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Meeting review

PALMÉN MEMORIAL SYMPOSIUM ON EXTRATROPICAL CYCLONES 29 AUGUST – 2 SEPTEMBER 1988, HELSINKI, FINLAND[1)]

by

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Program Chair

1. *Introduction*

The Palmén Memorial Symposium on Extratropical Cyclones and Their Role in the General Circulation of the Atmosphere was held at the University of Helsinki on 29 August – 2 September 1988. The Symposium was organized by the Geophysical Society of Finland and the American Meteorological Society in cooperation with the Danish, Norwegian and Swedish Geophysical Societies.

The objective 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. Particular emphasis was placed on (1) the role of extratropical cyclones in forcing the large-scale, lower-frequency components of the extratropical circulation; (2) subsynoptic-scale structures (including fronts and mesoscale circulation systems) and their roles in cyclone development; and (3) the role of the underlying surface in cyclone development, including topographic influences and energy exchange processes.

A motivation for holding the Symposium during the last week of August in Finland was that 31 August 1988 was the 90th anniversary of the birth of Professor Erik Palmén. Palmén was a distinguished member of the Academy of

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1) This meeting review appears also in the Bulletin of the American Meteorological Society, Vol. 70.

Finland. For almost forty years he worked at the Department of Meteorology of the University of Helsinki and was a visitor to many institutions internationally.

Initiative for the symposium came from Dr. Joseph Smagorinsky, President of the AMS in 1986, and a prospectus was drafted by Dr. Chester Newton. The International Programme Committee had nine members, three from the U.S.A. and six from Scandinavia. The response of the scientific community to the call for papers, first issued in February 1987, was excellent with more than a hundred papers submitted from 18 countries.

One of the principles in planning the meeting was not to have parallel sessions but rather to have observationalists and theoreticians to listen to each other. Accordingly, poster sessions played a large role. All poster presenters had the opportunity of giving a brief (3 minutes) introduction of their subjects, in a regular session. Ultimately, 62 full papers and 40 posters were presented. The number of registered participants was 134, with 29 accompanying persons. A program of the meeting appeared in the April 1988 issue of the AMS *Bulletin.*

The Symposium was opened in the University of Helsinki by Prof. Eero Holopainen, with welcoming remarks by Prof. Seppo Huovila, President of the Geophysical Society of Finland, and by Prof. Roscoe Braham Jr., President of the AMS. The opening session was attended by Mrs. Synnöve Palmén and ten others representing three generations of the Palmén family.

Social events during the symposium included receptions by the Rector of the University of Helsinki, Academician Olli Lehto, and by the Director of the Finnish Meteorological Institute, Prof. Erkki Jatila. A Ladies Program was organized by Mrs. Jatila. One afternoon there was an excursion to Vaisala Oy, where activities of the company were introduced and refreshments served. The Banquet, held in a beautiful island restaurant, was an important part of the memorial aspect of the Symposium. Dr. Alf Nyberg was the main banquet speaker. In addition, several other »students of the Chicago school» (R. Braham, C. Newton, Y-B. Xie) as well as some other participants (A. Eliassen, A. Wiin-Nielsen, J. Neumann, S. Kitaigorodsky, M. Shapiro) addressed the banquet audience with extensive laudatory remarks on Palmén.

A preprint volume of extended abstracts has been published by the AMS and is available from AMS headquarters. (This also includes some abstracts of papers that were accepted, but whose authors were unable to attend.) The AMS will also publish a bound volume comprising the 12 invited lectures and topical review papers. Contributed papers, presented in oral and poster sessions, will appear in a special issue of *Tellus.*

2. *Session reports*

The following session reports have been prepared by the chairs of the individual sessions, except for session 1. The reports refer to papers actually presented at the meeting.

a. Session 1. Retrospection and introduction (L. Vuorela, chair; C. Newton, reporter)

This session comprised three invited lectures, intended to give a view of Palmén's investigations related to extratropical cyclones; general circulation studies at the University of Chicago where he was a frequent visitor for two decades; and an overview of advances leading up to our present understanding of cyclones.

»Erik Palmén's contributions to the development of cyclone concepts» were outlined by C. Newton. Investigations during 1923–1942 encompassed cyclone movements and pressure change processes, upper-level flow patterns, and characteristics of air masses, fronts and tropopauses. With J. Bjerknes in 1937, Palmén made the first comprehensive aerological analysis of an entire cyclone. In the post-WWII era, within the setting of a broad attack on the problem of the general circulation, he established fundamental relations concerning frontal layers and the jet stream. These served as a framework for analyses of the 3-D structures and airflows in cyclones and anticyclones, which illuminated their roles in the meridional and vertical exchange processes.

In a general circulation concept in 1951, Palmén differentiated the subtropical and polar front jet streams, sustained respectively by the Hadley cell and by an overall direct circulation relative to the polar front zone, due to systematic ascent in the warm air and descent in the cold air of synoptic disturbances. These features were elaborated theoretically and observationally in his later works on angular momentum and energy conversion processes. He demonstrated that although KE generated by and exported poleward from the Hadley circulation sustains the westerlies, the intense generation of eddy KE in cyclones (enhanced by latent heat release) dominates energy conversions over the extratropical region as a whole. Through these investigations Palmén exerted a major role in establishing the three-dimensional structures and mechanisms of cyclones, the nature of the principal wind systems of the globe, and the cooperative roles of mean meridional circulations and synoptic disturbances in the momentum and energy processes of the global atmosphere.

H. Riehl reviewed »General circulation studies in Chicago from the 1940s into the 1950s» (presented by F. Baer). These were stimulated by C.-G. Rossby, who drew together an international team for an attack on this problem with Palmén

as co-leader. Important roles were played by conservation theorems, and by renewed emphasis on linkages between upper-tropospheric waves and synoptic disturbance development. A major objective was to explain the distribution of the upper westerlies and their concentration in the jet stream. Rossby's conception was that the jet stream manifests lateral mixing of absolute vorticity within the »polar cap», which results in maximum westerlies at its equatorward extremity (where an indirect solenoidal circulation was hypothesized). Palmén challenged the concept of a single jet stream and also the consistency of this scheme with energy conversion processes, proposing instead the additional existence of the subtropical jet stream, accounted for by the solenoidally-direct mean tropical circulation.

Riehl proceeded to discuss the roles of eddies and mean circulations in transporting energy, and their different roles in tropical and higher latitudes. »Rotating dishpan» calculations by Riehl and Fultz demonstrated that the mean circulation around the hemisphere can be indirect relative to latitude, and at the same time direct when averaged relative to the meandering jet stream. The eddies thus basically alter the circulation and heat transport mechanisms, in a way consistent with Palmén's scheme of the midlatitude circulations.

R. Reed presented »Advances in knowledge and understanding of extratropical cyclones during the past quarter century: A review», starting with a perspective of earlier developments. The polar front theory presented a synthesis introducing the concepts of a cyclone forming through instability on the front and evolving through a life cycle, and deriving its KE from the release of potential energy. Bjerkness' demonstration of the connection between upper-level waves and surface cyclones led to the Charney-Eady theory of baroclinic instability. This involves the whole troposphere rather than frontal instability, with support by Phillips' numerical simulation. Observational studies also revealed the 3-D nature of frontogenesis, and suggested the stratospheric origin of air in upper-level fronts. The Sawyer-Eliassen concept of frontogenesis arising from transverse ageotrophic circulations induced by geostrophic confluence was introduced. A major advance in diagnosis of cyclogenesis came from the work of Sutcliffe and Petterssen, which linked disturbance development to vorticity processes involving preexisting upper-level perturbations.

Building upon these foundations, the most impressive advances in the past 25 years have been in theoretical understanding of frontogenesis and in numerical modeling of cyclones in real situations. Numerous theoretical and numerical studies have elaborated frontogenetical processes, showing that ageostrophic circulations induced by geostropic deformation can lead to a thermal

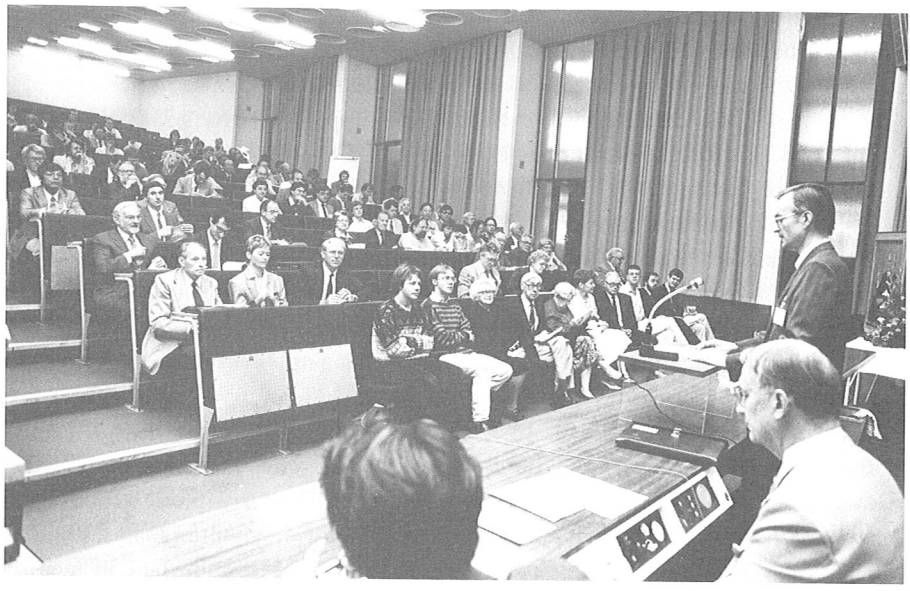
discontinuity near the ground, and examining the roles of surface friction, moist processes, and symmetric instability. Observations of various kinds have revealed the intense concentration of near-surface fronts and the character of their circulations. Stratospheric extrusion into upper-level fronts has also been confirmed, and diagnostic studies have identified the forcing mechanisms for »tropopause folding».

Meteorological satellites and radar have been principal tools in studying cloud patterns, mesoscale precipitation and motion fields. While broad features of the Norwegian model have been confirmed, new features have been revealed, including comma and spiral cloud systems, polar lows, and »instant occlusions». Sequential intensifications of cyclones under changing environmental circumstances have been intensively studied. Baroclinic instability theory has been extended in regard to the effects of lateral shear, moist processes, downstream propagation, and feedbacks to the zonal flow. Numerical modeling has greatly advanced in fidelity, and sensitivity experiments with and without various processes have led to further understanding. Extensive synoptic analyses and numerical simulations of explosive cyclogenesis have been important in identifying the physical conditions and processes influencing extreme events.

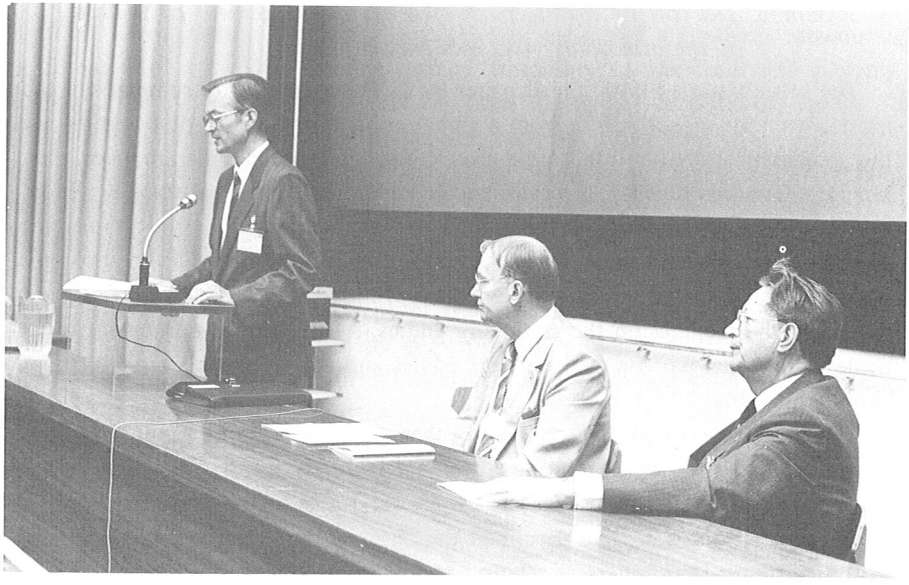
b. Session 2. The role of extratropical cyclones in the general circulation of the atmosphere (A. Wiin-Nielsen, chair)

The session started with a lead paper by E. Holopainen who summarized the most important recent results from a global point of view. The first part discussed the geographical distribution of the growth rate of baroclinic disturbances, the kinetic energy distribution of cyclone-scale eddies, and the total transient eddy kinetic energy distribution. In the second part the speaker discussed the forcing of cyclone-scale eddies upon the mean zonal flow as determined from the conventional and transformed Eulerian methods, followed by a description of the effects of these eddies on the stationary eddies. A still further refinement was made in the final part on cyclone-scale eddies and low-frequency variability, including blocking.

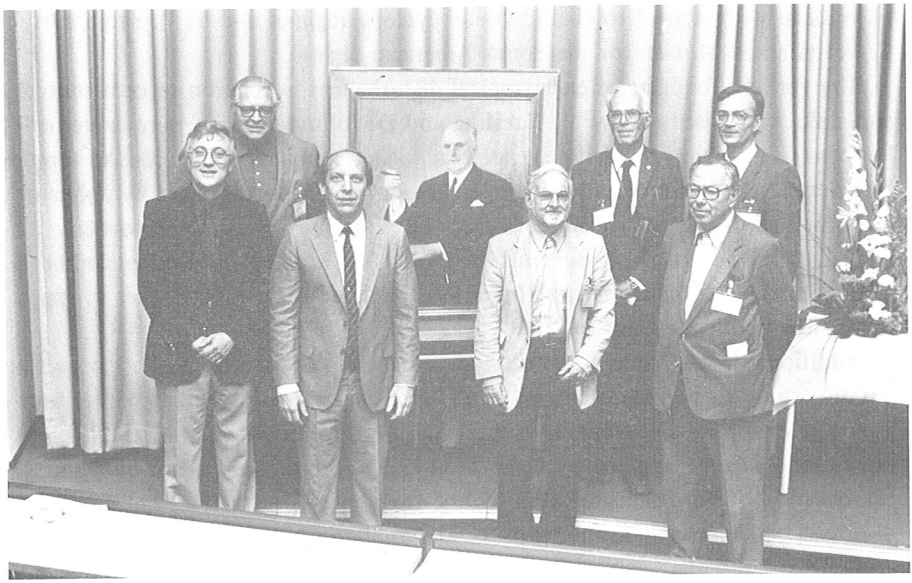
The themes presented by the lead speaker were taken up in a number of papers in the session, albeit often in a more regional sense. D. Karoly discussed the role of cyclone-scale eddies in the low-frequency variations of the Southern Hemisphere circulation. N.-C. Lau described the observed midlatitude cyclone tracks in the Northern Hemisphere in relation to low-frequency changes in the circulation, while M.-M. Lu discussed the effects of transient eddies on equatorially trapped waves. A similar theme was taken up by J. Anderson, J. Gyakum and



The Palmén Memorial Symposium on Extratropical Cyclones was opened in the University of Helsinki in the presence of representatives of three generations of the Palmén family (in the first row).



Prof. Eero Holopainen welcomes the participants to the symposium. Prof. Seppo Huovila, President of the Geophysical Society of Finland (middle) and Prof. Roscoe Braham Jr., President of the American Meteorological Society (right) addressed the symposium on behalf of their organizations.



The International Programme Committee of the Palmén Memorial Symposium around the portrait of »Maestro» Palmén. From left to right: Lennart Bengtsson, Aksel Wiin-Nielsen, Louis Uccellini, Dick Reed, Chester Newton, Arnt Eliassen and Eero Holopainen. Missing from the figure are Bert Bolin, Hilding Sundqvist and Lauri A. Vuorela.

Two students of the »Chicago school» from the latter part of the 1940's: Prof. Y-B. Xie from Peking University and Dr. C.W. Newton from NCAR.

M. Nadeau with respect to Pacific Ocean cyclone regimes and by P. Satyamurty, C. Ferreira and M. Gan for the South American region.

The vorticity budgets of extratropical disturbances in relation to heat sources and sinks were discussed by M. Hoerling and D. Johnson. These were examined in terms of »dynamic vorticity», related to vorticity flux through pressure torques by solenoids in an isentropic surface, as described in a poster paper by Johnson and Hoerling. H. van den Dool described the transient eddies in the vorticity budget of the time-mean anomalous flow. W. Metz investigated the possibility of empirical parameterization of the cyclone-scale eddy vorticity fluxes in terms of the low-frequency flow.

Additional interaction studies were reported. R. Dole and P. Neilly gave a comparative study of persistent anomalies and cyclone-scale eddy activity. The interaction of synoptic- and planetary-scale eddies during the development of a blocking episode was investigated by C.-H. Tsou and P. Smith. Related to blocking is the question of bimodality of atmospheric frequency spectra. This question was discussed and results were shown by H.-D. Schilling who confirmed the bimodality.

D. Straus and the team of B. Dugas and J. Derome presented comparative studies of the behavior of general circulation models and the real atmosphere, with Straus concentrating on the synoptic-scale eddies while Dugas and Derome considered anomalies.

The question of weather regimes and transient feedback mechanisms was discussed in two separate papers by B. Legras and B. Reinhold. A. Robertson tried to derive the extratropical cyclone activity from a stability analysis of the low-frequency pattern. Reinhold also gave a paper dealing with the structure of extratropical disturbances, wherein he sought to explain the »structural determinism» of cyclone eddies. This question is related to why the eddies slope much less than 90 degrees in the vertical direction (almost equivalent-barotropic disturbances) as determined by Lau from observations almost 10 years ago.

In summary, one may say that the papers presented in this session gave an excellent account of the more recent studies of the role of cyclone-scale eddies in various aspects of the general circulation. Very significant progress can be noted in the last decade or so. While the single distinction made in early studies some 30 years ago was between the zonal flow and the eddies, we are now subdividing the flow into stationary and transient component, and the latter are further divided in the frequency domain, at least into low- and high-frequency components but occasionally using further refinements. The observational studies give by now a rather detailed view of the various interactions between all these components. The picture is in a sense too detailed because it is difficult to see how these studies can help us to parameterize a higher-frequency component in terms of the param-

eters of a lower-frequency component. The lead speaker (Holopainen) took a rather pessimistic view stating »that a large fraction of the forcing caused by the cyclone-scale eddies can never be parameterized». He may very well be correct, but it would be worth-while to attempt a synthesis of the observational studies with the purpose of simplicity. It is indeed noteworthy that no paper in Session 2 attempted to treat the role of extratropical eddies in the general circulation from a theoretical point of view. One may hope that this situation will change in the future.

c. Session 3. Theory of extratropical cyclones (B. Hoskins, chair)

The eight papers in this session, in keeping with the spirit of the symposium, were all presented with a strong emphasis on the relevance and application of the theory to the real atmosphere. In the lead paper, B. Hoskins emphasized that there is no unique framework for understanding, but that time would limit him to a potential vorticity (PV) perspective. He showed that the downstream (upstream) development of neutral Rossby waves on a tropopause PV (surface θ) gradient can lead to the growth of a new ridge or trough in a day. However, larger growth occurs when the two mutually reinforce each other. He summarized numerical life cycle experiments and a real storm development using PV thinking. B. Farrel gave an eloquent plea that a normal mode view of baroclinic instability is not sufficient. He showed that one can determine the best initial conditions for various measures of growth. In particular, a baroclinically unstable normal mode is best triggered by a structure quite dissimilar to the mode itself.

The following three papers concentrated on normal mode instability. W. Peltier, G. Kent Moore and S. Polavarapu described their work on the stability of frontal structures, emphasizing the need to use the full primitive equations. They showed that an observed polar low type of basic flow did indeed exhibit a growth rate maximum at a wavelength of about 500 km with an e-folding time of the order of 6 hours. They also exhibited the multiple, strong frontal structures present in a numerical integration of the development of a baroclinic wave. C. Schär and H. Davies showed that some frontal waves were observed to occur in situations in which there was a low-level temperature maximum ahead of a cold front. With the aid of a quasi- or semi-geostrophic Eady-type model they investigated the stability of a flow with such a low-level temperature distribution and found unstable modes in some agreement with thos observed, even when the temperature maximum was quite weak. A. Joly and A. Thorpe, again using filtered models, investigated the stability of a similar situation in which the temperature maximum was replaced by an internal PV maximum which they envisaged to have been

created by diabatic heating. They too found modes whose energetics were dominated by conversions from the kinetic energy of the mean flow. They also discussed the stability of an evolving 2-D Eady wave to perturbations in the third direction.

J. Zehnder and D. Keyser examined the initial value problem for the Eady-type model with isolated perturbations on a horizontal length scale well below the Eady cut-off. For zero PV perturbations little growth was found until unstable Eady modes eventually dominated. For a positive PV anomaly near the lid, westward of one near the surface, significant transient perturbation energy growth was found.

K. Zhang used a primitive equation model to study the stability of the summer southwesterly low level jet over China. She found growth-rate peaks near 600 and 1800 km. A similar study, but with a representation of condensational heating, was applied to the Mei-Yu front and yielded symmetric instability modes on a 200-km scale.

P. Zwack, in a very different approach, produced an extension of the Pettersen-Sutcliffe surface vorticity tendency equation. A vertical velocity term, which in usual quasi-geostrophic theory is eliminated to yield essentially elliptic equations, was included on the right-hand side. The contribution of various items for cyclogenesis was discussed.

d. Session 4. Cyclogenesis (L. Uccellini, chair)

The lead paper by L. Uccellini reviewed the historical aspects of research on cyclogenesis over the past 150 years. During this period, meteorologists have debated the relative contributions of dynamic and thermodynamic processes to the development of extratropical cyclones. More recent studies which emphasize rapid cyclogenesis were then reviewed, again pointing toward the continuing controversy concerning the relative importance of various processes (upper-level troughs and jets, latent heat release, boundary layer physics) during cyclogenesis. Uccellini concluded by noting that these processes may represent necessary conditions for rapid cyclogenesis but are not sufficient when acting alone. Results from several model-based diagnostic and sensitivity studies were shown, emphasizing that the nonlinear interaction among these processes in the crucial element for rapid cyclogenesis, an interaction which is apparently accounted for by Sutcliffe's »self-development» concepts. The presentation was concluded with a video of a numerical model simulation of the Presidents' Day snowstorm. This clearly depicts (in three dimensions) the interaction of upper- and lower-level potential vorticity

maxima and also the airflow through a cyclone using model-based trajectory computations. The video, produced at the Space Science and Engineering Center of the University of Wisconsin-Madison, is available from Mr. William Hibbard of SSEC.

A climatological study of cyclone frequency in the North Pacific Ocean was presented by J. Gyakum, J. Anderson, R. Grumm and E. Gruner, based on an eight-year data sample. The study reconfirmed the influence that the warm Kuroshio current has on rapidly-developing Pacific cyclones. Although the largest cyclone frequency is located well north of 50°N in the Gulf of Alaska and in the vicinity of the Kamchatka Peninsula, the most active cyclogenesis is concentrated in a band south of 45°N extending eastward from the Asian coast to 160°E, an area which generally accounts for the most explosively-developing storms.

Papers by E. Rasmussen and T. Nordeng focused on polar lows. Rasmussen presented a survey of the various cloud distributions associated with polar low development as viewed by satellite. He noted that there is a spectrum of polar lows ranging from those characterized by baroclinic wave and associated »cloud-leaf» features to those dominated by convective cloud elements. Nordeng provided examples of numerical simulations of polar lows over the North Atlantic using the limited-area model developed at the Norwegian Meteorological Institute. His model results provide supporting evidence for the impact that upper-level forcing, low-level baroclinic zones associated with the ice edge, and sensible and latent heat fluxes in the boundary layer can have on the development of polar lows. The importance of boundary-layer fluxes during rapidly-developing cyclones was also emphasized in separate papers by M. Jean and M. Yau and by T. Pedersen. Jean and Yau conducted a synoptic analysis of one of the major cyclones observed during the Canadian Atlantic Storms Program (CASP). Their analysis shows that the explosive cyclogenesis was influenced significantly by boundary-layer fluxes in the cold air stream north of the cyclone and by latent heat release in addition to the classic baroclinic processes. Pedersen's study of a polar low using the high-resolution (55 km) HIRLAM model came to the same basic conclusion as the other model-based studies by showing the influence of various physical processes on the development of a polar low off the coast of Norway.

The emphasis on the role of boundary-layer sensible and latent heat fluxes in fueling the rapid development phase of extratropical cyclones was highlighted by K. Emanuel, C. Davis and M. Fantini. They cited the critical importance of large sea-air thermodynamic disequilibrium for rapid cyclogenesis. This paper set the stage for a lengthy discussion on whether boundary-layer fluxes precondition the environment by reducing static stability or whether these fluxes also continue to fuel the cyclone during its rapid development phase. The paper by P. Smith,

C-H. Tsou and M. Baker, that focused on static stability changes prior to oceanic and land-based cyclones, provided supporting evidence for the influence of boundary-layer processes in preconditioning the cyclogenetic environment over the Atlantic Ocean. The model results presented by Uccellini, Nordeng and Pedersen, and the Jean and Yau analysis, indicated that boundary-layer processes are also important during the cyclogenetic period for selected cases.

A number of other case studies emphasized various aspects of cyclones. K. Myrberg and J. Koistinen presented an example of a small-scale surface low which developed within a convective cloud cluster over the Baltic Sea. The cyclone then developed a comma-shaped cloud distribution as it intensified. This period of development was associated with the arrival of a short-wave trough and jet streak moving from west to east. They noted the problems that the HIRLAM forecast model had in properly simulating this storm, and speculated that these could be related to deficiencies in the convective parameterization scheme. Papers presented by Y. Qiu and by H. Cao and C. Fu described the transformation of frontal zones and entropy changes associated with cold waves and surface cyclones over eastern China. They noted the significant changes in the deep baroclinic structure and associated jet systems which are associated with these extratropical systems. R. Servranckx presented a diagnostic study of a North American cyclone based on a modified development equation derived by Zwack (Session 3). They displayed coherent ascent and descent patterns derived from a gridded radiosonde data base that correlated well with the major cloud regimes and clear zones associated with this cyclone.

While the emphasis in this session was on rapid, small-scale cyclogenesis, R. Dole and R. Black presented a comprehensive paper on cyclonic circulation systems which appear to fill an entire ocean basin. The »large-scale cyclogenesis» has a zonal extent of 70° to 80° longitude. These cyclones develop over the Atlantic and Pacific Oceans over a 1- to 3-day period, with little indication of significant anomalies over the region until immediately before the cyclogenetic period. The most systematic precursors are related to variations in jet intensity and associated thermal structure upstream of the incipient cyclogenetic region, and are often preceded by a major buildup of cold air over the upstream continental regions. These results suggest that baroclinic processes are important for the initial development phase, with barotropic processes becoming more important as the cyclonic circulation extends through a deeper portion of the troposphere.

e. Sessions 5 and 6. Synoptic and subsynoptic structure of extratropical cyclones (K. Browning and R. Reed, chairs)

These sessions began with three lead papers. The first, by K. Browning, dealt with the organization of clouds and precipitation in extratropical cyclones. On the basis of the relative motion on isentropic surfaces, three main flows within cyclones were distinguished – the warm conveyor belt, the cold conveyor belt and the dry intrusion. Conceptual models of these features were presented, including models of both rearward-sloping and forward-sloping warm conveyor belts. Also treated were the cloud systems formed during the so-called instant occlusion process, and, on the mesoscale, the broad and narrow banded features that are embedded within the general region of frontal precipitation.

The second lead paper, by M. Shapiro and D. Keyser, was concerned with the structure and dynamics of fronts, jet streams and the tropopause. Attention was given first to the problem of upper-level fronts and frontogenesis. The type of wind and temperature fields required to yield the characteristic indirect circulation of upper fronts was depicted, and examples were given of successful simulations of upper fronts by numerical models. Additional topics discussed were the coupling of upper- and lower-level frontal circulations, the lower-level frontal structure in occluded cyclones, and the narrow, intense cold frontal structures near the surface revealed by high-resolution measurements from acoustic sounders, instrumented towers and aircraft. Of particular interest were the remarkable thermal structures in the core of the occlusion revealed both by model simulations of the QE II storm and by aircraft measurements taken in an intense cyclone during the pre-ERICA test period.

Transverse circulations in frontal zones were the topic of the third lead paper by A. Eliassen. He reviewed the development of the well-known Sawyer-Eliassen equation, which expresses the transverse ageostrophic and vertical circulation in response to deformation in the primary semi-geostrophic flow. Noting that the equation originated with Sawyer he expressed the wish that the equation hereafter be referred to simply as the Sawyer equation, but his extraordinarily lucid presentation merely reinforced the view that dual attribution is justified. Moreover, Eliassen introduced the term expressing the transverse circulation induced by along-front differential temperature advection associated with lateral shear. He also discussed the theoretical work of Hoskins and Bretherton which allows evaluation of the change of frontal structure with time, with the evolution of sharp surface fronts and extrusion of stratospheric air into upper levels of frontal zones.

Y.-B. Xie summarized the results of observational and theoretical studies aimed at forcasting severe summer rainstorms over China. Particular emphasis was given

to the role of moist baroclinic instability in the rain events. H. Volkert and C. Bishop compared the results of numerical experiments of frontogenesis and geostrophic breakdown with results obtained analytically, finding that in general they were very similar. A paper by M. Cullen, G. Shutts and M. Holt described balanced models of frontal zones and axisymmetric circulations using a geometric Lagrangian method. The effects of diabatic processes on the cross-frontal circulations and on convectively-driven vortices were studied.

K. Szeto, C. Lin and R. Stewart (presented by Lin) treated the role of melting in producing velocity perturbations in regions of stratiform precipitation associated with warm fronts and mesoscale convective systems. The results from a nonlinear two-dimensional model indicated that the melting-induced mesoscale circulations extended beyond the immediate vicinity of the precipitation, both as gravity currents and as transient-gravity waves. In a related presentation R. Stewart, collaborating with S. Macpherson, N. Donaldson and C. Lin, again stressed the importance of melting effects, with special reference to their role in the development of fronts at rain-snow boundaries.

M. Kurz presented a synoptic case study showing the development of cloud patterns and relative motions during the mature and occluding stages of a typical cyclone. His study demonstrated the reality of the classical occlusion process during which part of the warm conveyor belt flow turns cyclonically above the cold conveyor belt. The behavior of the warm conveyor belt is quite different in the case of instant or false occlusions.

S. Zhao presented an analysis of cyclogenesis at the Mei-Yu front in China and illustrated the associated energy conversions. In the area of initial development barotropic and baroclinic processes were both important, the region of maximum energy conversions being localized in a narrow zone. In the poster session, Zhao also presented a numerical study of a cold frontal frontogenetic process over North China that is distinct from the quasi-stationary Mei-Yu front. Deformation was found to contribute very significantly to the frontogenesis and topographic effects were important.

M. Miller and S. Williams presented time-height sections of measurements obtained from VHF wind profiles within a band of heavy snow associated with an American east coast cyclone. The profilers revealed several mesoscale features. Despite the limitations of profilers for measuring close to the ground, a localized low-level easterly flow pattern was detected that was considered to be important in enhancing the snowfall intensity.

Sessions 5 and 6 also featured a large number of poster presentations. A. Joly and A. Thorpe investigated the development of fronts in two-dimensional moist Eady waves and showed that neutrality to slantwise convection in a growing baro-

clinic wave, following a period of dry amplification, led to the formation of two maxima of ascending motion and vorticity. K. Katsaros, G. Petty and U. Hammarstrand illustrated the value of microwave radiometry from satellites in determining the liquid water and water vapor contents in midlatitude cyclones. M. Kavvas, P. Puri and M. Saquib presented a stochastic model of precipitation fields in cyclones over the U.S.A. Structures similar to those observed in radar studies were obtained. Intercorrelation between cyclogenesis and frontogenesis in a selected case were shown by M. Kurz. The approach, which made use of Q-vector analysis, compared the frontogenetical component of the Q-vector to the vertical motion forced by the total Q-vector.

The poster by G. Pearson and S. Blackwell (introduced by R. Servranckx) presented an isentropic analysis of the airflow through a cyclonic system, interpreting it in terms of conveyor belt flows and showing the relationship of cloud edges to deformation fields. A. Akarrappuram and S. Raman presented measurements from the GALE project to demonstrate the major variations in surface heat and momentum fluxes that can occur in association with the strong gradients of sea-surface temperature off the Carolina coast. Exceptionally large fluxes were observed when cold dry wintertime air flowed out over the warm waters of the Gulf Stream. E. Rasmussen went on to describe how, during an outbreak of very cold air over the warm sea north of Norway, several polar lows with an unusually small scale of around 100 km developed within a larger-scale cyclonic circulation of about 800 km which he referred to as an arctic cyclone. F. Roux (collaborating with P. Amayenc, D. Hauser, Y. Lemaitre, G. Scialom and J. Testud) presented preliminary dual Doppler radar results from the European Mesoscale Frontal Dynamics Project/Fronts 87, showing the detailed flow pattern associated with line convection at a sharp ana-cold front. Observed features included efficient generation of heavy precipitation during abrupt ascent of air above a 1 km-deep nose of cold air, and significant evaporation of this precipitation as it descended through the cold air. P. Saarikivi described two studies: one, in collaboration with T. Puhakka, was an observational study which revealed a great deal of complexity in the fine structure of an aging occlusion. The other showed how the distribution over Finland of radioactive fallout from the Chernobyl accident could be related to flow patterns represented by conveyor belts. Deformation fields associated with the conveyor belt flows generated distinct filaments of contaminated air, and precipitation processes within these flows led to wet deposition of the radioactive debris.

f. Session 7. Influence of the underlying surface (especially topography) on extratropical cyclones (S. Tibaldi, chair)

The influence of topography, but more generally of the »lower boundary condition», upon both the generation and development of extratropical cyclones is so widely accepted as a major (and difficult to tackle) problem that the organizing committee decided to devote a separate session to this issue. Unfortunately in a way, orography once again took the lion's share, all papers but one dealing in some way or another with orographic influences on cyclones, and only one concerning diabatic effects.

The session was opened by a lead paper on »Orographic influences on cyclones» by S. Tibaldi (with A. Buzzi and A. Speranza), in which theories of orographic cyclogenesis were compared with synoptic descriptions and with numerical modeling results. Much of the emphasis was put on the »Bologna school» theory and modeling results, both because of the natural speaker's bias and of the good successes that the theory has had in describing the essential features of the phenomenon, not only in Alpine cases but also in other geographical regions.

The first contributed paper by A. Buzzi, P. Malguzzi and A. Trevisan, on »Statistical analysis and modeling of orographic cyclogenesis», showed how the underlying orography can significantly alter the high-frequency component of geopotential height variance (especially at low levels) and the mean horizontal and vertical structure of transient eddies, as well as of positive and negative anomalies. They also showed how a simple two-layer quasi geostrophic model captures, at least qualitatively, all the main features of such orographic influences.

A. Bratseth and L. Breivik proceeded to show, also by means of numerical modeling, how the effect of a mountain on a passing baroclinic zone strongly depends upon the conditions of stationary baroclinic waves. It was proposed that some of the patterns typical of the Bologna school lee cyclogenesis theory (and of observations and numerical modeling) could be interpreted in light of the same physical mechanism as the one acting in their model (and, to some extent, in R.B. Smith's theory as well). A wide and interesting discussion ensued and the majority opinion was that the matter needed (and was well worth) more detailed investigation.

After the presentation by K. Hoinka on the passage of a dry cold front over Bavaria, G.-X. Wu presented some theoretical considerations and numerical modeling results on the formation of summer vortices on the eastern flank of the Qinghai Tibetan Plateau. Such vortices are often responsible for torrential rains in the area and their correct forecasting is therefore of particular interest. Wu highlighted the importance of orographic dynamical forcing and of the three-dimensionality of the flow in describing the main features of the vortex.

The session continued the following morning with a paper by S.-H. Chou and A. Loesch on topographic effects on supercritical baroclinic disturbances, illustrating various features of the interaction between topography and baroclinity (*e.g.* topography tends to phaselock the disturbance, while baroclinity leads to its propagation). This was followed by a paper by K. Howard and E. Tollerud on the structure and evolution of Colorado cyclones that produce heavy snow on the eastern slope. To conclude the session, four poster papers were introduced. First, Z. A. Qian reported on a project to study the Tibetan Plateau vortices in summer. P. Alpert, B. Neeman and Y. Shay-el presented an observational study of Mediterranean cyclogenesis based on potential vorticity analysis performed on ECMWF data. N. Reynolds (introduced by S.-H. Chou) presented a theoretical study (based upon a low-order QG model) showing the topographically-induced vacillation obtained in the finite-amplitude evolution of a baroclinic wave (with some relationship to the work of Chou and Loesch): B. Wang concluded with a presentation on East Asia Summer Monsoon cyclogenesis, in which (in some, only apparent, contrast with previous results presented by Wu) the role played by latent heat release on the formation of the vortex was emphasized. Although this was a comparatively shorter session, the quality of the papers presented was high and the discussion was lively and interesting.

g. Session 8. Numerical prediction of the atmospheric circulation in the extratropics (L. Bengtsson, chair)

L. Bengtsson summarized in his introductory paper the extraordinary development which has taken place in numerical modeling during 35 years of operational weather prediction. Today's forecast error (January 1988) at day 5 (500 mb over Europe) by the ECMWF operational model is about the same as the error at day 1 obtained by the first operational forecasts produced in the early 1950s. It was demonstrated that there was no single cause for this improvement, which resulted from an overall improvement in the data base, in data assimilation, and modeling. Of particular importance has been the large increase in vertical and horizontal resolution and the incorporation of diabatic processes. It was also demonstrated that today's operational models are successful in predicting intense cyclogenesis on time scales of up to 5 days. Examples were given of successful forecasts during winter 1988 with, in one case, a correctly predicted deepening rate of 3 mb/hour. With reduction of the resolution from T106 to T63, notable deterioration could be seen; a model resolution of T42 was generally unable to predict the intense development. Of even greater importance is the effect of release of latent heat;

demonstrating the view expressed by *e.g.* Palmén that the release of latent heat is essential for the development of intense cyclones.

The findings of Bengtsson were supported by the results reported by A. Gadd and R. Kruze, who have studied the ability of the U.K. Meteorological Office operational model to predict intense cyclogenesis over the North Atlantic. An analysis/forecasting system with a horizontal resolution of 75 km generally does very well with extreme cyclones; an example was given by a very successful forecast of a cyclone on 15 December 1986 reaching 915 mb, but the detailed deepening profile and (especially) the filling of the cyclone need to be improved. Reducing the mesh width to 75 km is important for prediction of i) weather elements (*e.g.* associated with fronts), ii) winds for aviation application, and iii) marine surface winds and waves. Resolution in the analysis (space/time) is at least as important as the resolution in the forecast. S. Mullen and D. Baumhefner had studied the development of explosive ocean cyclogenesis in the NCAR GCM. Several cases of intense developments were observed and studied; the importance of the initial condition was stressed.

S. Tracton discussed predictability and its relation to the interaction between the cyclone-scale and planetary waves. Results so far obtained strongly suggest that the development of blocking is critically dependent upon the interplay of systems of different scales, especially including the nonlinear interaction between planetary and small-scale circulations. On another point in relation to the damping of transient eddies common in most models. Tracton's experiments suggested that gravity-wave drag and envelope orography both somewhat diminished transient eddies. However, these two factors appear insufficient to totally explain the damping of transient eddies, particularly since a similar damping also appears in the Southern Hemisphere. Another factor proposed by Tracton may be the use of climatological clouds, which appear to stabilize the middle troposphere. The use of interactive clouds may reduce this stabilization and the damping of transient eddies.

D. Söderman presented a very interesting video animation of cyclogenesis over the North Atlantic on 7–9 February 1988, the same cyclogenesis earlier presented by Bengtsson. The animation sequence highlighted vividly the very intense deepening and the powerful tool of animation to study such processes.

The session contained interesting displays of posters covering different aspects of predictability. The poster by G. White (introduced by S. Tracton) reported on the performance of the NMC medium-range forecast model. M. Morris highlighted the problem facing bench forecasters in cases of extraordinarily intensive systems. The importance of rapid pressure rise behind intense cyclones was stressed; such rapid rise of pressure is crucial for generating the very strong surface winds. Other

posters by E. Källén and X.-Y. Huang, and by F. Baer and J. Ming, stressed the importance of accurate initial states and high resolution, respectively.

h. Session 9. Diagnostics and prediction of cyclone development with limited-area models (R. Anthes, chair)

In the introductory paper, Anthes reviewed some of the contributions made by limited-area models (LAMs) to the understanding and prediction of cyclones. Developed originally for the purpose of improving weather forecasts, LAMs have become powerful research tools, complementing analytical mathematical studies and observational studies. Four types of applications of LAMs were discussed: (1) synoptic studies, (2) sensitivity studies, (2) diagnostic studies, and (4) observing system simulation experiments. Anthes provided examples of each of these applications, which have contributed to increased understanding of extratropical cyclones and methods of portraying observed cyclone structure.

In the second part of his paper Anthes described a simulation, using the Penn State/NCAR LAM, of the metamorphosis of Hurricane Hazel (1954) into an extratropical cyclone. Palmén made extensive synoptic and diagnostic studies of this unusual event in the late 1950s and early 1960s. The model simulated many of the observed features of this transformation, and confirmed Palmén's conclusions concerning the energetics, water budget, and circulation of the system made over 30 years ago.

In related papers, B. Machenhauer and P. Källberg (collaborating with B. Machenhauer, N. Gustafsson, B. Hansen Sass, J. Haugen, S. Järvenoja and N. Woetman Nielsen) described the High Resolution Limited Area Model (HIRLAM) developed in a joint Nordic/Dutch project for operational short-range weather forecasting in the participating countries. HIRLAM consists of five parts: a limited area version of the ECMWF objective analysis package, a nonlinear normal mode initialization scheme, a gridpoint model, an extensive physical parameterization package, and a supporting system for pre- and post-processing of data. A number of tests of the system involving data assimilation, lateral boundary conditions, initial conditions, and physics were described. In a case study of an explosively deepening cyclone over the North Sea (4–5 September 1985), Machenhauer clearly demonstrated the importance of initial data and analysis to the HIRLAM simulation.

H. Sundqvist described a novel treatment of clouds and precipitation in a LAM with horizontal resolution of about 55 km. His scheme accounts for condensation, cloud, and precipitation processes, and includes a prognostic equation for cloud water content. Sundqvist showed how a LAM using this scheme simulated the

intense storm of 5–6 September 1985 that crossed southern Scandinavia. The model storm compared favorably with the observed storm in many respects. He also compared the model-predicted cloud cover at different levels with NOAA9 satellite photographs, and showed many areas of qualitative agreement. In a related paper J. Kristjánsson described a simulation, using the same model, of an intense mesoscale low that formed over the Baltic Sea on 23 July 1985. As with the case described by Sundqvist, the model was remarkably successful in simulating the development of the mesoscale low and its heavy precipitation field. Sensitivity studies showed the importance of details of the cloud parameterization scheme to the success of the control model simulation.

Some of the most interesting mesoscale circulations in the world are observed over China, in association with the Tibetan Plateau. In summer, these circulations often cause heavy rainfall events and flash floods. Z. Qian (collaborating with H. Gu, H. Yang, Y. Chen, C. Li and J. He) and S.-J. Chen described model simulations of two separate heavy rainfall occurrences over China, the 11–15 July 1981 event over the Sichuan Basin and the 21–22 July 1982 heavy rainstorm over the middle Yangzi Valley. In the case of the Sichuan flood, the formation of a »Southwest Vortex» was critical in producing the heavy rainfall. A control model simulated this vortex very well; sensitivity experiments showed that the latent heat release associated with condensation was the most important physical factor in formation of the vortex. In simulations of the Yangzi Valley storm using the ECMWF LAM, S.-J. Chen (poster introduced by Y.-B. Xie) demonstrated the importance of vertical coupling between an upper-level and low-level jet. This coupling was dynamically induced, but greatly enhanced by the release of latent heat.

Mesoscale forecasts of explosive cyclogenesis in middle latitudes were discussed by J. Mailhot and C. Chouinard and by M. Cullen and T. Davies. Mailhot described two simulations of cyclogenesis during the Canadian Atlantic Storms Program using a 100-km resolution version of the operational Canadian regional finite-element model. Because both simulations were quite accurate, the model data were used to examine the mesoscale structure of these storms. The mesoscale structure of the model storms agreed well with the observed mesoscale structure of similar storms. Cullen described forecasts of the exceptional storm of 15–16 October 1987 over the U.K., which was not forecast well in real time. He showed that deficiencies in the operational forecast were related to errors in the initial conditions, caused by missing data, rather than deficiencies in the model.

Finally, C. Doswell and M. Antolik examined the relationship between quasi-geostrophic forcing and the vertical motion from a primitive equation numerical

model. In an examination of several cases, Doswell found good agreement in the patterns of QG forcing and model vertical motions in some regions, but poor agreement in others. Terrain variations and moist convective processes were implicated in producing many of the disagreements. Where there were disagreements, the primitive equation model's vertical velocities were better correlated with precipitation than with QG forcing.

3. *Concluding remarks*

Judging from the feedback received, the symposium was highly successful. During the symposium great progress was reported in our understanding of cyclone behaviour, and in our ability to predict cyclone development. It is sobering to note, however, that during two days of the symposium it rained even though no rain was forecast. I remember Palmén once saying that if it were possible to accurately forecast tomorrow's weather, he would not be interested in meteorology any more. With those two unforecast rainy days during the symposium one can say that we still have a lot to do, and that Erik Palmén, if alive, would still be interested in the weather!

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