos taken during the Symposium, in *Geophysica*, Vol. 24, pp. 67–87. A preprint volume of extended abstracts was published by the AMS and is available from AMS headquarters. Sixteen of the contributed papers appear in the January 1990 special issue of *Tellus A*, and some others have been published elsewhere.

The readiness of the authors of the lead papers to contribute to the present monograph was in itself a tribute to

the memory of Erik Palmén. Each of the twelve contributions, put in final form after the Symposium, was reviewed by two experts in the respective areas and by the editors.

The monograph should be of interest to researchers in dynamic and synoptic meteorology, climatology and mesometeorology, as well as in numerical modeling and weather forecasting. It is also appropriate for teaching meteorology at graduate and upper undergraduate levels.

Erik Palmén was a genuine world’s citizen. Finland was his home country, Swedish was his native tongue, and a lot of his research he made while working abroad. We cannot imagine any better way of commemorating the 90th anniversary of his birth than bringing together observationalists and modelers to present their most recent findings on extratropical cyclones, concerning which amazingly many new problems are still emerging. We also feel that this kind of monograph resulting from such a symposium would have been the only type of birthday present “Maestro” Palmén would have approved if still alive.

We want to acknowledge all authors and reviewers for their excellent contribution to the birth of the monograph. We appreciate the encouragement and advice of Kenneth Spengler and Evelyn Mazur, of the AMS, from the conception of the book through its later progress. The resources of the National Center for Atmospheric Research, and the supportive attitude of Warren Washington and others of the NCAR management, have been essential in carrying it to completion.

A very special acknowledgement of gratitude is due to Mrs. Dorene Howard of NCAR, for her expert and punctilious preparation of the whole text, and for her assistance with the editing. She has been a most valuable collaborator throughout, taking initiative and responding promptly and efficiently in a way that sustained the spirits of the technical editor (CWN). It is to her meticulous execution at all stages of the task, that we must attribute the high quality of the final product. Last but not least, we should acknowledge that the inspiration for a symposium to honor Erik Palmén came from a suggestion by Harriet Rodebush Newton.

CHESTER W. NEWTON
Boulder, Colorado

EERO O. HOLOPAINEN
Helsinki, Finland

Introduction

A core issue of meteorology of the atmosphere in the middle and high latitudes concerns the understanding of, and ability to predict, the behavior of extratropical cyclones. The past few decades have shown rapid development in our means of observing the atmosphere. Conventional data from synoptic and upper-air networks have been supplemented with data obtained by means of satellites, radars, remote-sensing profilers, etc. Equally fast has been the development of theoretical and numerical models of the atmospheric behavior. A comprehensive survey of the joint findings of observationalists and modelers on extratropical cyclones therefore appears timely. The present monograph, dedicated to the memory of the late Professor Erik Palmén who was a pioneer in cyclone studies, is devoted to this end.

The first two chapters have the character of a retrospection. C. W. Newton summarizes Palmén's contributions to concepts of cyclone structures and energy processes. H. Riehl describes the general circulation studies in the "Chicago school," giving a view of the emerging ideas of C.-G. Rossby, Palmén and others. Chapter 3, by R. J. Reed, is a review of the status of the cyclone problem prior to 1960 as well as during the past quarter century. It makes an excellent introduction to various aspects of the cyclone problem, such as the structures of fronts and cyclones and processes of frontogenesis and cyclogenesis. These are dealt with more extensively in later chapters which, besides reviewing recent developments in specific areas of the cyclone problem, also provide results not published earlier.

Chapters 4–10 concentrate mainly on our present understanding of various aspects of cyclones, and Chapters 11–12 on our ability to predict their behavior by numerical methods. In both groups, the presentations proceed roughly from larger to smaller scales.

Chapter 4 reviews recent observational studies of the role of cyclone-scale eddies in the general circulation of the atmosphere. The effects of cyclone-scale eddies on the zonally-averaged time-mean flow and on the stationary eddies during Northern Hemisphere winter are illustrated in terms of cyclone-induced mean-flow tendencies. The forcing effect of cyclones in cases of quasi-stationary flow, such as "blocking," is also discussed.

The theory of the structure and development of extratropical cyclones is discussed in Chapter 5 from several points of view. First, a "parcel theory" for slantwise displacements, and the quasi-geostrophic potential vorticity theory of cyclone development, are reviewed. Then, the isentropic potential vorticity perspective of cyclone devel-

opment is highlighted with several illustrative examples from models and from real nature.

Chapter 6 discusses, with use of synoptic examples and sensitivity experiments, processes contributing to the rapid development of extratropical cyclones. The discussion is to a large extent based on the isentropic potential vorticity perspective. The chapter gives a vivid view of how on the one hand upper-level and low-level processes, and on the other hand physical and dynamical processes, interact with each other during explosive cyclone developments.

According to Chapter 7 lee cyclogenesis can, to a large extent, be interpreted as orographic modifications induced on baroclinic transient waves. The different characteristics of the process in various parts of the world are due to different flow conditions and mountain geometries. The chapter deals mainly with recent theoretical, numerical and observational results concerning the effect of the Alps. This emphasis is motivated by the recent international Alpine Experiment (ALPEX).

Chapter 8 discusses the synoptic/subsynoptic scale cloud and precipitation structures of extratropical cyclones as revealed by satellite and radar observations, interpreted in terms of isentropic airflows relative to the moving systems. Conceptual models, such as warm and cold "conveyor belts," play an important role in this description and in condensing the information content of huge amounts of data.

The theory of transverse circulations in frontal zones is discussed in Chapter 9. Emphasis is on the development of quasi-geostrophic, two-dimensional theory. Recent studies of frontogenesis seen as a three-dimensional process, however, are reviewed as well. Chapter 10 provides a review, and a lot of new information on the observed structures, of fronts in the upper as well as in the lower troposphere. The diagnosis presented of some synoptic cases probably provides the most accurate analyses one can make on the basis of the various kinds of data currently available.

Chapters 11 and 12 demonstrate an impressive increase in the skill of numerical forecasts during the past 10–15 years. Besides prediction, models are nowadays an indispensable tool also in diagnosing the atmospheric behavior. For example, Chapter 11 presents probably the most accurate picture so far of global energetics as well as the nature of systematic modeling errors. Both chapters demonstrate that with the aid of models one can also assess the cause-effect relationships arising from physical processes, which earlier were almost impossible to estab-

lish. As an instructive example, Palmén's famous study of the transformation of hurricane Hazel into an extratropical cyclone is analyzed in Chapter 12 using a modern limited-area model. The fact that all Palmén's major conclusions are confirmed makes a worthy tribute to the Maestro's pioneering studies.

While the individual contributions emphasize particular aspects, the monograph as a whole summarizes the major features of various kinds of extratropical cyclones that have been learned through observational analyses, theory and numerical experimentation. Comprehensive references are provided, along with a Subject Index and cross-references linking topics common to the different chapters.

A question not explicitly considered at length in this monograph concerns the feedback of subsynoptic-scale features on the larger-scale flow. For example, how sensitive is the prediction of the intensity of an extratropical cyclone to the detailed simulation of, say, the mesoscale rainbands? Such a simulation will require a much higher resolution than what we today have in global models. What we know, e.g., on the basis of results presented in this monograph, is that increased model resolution, as well as improved physics and model formulation, has so far resulted in improvement in predictions of the synoptic-scale flow. It is probably a safe forecast that scale interaction questions of this type will come up at many meetings in the future.