REVIEWS OF GEOPHYSICS: U.S. NATIONAL REPORT TO INTERNATIONAL UNION OF GEODESY AND GEOPHYSICS
1991-1994

COOL SEASON CYCLOGENESIS AND ASSOCIATED MESOSCALE WEATHER

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1. Introduction

The modernization of the National Weather Service (NWS) and a profusion of recent field experiments[1] are bringing an explosion of mesoscale[2] observations to the meteorological community during the 1990's. These new observational resources in combination with unprecedented growth in our computing and data handling capacities[3] have facilitated a renaissance in our ability to probe the mesoscale structure and evolution of winter cyclones in recent years. Many recent advances have provided substance for a new generation of texts. For example, textbooks by Carlson (1991) and Bluestein (1992) focus on synoptic and mesoscale weather systems, while Holton (1992) presents an updated treatment of their dynamics. Kraus and Businger (1994) review the air-sea interaction in cyclones, and Houze (1993) and Emanuel (1994) focus on the dynamics and structure of precipitating systems.

In this review, progress during the period 1991-early 1994 will be summarized. The review is roughly divided into the following topical sections: 2) winter cyclones and cyclogenesis, 3) jets, fronts and frontogenesis, and 4) precipitation structures[4]. An effort is made to review theoretical and applied aspects of each. In the section 5) applications are presented, and the final section provides a summary and brief discussion of frontiers and new research opportunities. The scope of this review is limited by space constraints to mesoscale weather systems associated with cool season cyclones.

2. Winter Cyclones and Cyclogenesis

2.1. Theoretical Investigations

The objective of theoretical investigations is to isolate fundamental physics and construct a simple conceptual framework that can be used to interpret more realistic and complex flow models. Despite technological advances in our ability to forecast cyclogenesis, one cannot say that the cyclone problem is solved in the sense that a complete intuitive picture of cyclogenesis exists. Our ability to forecast the impact of mesoscale weather systems will improve with the sophistication of the conceptual models that we can apply to the observations and numerical model output. Within the domain of what has traditionally been defined as "basic" research, progress has been focused in a number of related concentrations of cyclone research including: rapid cyclogenesis, upper tropospheric jets and frontogenesis, lower tropospheric frontogenesis and precipitation structures.

Satellite imagery has revealed that cyclogenesis takes place on a continuum of scales from large semi-permanent cyclones to vortices within mesoscale cyclones, each of which form within a range of physical environments. Possible physical mechanisms that influence these developments and which is dominant in a

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[1] Including: Genesis of Atlantic Lows Experiment (GALE) (Dirks et al. 1988), the Canadian Atlantic Storms Project (CASP) (Stewart et al. 1987) along the east coast of North America, the Experiment on Rapidly Intensifying Cyclones over the Atlantic (ERICA) (Hadlock and Kreitzberg 1988) that extended detailed observations further out to sea, the Winter Icing and Storms Project (WISP) (Rasmussen et al. 1992), Lake Ontario Winter Storms (LOWS) Project (Reinking et al. 1993), STorm-scale Operational and Research Meteorology-Front Experiment System Test (STORM-FEST) field experiment in the central United States (Cunning and Williams 1993), the Ocean Storms Project over the eastern Pacific Ocean (Bond and Shapiro 1991b), and FRONTS 87 in Europe (Thorpe and Clough 1991).

[2] The term "mesoscale" used in this paper refers to horizontal dimensions ranging from a few tens of kilometers to a few hundred kilometers. Thus, a Doppler weather radar is a tool that can make observations of mesoscale weather phenomena; for example air-flow in a thunderstorm.

[3] For example, high speed workstations and widespread use of CD ROMs for data dissemination.

[4] The interrelation of these in an evolving cyclone and their treatment in the literature makes distinctions ambiguous at times, and some overlap unavoidable.

Table 1. Recent Field Experiments

Project	Area	Reference
Genesis of Atlantic Lows Experiment (GALE)		*Dirks et al.*, 1988
Canadian Atlantic Storms Project (CASP)	east coast of North America	*Stewart et al.*, 1987
Experiment on Rapidly Intensifying Cyclones over the Atlantic (ERICA)	Atlantic Ocean	*Hadlock and Kreitzberg*, 1988]
Winter Icing and Storms Project (WISP)		*Rasmussen et al.*, 1992
Lake Ontario Winter Storms (LOWS) Project	Lake Ontario	*Reinking et al.*, 1993
Storm-scale Operational and Research Meteorology-Front Experiment System Test (STORM-FEST)	central United States	*Cunning and Williams*, 1993
Ocean Storms Project	eastern Pacific Ocean	*Bond and Shapiro*, 1991b
FRONTS 87	Europe	*Thorpe and Clough*, 1991

particular situation are questions of active investigation. Several mechanisms exist in current instability theory that in combination or alone might explain the formation of cyclones. They include: baroclinic instability, conditional instability of the second kind (CISK), air-sea interaction instability and barotropic instability.

Baroclinic instability, a hydrodynamic instability arising from the existence of a meridional temperature gradient, and hence thermal wind, is a well accepted theoretical explanation of cyclogenesis (Eady 1949). The Eady normal mode approach has been extended to explain the maintenance of upper-tropospheric synoptic scale waves (Rivest et al. 1992) and wave mean flow interaction (Feldstein 1992). Recent work has focused on examining the initial value problem of baroclinic growth, following the observation that large amplitude disturbances in the upper troposphere are often present before development commences (Farrell 1984; Zehnder and Keyser 1991; Davis and Emanuel 1991; Finley and Nathan 1993; Swanson and Pierrehumbert 1994), and has been applied to understanding lee cyclogenesis (Bannon 1992) and downstream energy propagation (Orlanski and Sheldon 1993). Orlanski and Gross (1994) study the orographic modification of cyclones and find that baroclinic development is enhanced where the topography slopes in the same direction as the isentropes, and that vorticity growth is larger than that in baroclinic eddies that grow over flat terrain. Another area of theoretical investigation is the non-linearity in the evolution of synoptic scale cyclones, and the influence of condensation in the structure and evolution of baroclinic waves (Robichaud and Lin 1991; Hedley and Yau 1991; Grotjahn and Lai 1991; Davis et al. 1992; Polavarapu and Peltier 1993; Thorncroft et al. 1993; Whitaker and Davis 1994).

Paralleling the studies of the role of baroclinic instability in cyclone development have been a number of studies that have examined the role of diabatic processes. Conditional Instability of the Second Kind (CISK) theory explains cyclone formation as the result of a cooperative interaction between cumulus convection and the large-scale circulation in which a positive feedback develops between the cloud scale and the developing vortex scale (Charney and Eliassen 1964). Large sensible heat fluxes observed in polar-air outbreaks over open water result in significant convective available potential energy (CAPE), raising the possibility of CISK as a mechanism in cyclogenesis in cold air masses, and in the cores of some rapidly developing midlatitude cyclones (e.g., Businger 1991).

Air-sea interaction instability, in which enhanced surface winds result in anomalous fluxes leading to deepening, has been explored in the context of cyclones that form in polar air outbreaks (Emanuel and Rotunno 1989). Results from calculations using axi-symmetric numerical models, show that the air-sea interaction hypothesis is consistent with observed arctic low development, with the requirement that a pre-existing disturbance act as a triggering mechanism before the air-sea interaction instability can operate. This two-stage development is consistent with evidence for baroclinic and surface-flux driven stages in the life cycle of these disturbances (Businger and Baik 1991). Craig and Cho (1992) show the importance of potential vorticity[5] formation associated with surface fluxes as the reason that growth in comma clouds tends to be confined to the heating region on the cold air side of the jet.

Sinton and Heise (1993) investigate frontal instability in a sheared basic state, and describe two new unstable geostrophic[6] modes: one characterized by barotropic instability[7], the

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[5] Potential vorticity or absolute potential vorticity is the product of the absolute vorticity and the static stability.

[6] Geostrophic refers to a balance between the Coriolis force and the pressure gradient force.

[7] Barotropic instability is a hydrodynamic wave instability associated with the horizontal shear in a jet-like current, and grows by extracting kinetic energy from the mean flow.

other is a shallow mode characterized by a mixed barotropic-baroclinic instability. In some cases these modes lead to triple the growth rate of unsheared waves.

2.2. Applied Science

Significant research has concentrated on the wealth of observational data available in recent years. For example, Wakimoto et al. 1992, Neiman and Shapiro 1993, and Neiman et al. 1993 document, with unprecedented detail, an explosively deepening marine cyclone that formed during the ERICA field experiment leading to new insights into the structure and evolution of these storms. Although sensitivity studies using numerical models are continuing to provide insights (e.g., Holt and Chang 1993), growing confidence in high resolution numerical simulations are leading to increasingly detailed structural analyses of simulated cyclones, with comparisons to the observational data sets (Kuo et al. 1991a,b; Reed et al. 1993a,b; Chang et al. 1993). The results of these combined efforts have produced refined conceptual models of the life cycle of midlatitude cyclones (e.g., the marine cyclone model of Neiman and Shapiro 1993), cyclone airflows (e.g., the fan model of air parcel trajectories, Kuo et al. 1992; Mass and Schultz 1993), and mesoscale precipitation structures within cyclones (Nieman et al. 1993; Schultz and Mass 1993).

Rapid cyclogenesis is the product of large scale dry cyclogenesis (Alberta et al. 1991; Bullock and Gyakum 1993) and moist cyclogenesis acting on the mesoscale (Gyakum 1991; Fosdick and Smith 1991; Holt and Chang 1993). Preconditioning of atmospheric stability and moisture through surface fluxes (Kuo et al. 1991a; Reed et al. 1993b; Cione et al. 1993), vorticity advection aloft (Wash et al. 1992; Hirschberg and Fritsch 1991a,b; Roebber 1993; Sortias et al. 1993) and creation through diabatic processes (Gyakum et al. 1992; Dudhia 1993), and baroclinic instability are important factors in rapid cyclogenesis, with the relative contribution of each varying from case to case (Rogers and Bosart 1991; Lapenta and Seaman 1992).

Subsynoptic scale cyclones are a subject of continued research interest. Traditionally it has been thought that these lows preferentially form over the ocean. However, a climatological investigation of cyclones during GALE by Nielsen and Dole (1992), reveals that most cyclones forming over the U.S. are of subsynoptic scale. Their study shows that only the strongest cyclones have a size consistent with classical baroclinic instability. Moreover, they show that subsynoptic scale cyclones that form over land are relatively weak and last no more than 48 hours, confirming the contribution of sea surface fluxes to the strength and longevity of these lows (Shay-el and Alpert 1991; Businger 1991; Crescenti 1992; Alpert and Neeman 1992).

Subsynoptic lows that form over the water in polar air masses are generally referred to as polar lows. Bond and Shapiro (1991a) analyze a series of polar lows that formed in a reversed shear flow associated along a occlusion cloud band of a mature midlatitude cyclone that occurred during the Ocean Storms field experiment, and attribute development to baroclinic processes. A number of studies have focused on polar lows that form over the southern oceans (e.g., Fitch and Carleton 1991). Climatological investigations reveal two types of disturbances, those associated with positive vorticity advection[8] aloft (Sinclair and Cong 1992; Turner et al. 1993a), and those that form near Antarctica in areas of enhanced low level baroclinicity resulting from the clash between katabatic[9] flows off of the Antarctic plateau and warmer air from over the ocean (Bromwich 1991; Carrasco and Bromwich 1993; Turner et al. 1993b; Fantinni and Buzzi 1993). Analogously, differential surface fluxes across the Gulf Stream result in low-level baroclinicity and an environment conducive to mesoscale cyclogenesis (Huang and Raman 1991, 1992; Doyle and Warner 1993a).

3. Jets, Fronts and Frontogenesis

3.1. Theoretical Investigations

Progress has been made in our understanding of frontal evolution and propagation through the application of theoretical models that isolate the physical processes involved. For a discussion of the history of frontal wave development the reader is referred to Joly and Thorpe (1991). Issues investigated include non-linearity in frontogenesis (Boyd 1992; Blumen 1992a; Snyder et al. 1993; Gamage and Blumen 1993), effects of diabatic heating (Moore 1991; Montgomery and Farrell 1991; Bishop and Thorpe 1994a,b; Chan and Cho 1991; Lagouvardos et al. 1993; Castelli et al. 1993) and impacts of

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[8] Positive vorticity advection (PVA) increasing with height, in the absence of compensating cold advection, induces upward motion to maintain thermal wind balance in the atmosphere. Thus, PVA aloft is found to be associated with cyclogenesis and the development of precipitation.

[9] Katabatic flow is any flow that moves down an incline; usually negatively buoyant.

orography on the evolution and propagation of fronts (Williams et al. 1992; Blumen 1992b; Keuler et al. 1992). Thorpe et al. (1993) show that in conditions of flow parallel to the main Alpine chain, the mountains are a significant source of potential vorticity anomalies in the lower troposphere due to frictional processes, with implications for both frontogenesis and cyclogenesis. Details of upper tropospheric undulations and their relation to cyclogenesis have also received attention (e.g., Hines and Mechoso 1991; Whitaker and Barcilon 1992, Hirschberg and Fritsch 1993).

A number of papers in recent years have focused on potential vorticity (PV) in diagnosing cyclogenesis (e.g., Reed et al. 1992; Davis 1992a). The attention is the result of two attractive features of this variable (Hoskins et al. 1985): i) its conservation for adiabatic and inviscid flow, and ii) fields of wind, temperature and pressure in a domain can be obtained solely from knowledge of the PV distribution, provided a balance condition and reference state are specified and the inversion problem is solved globally with the proper boundary conditions (the “invertibility principle”) (e.g., Davis 1992b; Browning 1993). These features also make PV useful in diagnosing frontogenesis (Cooper et al. 1992; Xu 1992b; Koshyk and Cho 1992; Malardel et al. 1993) and physical mechanisms for rainband formation, such as symmetric instability[10] (Cho and Chan 1991; Jones and Thorpe 1992; Cho 1993; Moore and Lambert 1993).

Advances in representing and diagnosing frontal circulations in three dimensions using traditional and more general equation systems have been made. In striving for conceptual, qualitative understanding, a hierarchy of simplified theories have been formulated over the years that starts with the simplest balanced theory and progresses to increasing complexity and realistic representations, gradually approaching that of full primitive equation models. Quasi-geostrophic theory (e.g., the Q-vector[11]) and semigeostrophic theory (Hoskins 1975) are perhaps two of the best known members of this hierarchy. Diagnostic schemes based on quasi-geostrophic theory have been applied to frontogenetic and cyclogenetic processes and the correlation between them through their relationship with baroclinicity (Sanders and Hoskins; 1990; Lupo et al. 1992; Sanders 1993). Barnes and Coleman (1993) describe a new quasi-geostrophic scheme that is capable of separating from the total QG forcing field the cross-isentrope, ageostrophic circulations associated with jet-streak dynamics. As an extension of Q-vector theory, Xu (1992a) introduces a newly defined geostrophic forcing vector, the C-vector. By combining the two Q-vector component equations with a third quasi-geostrophic diagnostic equation for vertical ageostrophic vorticity, he produces a complete set of diagnostic equations in the form of a three dimensional vector.

Semigeostrophy like quasigeostrophy depends on approximate geostrophic balance, but includes advection by the ageostrophic wind and can produce a frontal singularity in finite time. For many nonlinear aspects of baroclinic waves, simulations based semigeostrophic theory have provided more realistic representations than the simpler quasi-geostrophic theory (Davies et al. 1991; Schar and Wernli 1993; Magnusdottir and Schubert 1991). When Snyder et al (1991) compared a simulation using a full primitive equation model with one based on the semigeostrophic equations, they found that the semigeostrophic model errs in the treatment of terms involving ageostrophic vorticity. They then propose an equation set that includes the leading-order dynamical contributions of the ageostrophic vorticity, resulting in an improved simulation.

3.2. Applied Science

The formation of fronts through a kinematic concentration of baroclinicity in classical baroclinic waves, results in ever greater temperature gradients and shear, until turbulence limits the process. Therefore, a scale dependent separation of the processes operating in fronts is almost impossible, and it is necessary to collect data over a broad range of scales. Collecting such observational data sets has been the focus of recent field experiments[12] . A number of investigations have focused on the structure of the pre-cold front, low-level jet, and its relationship to precipitation and cyclogenesis (Parsons 1992; Benard et al.

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[10] Symmetric instability, in which parcels that are stable to vertical and horizontal displacements, are unstable to slantwise displacements, occurs in the presence of vertical shear, and may be regarded as a special form of baroclinic instability in which the perturbations are independent of the coordinate parallel to the mean flow.

[11] The Q-vector indicates the horizontal gradient of vertical motion and the vertical gradient of the ageostrophic wind component, as required to maintain hydrostatic- and thermal-wind balance in the face of the disruptive advections of temperature and vorticity (Hoskins et al. 1978; Holton 1992).

[12] For example, STORM-FEST in the central United States, and FRONTS’87 in Europe.

1992a; Kotroni and Lagouvardos 1993; Dolye and Warner 1993c). Another series of articles documents the impact of advancing cold, dry air at midtropospheric levels[13] on stability and the formation of convective rainbands and squall lines (Businger et al. 1991; Martin et al. 1992).

The orographic influence on fronts was recognized very early in the formulation of the Norwegian frontal model through the impact of the Scandinavian mountains (Bjerknes 1919). Recently, considerable improvement towards a quantitative understanding of this influence have been achieved (see Blumen 1992b and Egger and Hoinka 1992 for reviews). Flow blocking by mountain ranges results in low level frontogenesis and enhancement of precipitation as documented by studies in both hemispheres (Dunn 1992, Businger et al. 1991, Smith et al. 1991, Doyle and Warner 1991, 1993c). The effects on airflow and precipitation over complex terrain during the passage of frontal systems were documented (Campistron et al. 1991, Bruintjes et al. 1994). It was separately found that turbulence is enhanced in association with precipitation bands, and that the precipitation distribution was influenced by gravity waves excited by flow over the mountains. Mass et al. (1994) explore the ageostrophic acceleration of a destructive arctic density current through a gap in the British Columbia Coast Range and its mesoscale and microscale structure over northwestern Washington State. The nature of the cold-air damming along the east slopes of the Rockies was the subject of studies by Mecikalski and Tilley (1992) and Hartjenstein and Bleck (1991).

4. Precipitation Structures

The mesoscale organization of precipitation in winter storms has received a great deal of attention during the past decade. A variety of physical mechanisms have been proposed in the literature to explain the characteristics of mesoscale structure within winter storms, including frontal circulations, conditional symmetric instability (in which saturated air parcels are unstable to slantwise ascent), inflection point instability[14] and gravity wave initiation, among others[15] . Most observational studies of these structures have been conducted in coastal regions; along the northwest and east coasts of the U.S., and west coast of Britain. Increasing attention has recently been paid to storm precipitation structures over the continental U.S. (Ramamurthy et al. 1991; Shields et al. 1991; Marwitz and Toth 1993), and the west coast of Europe (Lagouvardos et al. 1992; Kotroni and Lagouvardos 1993). Research focusing on the region of winter cyclones in which precipitation transitions from rain to snow is reviewed by Stewart (1992).

Analysis of output from primitive equation models in concert with observational data has proven effective since the temporal and spacial resolution of the model output allows the evolution of structures to be probed in ways previously not possible (e.g., Reed et al. 1993b; Riordan and Lin 1992; Doyle and Warner 1993c,d). Results of these studies have found similarities with (Schultz and Mass 1993; Mcbean and Stewart 1991), and differences from the classic Norwegian model (e.g., Kuo et al. 1991b; Neiman and Shapiro 1993), and documented mesoscale variability in the precipitation structures within frontal zones (e.g., Neiman et al. 1993; Bond and Shapiro 1991b; Wakimoto et al. 1992; Roux et al. 1993), leading the way to a more thorough understanding of these features and the dynamics operating (e.g., Thorpe and Clough 1991; LeMaitre and Scialom 1991; Benard et al. 1992a,b). The role of precipitation type and the diabatic impact of evaporation on the mesoscale circulations in precipitation bands has been probed (Clough and Franks 1991; Gedzelman and Arnold 1993), as has the influence of differential surface heating on these circulations (e.g., Segal and Arritt 1992).

Propagating gravity waves are a ubiquitous phenomena in the atmosphere that can produce significant mesoscale weather events, such as strong gusty surface winds and clear-air turbulence that represent a serious hazard particularly to aviation interests. Gravity waves have also been observed to initiate or enhance strong convection. Gossard and Hooke (1975) list five mechanisms for the initiation of mesoscale gravity waves: i) orographic forcing, ii) shear instability, iii) geostrophic adjustment processes, iv) density impulses (accelerating fronts), and v) convection. Uccellini and Koch (1987) argue that large increases in ageostrophy occur in the right exit region when a jet streak approaches an inflection in the flow field. Fritts and Luo (1992) and Luo and Fritts (1993) examine the gravity wave field induced by an unbalanced Gaussian jet, and find that the scale and frequency of the forced waves are controlled by the horizontal and vertical

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[13] Hobbs et al. (1990) use the term cold front aloft (CFA) to denote cold-frontal zones whose bases are above the surface in the lower or middle troposphere.

[14] Inflection point instability is a dynamic instability that arises from vorticity maxima located at inflection points in vertical profiles of horizontal wind.

[15] See Parsons and Hobbs (1983); Businger and Hobbs (1987) for reviews.

extent of the initial perturbation, with the adjustment occurring within an inertial period.

Ramamurthy et al. (1993) detail several large gravity waves that impact the Midwest. The waves are long lived and form in environments consistent with the theory on ducting of gravity waves (Lindzen and Tung 1976). Lindzen and Tung showed that waves can be ducted for long periods of time and over great horizontal distances if a stable lower troposphere is capped by a layer above which effectively reflects the vertical propagation. In this situation there is only a small loss of wave energy, and continual forcing is not required. Powers and Reed (1993), in a mesoscale modeling study successfully simulate gravity waves that occurred during explosive cyclogenesis over the Midwest on 14-17 December 1987. It is concluded that both ducting and wave-CISK[16] contributed to the maintenance of the observed waves.

Koch et al. (1993) provide a detailed study of the vertical structure of mesoscale gravity waves that played a significant role in the generation of a mesoscale convective complex. They compare wave induced pressure perturbation fields derived from triple-Doppler wind fields within regions of essentially nonconvective precipitation, pressure perturbation fields obtained by bandpass filtering of surface mesonetwork data, and the vertical structure of the pressure Eigen functions as predicted from a linear stability analysis. Nastrom and Fritts (1992) and Fritts and Nastrom (1992) use aircraft measurements of winds and temperatures collected during the Global Atmospheric Sampling Program (GASP) program to study the effects of topography as a source of mesoscale variability and compare the results with gravity wave theory.

5. Implementation

A dramatic improvement of numerical models over the past 30 years has made possible relatively accurate forecasts of cyclogenesis (Grumm 1993; Oravec and Grumm 1993). The challenge for the '90's will not only include how far in advance we can predict cyclogenesis (Sanders 1992; Mureau et al. 1993), and how accurately mesoscale features and the impact of orography can be represented (Bosart and Sanders 1991; Pauley and Bramer 1992; Grumm et al. 1992; Powers and Reed 1993; Doyle and Warner 1993b), but also requires construction of more complete conceptual models of the phenomena observed (Mass 1991; Davis and Emanuel 1991).

As a result of experience during recent field experiments in which special forecast centers were operated to tackle the mesoscale forecast challenge, the benefit of powerful workstations for assimilation and graphical display was demonstrated (e.g., Stewart 1991; Reinking et al 1993). The National Weather Service modernization, with the goal of improving mesoscale forecasting in the U.S., includes such capabilities to facilitate the analysis of new data streams from Next Generation Weather Radar (NEXRAD), automated surface observing system (ASOS) and satellites, and to construct mesoscale forecasts for timely dissemination. New developments pertaining to the issue of data handling include a 3-hour intermittent data assimilation system (Mesoscale Analysis and Prediction System--MAPS) for real time operation (Benjamin et al. 1991). The major components of this system are data ingest, objective quality control and analysis, and a mesocale forecast model. Isentropic coordinates are used to take advantage of the improved resolution near frontal zones and greater spatial coherence of data that this coordinate system provides. Each 3-hour forecast becomes the background for the subsequent analysis, allowing a four dimensional set of observations to be assimilated.

Adverse weather associated with mesoscale features in winter storms results in widespread disruption of transportation systems (Martner 1992, Rhodes 1992; Rasmussen et al. 1993). Our ability to correctly predict snow squalls, freezing rain, icing, turbulence and low visibility, in turn depends on an ability to analyze and predict correctly the evolution of mesoscale systems (of order ≤50 km). Application of high resolution numerical prediction models that assimilate non-synoptic data sources[17] (Benjamin et al. 1991; Manobianco et al. 1991, 1994; Brill et al. 1991; Neiman et al. 1992; Sayhegyi et al. 1993; Chang and Holt 1994), followed by innovative graphical display of resultant output in conjunction with observations has led to progress in our ability to predict these phenomena. The Lake Ontario Winter Storms (LOWS) project was conducted to demonstrate and evaluate the potential for real time mesoscale monitoring and location specific prediction of lake effect storms and freezing rain, using the newest of available technologies. LOWS employed an array of

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[16] Wave-CISK is a coherent, constructive interaction between convection and gravity waves in the atmosphere.

[17] For example, NEXRAD, ASOS, ACARS (Aircraft Communications, Addressing and Reporting System) aircraft, wind profiler, radio acoustic sounding system (RASS), and satellite data.

specialized atmospheric remote sensors[18], and mesoscale numerical models with favorable results (Reinking et al 1993).

As part of the modernization of the NWS there is a drive for increased synergy between the research community and the NWS. Early fruits of this new emphasis include collocation of a number of NWS offices on university campuses, and increased progress in development of operational tools to aid forecasters in dealing with regional forecast problems (e.g., Keeter et al., 1994). For example climatological (Keeter and Cline 1991, Burrows 1991; Hsu 1992; Heppner 1992; Ferber et al. 1993), and remote sensing techniques (Velden 1992; Herzegh 1992; Martner et al. 1993; Cheng and Brown 1993) have been employed to create forecast tools to help with the prediction of precipitation amounts and precipitation type in winter storms. Weiss (1992) and Hsu (1992) developed climatologically-based tools that aid in forecasting thunderstorm outlook and frontal overrunning along the Gulf coast. Work is also being done to improve forecasts of water levels and wind waves as a result of storm forcing (e.g., Dell'Osso et al. 1992; Neuherz et al. 1993). Objective techniques of analyzing and tracking gravity wave activity such as those employed by Koch et al. (1993), Eckermann and Vincent (1993) and others may have important operational applications in the near future.

6. Summary and Future Outlook

As highlighted in this review, an active research community has made progress during the past several years in the area of winter cyclones. Advances in representing and diagnosing frontal circulations in three dimensions using traditional and more general equation systems have been made. Analysis of observational data sets from field experiments in concert with output from high resolution numerical models has proven to be a fruitful research approach to gain insight into the mesoscale structure and evolution within winter storms.

The deployment of new observing systems as part of the NWS modernization provides new impetus to launch a multi-scale U.S. weather research field project. Progress is expected to continue in the area of four dimensional data assimilation as data from the Next Generation Weather Radar (NEXRAD), Automated Surface Observing System (ASOS), wind profilers and new satellites come on line. Recent research has already shown the promise these new data streams will hold for mesoscale research and forecasting (Neiman et al. 1992; McMurdie and Katsaros 1991; Miller and Katsaros 1992; Klazura and Imy 1993).

An area that will likely see significant progress in the near future is the analysis of water vapor. Lack of information on the temporal and spacial variability in water vapor has been cited as the single greatest obstacle to improved short-range precipitation forecasts. New sensors on the Geostationary Operational Environmental Satellite System (GOES) I and J satellites, the Commercial Aviation Sensing Humidity (CASH) project (Fleming and Hills 1993) and a pioneering technique to use the Global Positioning System (GPS) to measure water vapor (Bevis et al. 1992), will provide new resolution for this critical variable. The import of these data are illustrated by Kuo et al. (1993), who show that when predicted precipitable water vapor is relaxed toward an observed value, the model recovers the vertical structure of water vapor with an accuracy much greater than that from statistical retrieval based on climatology, leading to significantly improved short range precipitation forecasts.

The representation of cyclone and frontal circulations through diagnostic equation sets will continue to be an important area of basic research toward improved conceptual understanding of the evolution of cool season cyclones and associated mesoscale weather. Headway can be expected in dealing with the forecasting challenge posed by mesoscale circulation systems, and their interaction with local geography, as numerical weather prediction models gain resolution, and data resources continue to improve.

Acknowledgments. The author would like to thank Prof. Thomas Schroeder, Prof. Fei-Fei Jin, Dr. Roger Pielke and two anonymous reviewers for their constructive comments on the manuscript. The preparation of this review was supported by the National Science Foundation under grant ATM-9121126 and ATM94-96335.

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[18] Including, dual polarization short wavelength radar, microwave radiometer, radio acoustic sounding system, and three wind profilers.

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