Winter Weather Forecasting throughout the Eastern United States. Part I: An Overview

GEORGE J. MAGLARAS
NOAA, NWS Forecast Office, Albany, New York

JEFF S. WALDSTREICHER*
NOAA, NWS Eastern Region Headquarters, Scientific Services Division, Bohemia, New York

PAUL J. KOCIN
National Meteorological Center, NOAA, NWS, Washington, D.C.

ANTHONY F. GIGI
NOAA, NWS Forecast Office, New York, New York

ROBERT A. MARINE
NOAA, NWS Forecast Office, Portland, Maine

(Manuscript received 3 March 1993, in final form 29 November 1993)

ABSTRACT

The complex combination of synoptic- and mesoscale interactions, topographic influences, and large population densities poses a multitude of challenging problems to winter weather forecasters throughout the eastern United States. Over the years, much has been learned about the structure, evolution, and attendant precipitation within winter storms. As a result, numerous operational procedures, forecast applications, and objective techniques have been developed at National Weather Service offices to assess the potential for hazardous winter weather.

An overview of the challenge of forecasting winter weather in the eastern United States is presented, including a historical review of several legendary winter storms, from the Blizzard of 1888 to the Halloween Nor'easter of 1991. The synoptic-scale features associated with East Coast winter storms are described. The mesoscale nature of many eastern winter weather events is illustrated through an examination of the Veterans' Day Snowstorm of 11 November 1987, and the Long Island Snowstorm of 13 December 1988. The development of applied forecast techniques and the potential for new remote sensing technologies (e.g., Doppler weather radar and wind profilers) and mesoscale models to improve operational forecasts of winter weather hazards are also discussed. Companion papers focus on cyclogenesis, terrain-related winter weather forecast considerations in the Southeast, and lake effect snow forecasting.

1. Introduction

The influences of the Atlantic Ocean, Gulf of Mexico, Gulf Stream, Great Lakes, and Appalachian Mountains on the moisture, wind, and temperature fields across the eastern United States play prominent roles in the evolution of winter weather systems. The combined effects of these features make this region a favored site for the development of major winter storms (Reitan 1974; Colucci 1976; Sanders and Gyakum 1980; Roebber 1984). The frequency of these storms, combined with the population density of the region, presents many difficult and unique challenges to the operational meteorologist.

Winter storms bring a multitude of forecast problems. In addition to substantial snowfalls, weather hazards such as freezing precipitation, flooding rains, high winds, bitterly cold temperatures, coastal flooding (and erosion), and even strong convection confront forecasters in the East during the cold season. This document presents a survey of the synoptic- and mesoscale features associated with forecasting winter weather in the eastern United States. First, we will provide an overview (section 2) of the unique forecast problems posed by winter weather throughout the region. Section 3 presents a historical perspective of East Coast winter storms through reviews of several "legendary" events.

---

* Current affiliation: NOAA, NWS, Binghamton, New York.

Corresponding author address: Jeff S. Waldstreicher, National Weather Service, 32 Dawes Drive, Binghamton Regional Airport, Johnson City, NY 13790.

Section 4 details the synoptic-scale aspects of winter weather forecasting in the East, while section 5 focuses on the mesoscale. Section 6 is a brief survey of some of the techniques for forecasting winter weather employed by operational meteorologists in the eastern United States. Finally, with the anticipated implementation of new remote sensing systems [e.g., the Weather Surveillance Radar-1988, Doppler (WSR-88D) and wind profilers], some prospects for the future are discussed in section 7.

Companion papers will address specific aspects of winter weather forecasting in the East. Gurka et al. 1995 (Part II) concentrates on East Coast cyclogenesis from an operational perspective, focusing on methods to diagnose explosive deepening. Keeter et al. 1995 (Part III) reviews the unique aspects of forecasting winter weather in the Southeast. Finally, Niziol et al. 1995 (Part IV) examines the problem of forecasting lake effect snows.

2. An overview of the forecast problem

The east coast of the United States provides an excellent breeding ground for the genesis of major winter storms. During most of the winter, the interior of North America is dominated by polar and arctic air masses. Strong midtropospheric short waves that travel through the central United States sometimes do not result in strong cyclogenesis due to a lack of adequate low-level thermal and moisture gradients. However, as these features approach the East Coast, they encounter the sharp thermal contrast between the warm waters of the Gulf Stream and the colder continent. Short waves interacting with this inherent baroclinic zone, in concert with diabatic heating and moisture available from the warm waters, initiate cyclogenesis, with development sometimes occurring quite rapidly. In many instances, cyclones that affect the eastern United States originally form in the southern or central part of the country, and have already tapped considerable moisture from the Gulf of Mexico before reaching the East Coast. These storms may already be quite intense as they approach the eastern seaboard. However, favorable conditions along the East Coast can produce further intensification.

The synoptic pattern associated with East Coast cyclogenesis typically includes a strong surface anticyclone over southeast Canada or northern New England. This anticyclone provides a source of low-level cold air that can result in increased frozen or freezing precipitation. The clockwise flow around this anticyclone further intensifies the temperature gradient along the East Coast by forcing cold air down the coastal plain and pushing it up against the east slopes of the Appalachians. The anticyclone also increases the flow of Atlantic moisture into the developing cyclone, especially at the lower levels. These mechanisms are described in greater detail in section 4.

As major storms along the East Coast mature, and the influx of Atlantic moisture becomes well established, snowfall rates of 5–8 cm h^{-1} (2–3 in. h^{-1}) become common. These high snowfall rates, combined with strong winds, often produce widespread areas of near-zero visibility. Total snowfall accumulations in the more intense storms can exceed 30–60 cm (1–2 ft), with drifts in the more extreme cases reaching as high as second story windows. In some winter storms, freezing rain and/or sleet, rather than (or in addition to) heavy snow, pose the greatest threat. During major freezing rain events, glaze accumulations can exceed 2.5 cm (1 in.), and as documented by Businger et al. (1992), extreme sleet accumulations in excess of 10–15 cm (4–6 in.) have occurred with past winter storms. During such devastating storms, even the best prepared municipalities and utility companies cannot keep up their services, with transportation facilities and electrical services sometimes paralyzed for several days after the frozen or freezing precipitation has ended.

Most East Coast winter storms track toward the northeast or north-northeast (Kocin and Uccellini 1990), which is parallel to the coastline, as well as the warm waters of the Gulf Stream. Several major metropolitan areas (population 500 000 or more) are located along the East Coast, and are oriented in a corridor parallel to the coastline. In fact, from southern Maine to South Carolina, more than 50 million people live within 370 km (200 mi) of the coast. Therefore, when significant winter storms occur, a dozen or more major metropolitan areas are usually impacted. This is especially true of the corridor from Washington, D.C., northeast to Boston. Approximately 40 million people live in this area, which has been the target of many major winter storms during the past decades. These storms have resulted in snowfalls or ice accumulations that have completely shut down much or all of the region.

A classic example of such a snowstorm occurred on 8–10 February 1983 and has been referred to as the "Megalopolitan Snowstorm" (Sanders and Bosart 1985a,b). This storm dumped 30 cm (1 ft) or more of snow from the mountains of North Carolina, northeast to Massachusetts (Fig. 1; Kocin and Uccellini 1990; U.S. Department of Commerce 1983). The greatest snowfall occurred in northern Virginia where accumulations exceeded 80 cm (32 in.). There were 46 deaths as a result of this storm, 33 of which were the result of a freighter capsizing off the Virginia coast.

The flow around strong East Coast storms typically results in gale force (>18 m s^{-1} or >34 kt) onshore winds ahead of the storm as it moves northward along the coast. Sustained winds exceeding hurricane force (>33 m s^{-1} or >64 kt) have been measured in the more intense systems. These strong winds can produce severe coastal flooding and beach erosion. Coastal flooding can be particularly severe when the strong onshore winds are accompanied by high astronomical

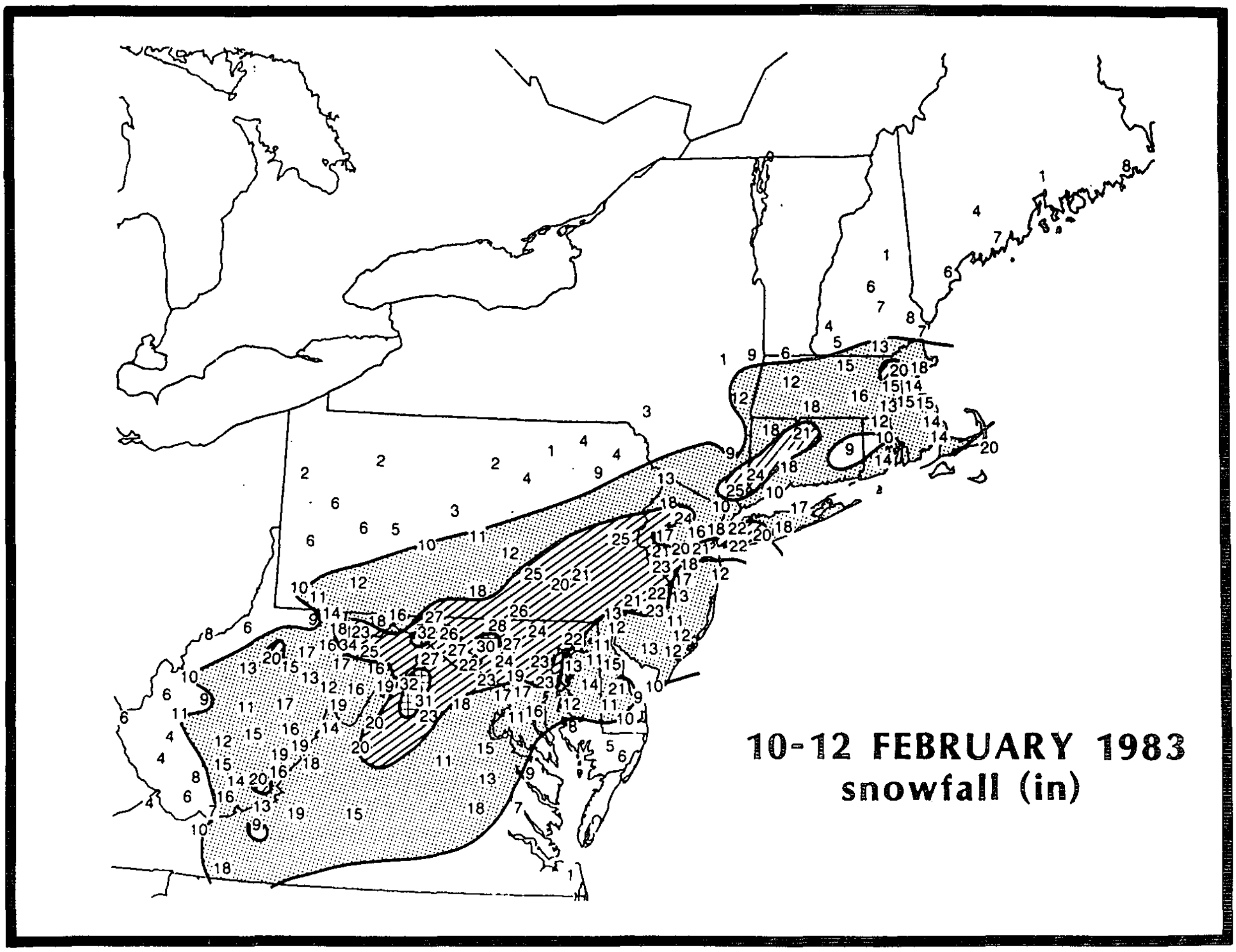

FIG. 1. Observed snowfall (in.) for 18-20 February 1983.

tides, especially when a major anticyclone over northern New England or southeast Canada combines with an approaching storm to enhance the overwater fetch. One storm that produced widespread and severe damage along the East Coast occurred on 5-8 March 1962. This slow-moving storm coincided with a period of high astronomical tides. From South Carolina to southern Maine, but particularly from North Carolina to New York, the storm killed 38 people and caused \$300 million (1962 dollars) in damage along the coast, where winds were as high as 38 $\mathrm{m\ s^{-1}}$ (74 kt) (U.S. Department of Commerce 1962). At the same time, 30-60 cm (12-24 in.) of heavy wet snow fell in the mountains of western North Carolina, western Virginia, western Maryland, eastern West Virginia, and central and western Pennsylvania, resulting in two fatalities.

A coastal flood event of similar proportion occurred 28 October through 1 November 1991, as a strong anticyclone (1045 mb) over the Canadian Maritimes combined with a cold front moving off the East Coast, and Hurricane Grace, which tracked just to the west of Bermuda before turning to the north (National Oceanic and Atmospheric Administration 1992). Fed by the cold anticyclone and the warm, moist air from Grace, a wave formed on the cold front. This wave deepened rapidly (28 mb in 24 h), reaching a pressure of 972 mb in the vicinity of 39°N, 64°W at 1200 UTC 30 October. This low subsequently moved in an atypical path, tracking from east to west, and then to the south, before recurving back toward the northeast.

This storm, the "Halloween Nor'easter of 1991," resulted in a long, east to northeast wave generating fetch directed toward the East Coast for several days. Along the North Carolina coast, a heavy surf advisory was in effect for 5.5 days, and a coastal flood warning for 3.5 days (National Oceanic and Atmospheric Administration 1992). Seas in association with this storm were as high as 4.5-10 m (15-30 ft) within 10 nmi of the coastline; 7.5-12 m (25-40 ft) over the continental shelf (shoreward of the 1000-fathoms contour); and 12-23.5 m (40-78 ft) offshore (seaward of the 1000-fathoms contour). Damage from this event was reported from Maine south to the north shore of Puerto

Rico, and totaled approximately $250 million. In addition, there were 12 deaths and 16 injuries associated with the storm (National Oceanic and Atmospheric Administration 1992). The greatest damage occurred along the Massachusetts coast. As the low tracked to the west, wind gusts at Chatham, Massachusetts, exceeded 27 m s^{-1} (52 kt) for 15 consecutive hours, and exceeded 32 m s^{-1} (60 kt) for 6 h. Tides along the Massachusetts coast were over 1 m (3–4 ft) above normal, and the widespread damage included President Bush's Kennebunkport, Maine, residence.

Because the East Coast features an environment conducive to the formation and rapid intensification of major storms, forecasters must frequently issue winter storm watches long before synoptic-scale systems have begun to produce snow or ice and often before there is any real-time indication as to precisely where and when the surface cyclone will begin to form. In cases of offshore cyclogenesis, this problem is exacerbated by the lack of real-time observational data over water. The density of marine surface (and upper air) observations (e.g., buoys and ships) is substantially less than those from land-based stations, and many of these reports are not received at field offices in real time. As a result, forecasters must rely on data from remote sensors, such as satellite imagery, to observe (Smigielski and Mogil 1993) and nowcast (Gurka et al. 1995) marine cyclogenesis.

The timely issuance of storm watches allows the public, and emergency management officials, to prepare for the onset of frozen and/or freezing precipitation. On the other hand, overforecasts of heavy snow or ice can erode the public's confidence in future watches and warnings. Of course, missed events, such as the Long Island, New York, "surprise" snowstorm of 13 December 1988 (discussed in detail in section 5b), do little to improve public perception.

The location where a cyclone initially develops, and the subsequent path it takes, is critical for the attendant weather that a particular location will experience. Hence, the orientation and density of the population along the East Coast presents a special challenge regarding the public's perception of a forecast. Missing the position of an often relatively narrow band of heavy snow, a small area of freezing rain, or the rain–snow line associated with these storms by only 30–50 km (not a bad forecast by most meteorological standards) could result in what is perceived to be a poor forecast by tens of millions of people.

The Halloween Nor'easter of 1991 provides a vivid example of how an excellent forecast can still be perceived by the public as an unwarned event. The National Weather Service (NWS) Forecast Office in Boston, Massachusetts, first mentioned the possibility of a coastal flood event in their state forecast discussion issued at 0320 EST 27 October 1991. Later that day, the staff at Boston began contacting emergency managers, and issuing media alerts via public information statements (National Oceanic and Atmospheric Administration 1992). These issuances were three days in advance of the storm. (Note, other NWS offices issued similar statements well in advance of the event.) A coastal flood watch was issued for the southern New England coast at 0300 EST 29 October, 36 h prior to the first of several flooding high tide cycles. Subsequent coastal flood and high wind warnings were also issued. Despite this substantial lead time, the *Marblehead Reporter,* a weekly newspaper in the town of Marblehead, Massachusetts, approximately 15 mi north of Boston, had the following front page headline in their 7 November 1991 edition: "Without warning: Storm with no name leaves deep marks on the town" (Zimm 1991).

Unfortunately, this headline is not a one-time occurrence. Rather, most forecasters have probably experienced an event during which they felt a high-quality forecast was issued, yet was perceived differently by the general public. It is not clear whether this reporter was simply looking for a headline, or if it is indicative of an impacted population that felt they were not adequately forewarned of the threat. Regardless, this case points out that the issuance of timely watches and warnings is only part of the process of alerting the public to weather-related hazards. The watch or warning must also be received and understood by its intended audience and evoke the necessary response to protect life and property.

Even today's sophisticated guidance products do not always provide the necessary resolution and accuracy required to adequately predict the type and distribution of winter precipitation 24 h in advance. For example, during a single storm, a forecaster in New York City often has to determine, 12–24 h in advance, what percentage of the 16 million people in the metropolitan area will receive a heavy snowfall, which areas might experience only light snow, what sections are at risk for sleet and freezing rain, and who will receive only rain. Of course, winter storms are rarely simple, with many areas experiencing several, or even all, of these conditions during different stages of the same event.

3. A historical perspective

To understand how the frequency and severity of winter weather in the populous eastern United States has led to hardship on its inhabitants, one simply needs to look at the historical record of major weather events. Between 1900 and 1966, 30 of the 59 snowstorms listed in the Environmental Science Service Administration's (1966a) publication *Some Outstanding Snowstorms* occurred in the eastern United States. Blizzards are rare here, but even so, the listing of *Some Outstanding Blizzards* (Environmental Science and Service Administration 1966b) indicates that 6 out of the 25 blizzards during the 1900–1966 time period occurred in the eastern United States.

In recent memory, the worst blizzard to strike the East Coast occurred on 5–7 February 1978 (Kocin and Uccellini 1990; U.S. Department of Commerce 1978). From northern Virginia, Maryland, and Delaware, all the way to Maine, 30–90 cm (1–3 ft) of snow was whipped into huge drifts. Gale force winds were common throughout the region, but from eastern Massachusetts to Maine, winds exceeded hurricane force. Boston recorded a wind gust to 35.5 m s^{-1} (69 kt), forcing air traffic controllers to evacuate the Logan International Airport control tower when it began to sway. Wind gusts at Chatham, Massachusetts, reached 41 m s^{-1} (80 kt). Tides at Portland, Maine, were 4.3 m (14.17 ft), the highest on record. This storm killed 99 people, many drowning from coastal flooding, and caused $600 million in damage. Massachusetts and Rhode Island were in a state of emergency for almost an entire week.

Farther inland, the area from the Saint Lawrence Valley to western New York and northern Ohio was ravaged by a terrible blizzard from 28 January through 1 February 1977 (U.S. Department of Commerce 1977). Wind gusts to 29 m s^{-1} (56 kt) whipped 15–30 cm (6–12 in.) of new snow, as well as previously fallen snow still on the ground, into drifts as high as 7.5 m (25 ft). Lake-enhanced snowfall during this period dumped 1.5 m (5 ft) of new snow near Watertown, New York. At Buffalo, New York, the visibility was officially recorded as zero for 25 consecutive hours. Wind chill temperatures during this blizzard were around −45°C (−50°F). By the time the blizzard was over, 37 people had died, many frozen to death.

February 1958 through February 1961 was a period when the eastern United States was repeatedly battered by severe winter storms. Ten widespread heavy snowstorms, some of them blizzards, hit the region during those three years (Environmental Science and Service Administration 1966a,b). These 10 storms killed a total of 542 people and caused billions of dollars in damage and economic loss. From Virginia northward, the worst storm was the blizzard of 10–12 December 1960. Many areas were unprepared for such a storm this early in the season, and the result was 137 people killed. From Virginia southward, the storm of 2–5 March 1960 was the most notable. Although the death toll was small, snowdrifts to 9 m (30 ft) in parts of North and South Carolina left roads impassible for an extensive period. Airlifts of food and supplies were required in the mountains.

Farther into the past, the legendary snowstorm of 27–29 January 1922 struck the region from South Carolina to southeast New England (Environmental Science and Service Administration 1966a). More commonly known as the "Knickerbocker Storm," up to 1 m (3 ft) of snow fell across North Carolina. However, the most noteworthy aspect of this storm was the collapse of the roof of the Knickerbocker Arena in Washington, D.C., from the heavy snow accumulation. The arena was full at the time, resulting in 98 deaths and hundreds of injuries.

Snow is not the only form of precipitation that can have a significant impact on the lives of inhabitants of the eastern United States. In some cases, freezing precipitation can be the most noteworthy feature of a winter storm. Generally, freezing rain (and sleet) falls in a narrow "transition" zone between much larger areas of rain and snow. Frequently, this transition zone shifts from one location to another as the winter storm evolves; thus, freezing precipitation usually occurs for only a short period of time at a given location without substantial accumulations of ice. However, when this transition zone remains nearly stationary for an extensive period, the resulting ice accumulation can be disastrous. [A more thorough discussion of the formation and impacts of freezing precipitation, and forecasting precipitation type, can be found in a companion paper by Keeter et al. (1995).]

In western New York, the "Great Ice Storm" of 3–4 March 1991 is a representative example of what can happen when heavy freezing rain falls over an area for many hours. In the area south of Lake Ontario, from Jamestown and Batavia east to Elmira and Watertown, about 300 000 homes and businesses lost power as the buildup of ice downed power lines. Some areas remained without power for several days. Downed limbs and trees blocked roads and littered residential and recreational areas with tremendous amounts of debris. The city of Rochester was essentially crippled, with most of the homes and businesses without power at one point in the storm. In the downtown area, 100-lb blocks of ice fell from high-rise buildings. Nineteen counties in western New York were declared to be in a state of emergency. Even prison inmates were called upon to help clean up the debris.

To end this brief discussion of great winter storms in the eastern United States, we will close with the blizzard that remains a legend even to this day, the "Blizzard of 1888" (Kocin 1983; Environmental Science and Service Administration 1966a,b). For four days, from 11 to 14 March 1888, the region from the Chesapeake Bay to Maine was paralyzed by snow, wind, and severe cold. From New Jersey and southeast New York, to Connecticut and Massachusetts, 100–125 cm (40–50 in.) of snow fell, resulting in drifts as high as 12 m (40 ft). A total of 400 people died, 200 in New York City alone. Damage in 1888 dollars was an incredible $25 million. The blizzard destroyed much of the aboveground communication system in the region, leading to the decision to bury overhead wires underground in order to avoid a repeat of the prolonged disruption to communications.

4. Synoptic considerations

A myriad of weather patterns are associated with winter precipitation events that occur from South Carolina to Maine, but some common features have been identified over the years. Much of the initial work was documented by Bailey and George (George 1960). Subsequent comprehensive overviews (Kocin and Uccellini 1990) and individual case studies of snowstorms, such as the February 1979 "Presidents' Day Snowstorm" (Bosart 1981; Uccellini et al. 1984; Uccellini et al. 1985; Uccellini et al. 1987) and the February 1983 "Megalopolitan Snowstorm" (Bosart and Sanders 1986; Sanders and Bosart 1985a,b), as well as freezing rain events (Forbes et al. 1987), have provided valuable information regarding the contribution of synoptic- and mesoscale features and processes for the development and evolution of the precipitation produced by these winter storms.

The synoptic setting for frozen (or freezing) precipitation can be generalized according to the following scenario. During the winter season, cold anticyclones (high pressure systems of Canadian or polar origin) often provide the source of cold air necessary for snow, ice pellets, and freezing rain. When these anticyclones become entrenched over the eastern United States and do not move offshore, approaching cyclones, or low pressure systems, can interact with the anticyclones and produce copious amounts of wintry precipitation.

Often, cold air moves southward along the eastern slopes of the Appalachian Mountains and forms a wedge of high pressure along the Atlantic coastal plain. This wedge of cold air forms through a process known as cold air damming (Richwein 1980). With a persistent anticyclone continuing to channel cold air southward along the eastern slopes of the Appalachians, a zone of enhanced lower-tropospheric temperature gradients and convergence forms along the coastline (the so-called coastal frontogenesis; Bosart 1975). As an upper-level trough and its associated surface cyclone approach the eastern United States with a strong anticyclone anchored over or to the north of the region, the cold air dome persists along the Atlantic coastal plain. However, pressures fall along and to the west of the mountains, as well as along the coastal front. With sufficiently strong upper-level forcing and lower-tropospheric feedback (such as enhanced thermal advections), cyclogenesis can proceed quite rapidly along the coastal front. Heavy precipitation in the form of rain, freezing rain, and snow may result, especially to the west of the coastal front as relatively warm, moist air off the Atlantic Ocean ascends the cold dome. More detailed discussions of coastal frontogenesis and cold air damming can be found in a companion paper by Keeter et al. (1995).

These slow-moving cold anticyclones are often found beneath a region of upper-level confluence (easily observed at either 500 mb or 300 mb). The upper-level confluent regimes are often found with deep quasi-stationary troughs across eastern Canada, sometimes in association with a nearly stationary upper ridge across northeastern Canada or Greenland, the so-called Greenland Block. This pattern is conducive to below-normal temperatures throughout the eastern United States and increases the likelihood of frozen precipitation.

The orientation of the anticyclone to the north, and the developing cyclone to the south, establishes an east-northeasterly low-level flow of air off the Atlantic Ocean that contributes to the potential for widespread moisture influx. With the anticyclone remaining entrenched over the region, surface winds over land will retain a northerly component (especially northeast) that can reinforce the low-level flow of cold air. If the surface anticyclone to the north does not progress too far to the east, which would allow air temperatures near the earth's surface to warm from sensible and latent heating off the ocean (an influence more pronounced near the coastline), the potential for frozen precipitation is enhanced. Of course, the farther north or inland, the greater the chance for frozen precipitation. Frozen precipitation is less of a threat for most situations that result in southerly winds (e.g., when the surface anticyclone moves offshore, or the cyclone moves to the west and north).

Storms that yield frozen precipitation typically approach the region from the south or the west, but on occasion, so-called Alberta Clippers from the northwest drive southeastward with a snow band often found to the north of the low center's track. In some instances, secondary surface cyclonic development may occur as the initial cyclone propagates toward the Appalachian Mountains from the south, west, or northwest. Secondary cyclogenesis occurs along, or close to the coast, where large temperature differences may exist, especially along a preexisting coastal front. Secondary cyclogenesis is a phenomenon common to the east coast of the United States and is a particular concern to forecasters, since the ability to predict the onset of cyclogenesis, and the subsequent track of the surface low pressure center, are key factors in the forecast of when and where the heaviest frozen precipitation will occur.

For major East Coast snow events, as shown by Kocin and Uccellini (1990), the approaching upper-level trough associated with the surface cyclone is often highly amplified, frequently attaining a characteristic "negative tilt" from northwest to southeast. These systems frequently exhibit marked characteristics of "self-development" described by Petterssen (1956) and Palén and Newton (1969, 324–326), often with decreasing distance between the upper-trough axis and its downstream ridge and the development of a cyclonic vortex (e.g., a closed circulation) aloft. While any given frozen precipitation event may be associated with an upper trough that exhibits a wide range of amplitudes and wavelengths, many of the major events are associated with the large surface anticyclones and the confluent pattern aloft.

As described by Uccellini and Kocin (1987), and Kocin and Uccellini (1990), eight major East Coast winter storms were characterized by patterns similar to those discussed previously. A pattern of upper-level jet streaks, one associated with the configuration of a cold surface anticyclone and its associated upper-level confluence, and the other found with the approaching surface cyclone and its associated upper trough and diffluent pattern downwind of the trough axis (Fig. 2), contributes to heavy snowfall in the following manner.

1) An upper trough approaches the East Coast from the west, for example. A jet streak at the base of the trough enters a diffluent region downwind of the trough axis. Cyclogenesis occurs where upper-level divergence is locally enhanced relative to the trough and the exit region of the jet.

2) A separate upper-level trough over southeastern Canada and a jet streak embedded in the confluence zone over New England (upwind of the trough axis) are associated with the cold surface high pressure system, which is usually found beneath the confluent entrance regions of the jet streak.

3) Indirect and direct transverse circulations that extend through the depth of the troposphere are located in the exit and entrance regions of the southern and northern jet streaks, respectively.

4) The rising branches of the transverse vertical circulations associated with the two jet streaks appear to merge, contributing to a large region of ascent that produces clouds and precipitation between the diffluent exit region near the East Coast, and confluent entrance region over the northeastern United States.

5) The advection of Canadian air southward in the lower branch of the direct circulation over the northeastern United States maintains the cold lower-tropospheric temperatures needed for snowfall along the East Coast. In many cases, the lower branch of this circulation pattern is enhanced by the ageostrophic flow associated with cold air damming east of the Appalachian Mountains (Bell and Bosart 1988).

6) The northward advection of warm, moist air in the lower branch of the indirect circulation over the southeastern United States rises over the colder air north of the surface low. An easterly or southeasterly low-level jet streak typically develops within the lower branch of the indirect circulation beneath the diffluent exit region of the upper-level jet.

7) The combination of the differential vertical motions in the middle troposphere and the interactions of the lower branches of the direct and indirect circulations appears to be highly frontogenetic, increasing the thermal gradients in the middle and lower troposphere during the initial cyclogenetic period.

While this scenario is common for the major snow events, other frozen precipitation events evolve in a similar fashion, although not all of the factors are as distinct as in the heavy snow case. For example, for light or moderate snow events, the upper trough associated with the surface cyclone could be relatively weak. The upper-level jet streak may also be weak (e.g., alongstream variations of wind speed would be small), and the resultant upper-level divergence and indirect circulations would also be diminished. Thus, vertical motions and precipitation would be reduced.

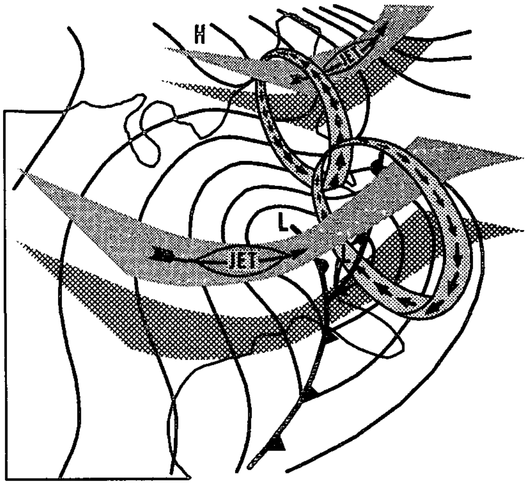

FIG. 2. Schematic of dual jet-related circulation patterns during East Coast snowstorms. Circulations are represented by pinwheels, jet streaks are embedded within confluent and diffluent regions, and solid lines are sea level isobars.

While the synoptic setting for freezing rainfall sometimes evolves in ways that resemble some of the previously mentioned features, these events can also evolve in a completely different manner from snowfall situations, although these differences are often very subtle. Any synoptic setting that retains cold air at the surface and yields a sufficient degree of warming aloft that causes melting aloft is a candidate for freezing rain. As with snowfall, strong cold anticyclones are usually a necessary ingredient for most widespread freezing rain events, with a pronounced inverted ridge axis along the Atlantic coastal plain indicative of cold air damming. In some instances, surface cyclones that pass to the west of the Appalachians allow the warming aloft that would preclude the occurrence of snowfall, but a thin layer of cold air may remain near the surface that supports freezing rain.

5. Mesoscale aspects

Two recent cases illustrate the mesoscale complexity of eastern United States winter storms. While mesoscale snowfall distributions are more commonly associated with "lake effect" snowfall near the Great Lakes, the eastern United States can also experience localized snowbursts within widespread synoptic-scale storms such as the Megalopolitan Storm of February 1983. These mesoscale areas of enhanced snowfall can stymie even the most experienced forecaster. The Veterans' Day Snowstorm of November 1987 and the Long Island Surprise Snowstorm of December 1988 presented tremendous challenges to the forecasting community since relatively isolated occurrences of heavy snowfall affected millions of lives. Brief descriptions of each event are presented here to highlight these forecast challenges.

a. The 11 November 1987 Veterans' Day Snowstorm

The early season snowfall that affected Washington, D.C., on 11 November 1987 was an event that put forecasters' professional skills to the test. On this day, much of the Washington, D.C., metropolitan area was paralyzed by an unforecast major snowfall. The 29-cm (11.5 in.) accumulation recorded at Washington National Airport was the greatest 24-h November snowfall on record and eclipsed the monthly snowfall record. The storm forced the closure of the Wilson Bridge, which spans the Potomac River. As a result, a number of holiday travelers were stranded in their cars on Interstate 95 for almost 24 h. If not for its occurrence during a federal holiday, disruptions to transportation and commerce, which were severe, would have had a much greater impact. Snowfall across the metropolitan region varied greatly with as little as 5 cm (2 in.) in the northwestern suburbs to as much as 43 cm (17 in.) in the eastern suburbs, a difference of almost 40 cm (15 in.) over a distance of only 30–40 km (Fig. 3).

The heavy snowfall in the Washington area was associated with an advancing upper-level trough/jet system and developing surface cyclone off the Virginia coast, two features characteristically associated with heavy snowfall (e.g., Kocin and Uccellini 1990). However, the heavy snowfall in the Washington area developed and dissipated locally, and the axis of heavy snowfall did not translate northeastward through the Philadelphia–New York corridor. Heavy snow bypassed this region as the surface cyclone deepended over the Atlantic Ocean and moved northeastward to a position off the Massachusetts coast early on 12 November. The heavy snow redeveloped across southeastern New England, where accumulations of 20–30 cm (8–12 in.) were common (Fig. 4).

The storm presented a difficult challenge for a number of reasons: 1) Heavy snowfall was remarkably localized within the Washington, D.C., area, with accumulations of 25 cm or more occurring in a band only 40 km wide and 200 km long. 2) The snow fell very early in the "winter" season, with few historical precedents. 3) The storm exhibited a complex evolution, with heavy snowfall occurring in three distinct stages (labeled A, B, and C in Fig. 4) across mostly separate, but in some cases partially overlapping areas. 4) Operational dynamical models failed to adequately simulate the amount and distribution of precipitation, although the Nested Grid Model (NGM) did indicate the potential for a major snowfall with each subsequent run as the event began to unfold. The combination of all these factors contributed to a very difficult forecast problem. Because of the mesoscale nature of the heavy snowfall, a general forecast of heavy snow for the Washington, D.C., area, in spite of the atypical time of year, would not have told the whole story.

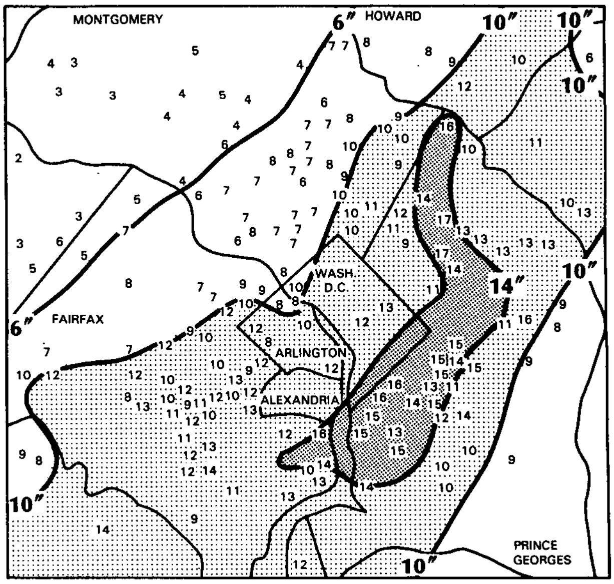

FIG. 3. Observed snowfall (in.) in the Washington, D.C., metropolitan area for 11 November 1987.

This case is presented to contrast the more widespread heavy snow bands, which accompany many major snowstorms across the northeastern United States. Kocin and Uccellini (1990) showed that bands of heavy snowfall often covered hundreds of kilometers. As such, once the initial location of the heavy snowfall has been established, the axis of heaviest snow often can be extrapolated in the direction of the band. The narrow band that fell across the Washington area on 11 November did not translate to the northeast through the metropolitan areas of Philadelphia and New York City, where only 2.5 cm fell (Fig. 4). Nor did it translate to the east across the Delmarva Peninsula of Maryland, Delaware, and Virginia, where mostly mixed precipitation fell. Heaviest melted precipitation appeared to fall mainly in the Washington area, and the combination of lesser total precipitation amounts and mixed precipitation reduced accumulations in areas south and east of Washington.

Snowfall rates during this storm exceeded 7.5 cm h^{-1} (3 in. h^{-1}) at some locations, which persisted for several hours. Many reports of lightning and thunder were also noted during the event, as have also been noted for several other East Coast mesoscale snow events (Bosart and Sanders 1986; Kocin et al. 1985). No mesoscale surface boundary, such as the one shown by Kocin et

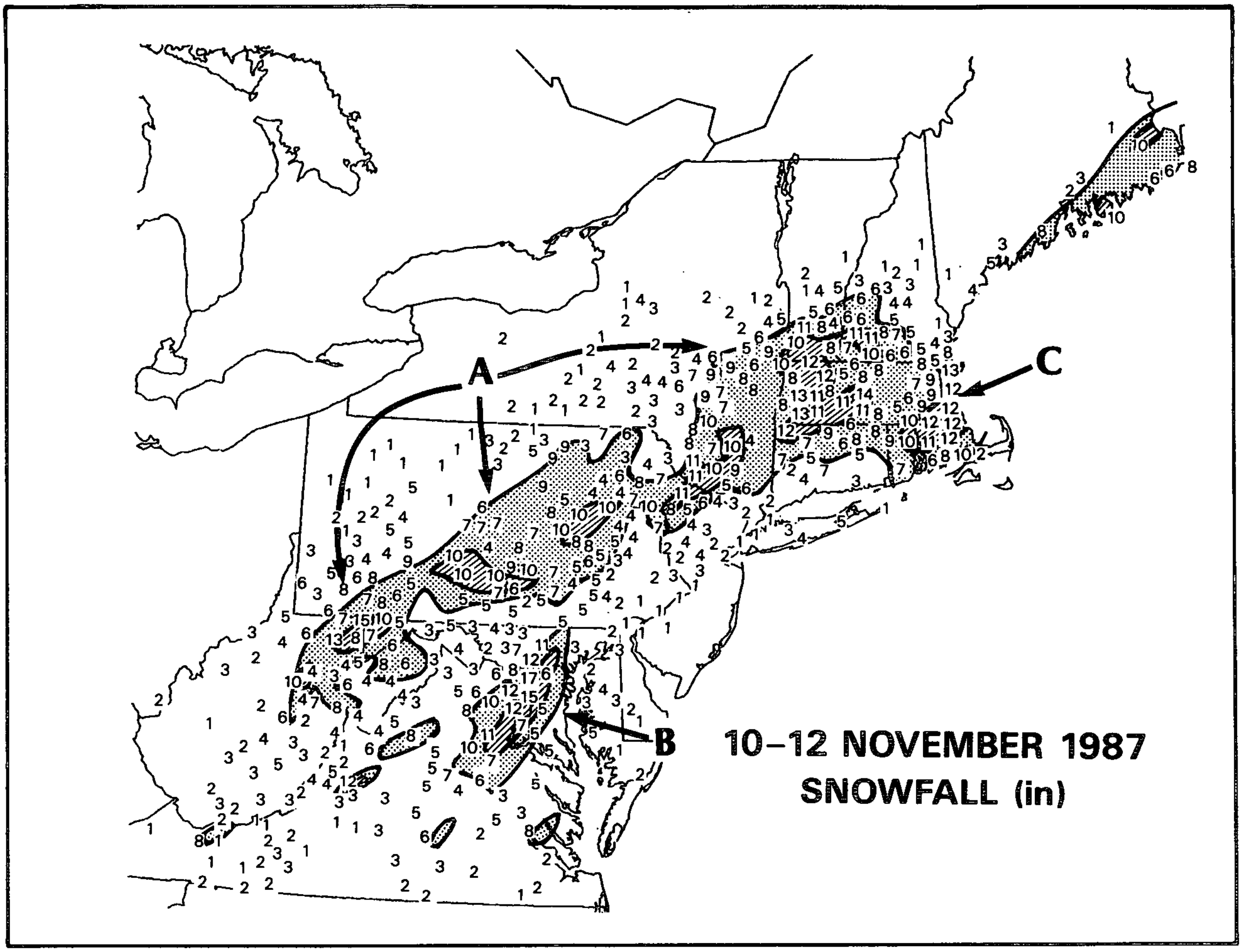

Fig. 4. Observed snowfall (in.) in the Northeast for 10–12 November 1987. Heavier snow bands are labeled A, B, and C, respectively.

al. (1985) for an earlier mesoscale snowburst, was in evidence prior to or during the event.

The NGM simulation initialized at 0000 UTC 11 November was the latest forecast available to local forecasters before the onset of the Washington snowfall. The 24-h forecast valid for the 12-h period ending at 0000 UTC 12 November (Fig. 5), the period during which the snowfall event occurred, placed an ascent maximum near New York City, with precipitation totals of 1.2 cm (0.5 in.) or greater from northern Virginia to Connecticut (these forecast amounts were much greater than earlier simulations). This forecast indicated that accumulating snowfall would fall across the Middle Atlantic states, but was no more likely in Washington than in New York City. In addition, none of the forecasts indicated that a local enhancement of the snowfall in the Washington area would occur. If anything, the model seemed to be depicting the evolution of a snow situation more typical of those described by Kocin and Uccellini (1990), with a region of vertical motion increasing to the northeast along the Northeast coastline, with heaviest snow amounts increasing from Virginia to New England.

b. The Long Island surprise snowstorm of 13 December 1988

Another East Coast mesoscale forecast problem occurred on 13 December 1988, when an unpredicted heavy snowfall affected portions of the New York City metropolitan area. A narrow band of snowfall across central Long Island (Fig. 6), with accumulations of up to 28 cm (11 in.) left forecasters scratching their heads. The New York City forecast office issued the following special weather statement (SPS) during the late afternoon as they tried to deal with a difficult situation that defied comprehension:

> Events like this cause weather forecasters to lose their hair at an early age and in some cases to develop stomach ulcers. We have to admit the existence of many weather events that are . . . at this stage of our weather science . . . unforecastable. There are situations that

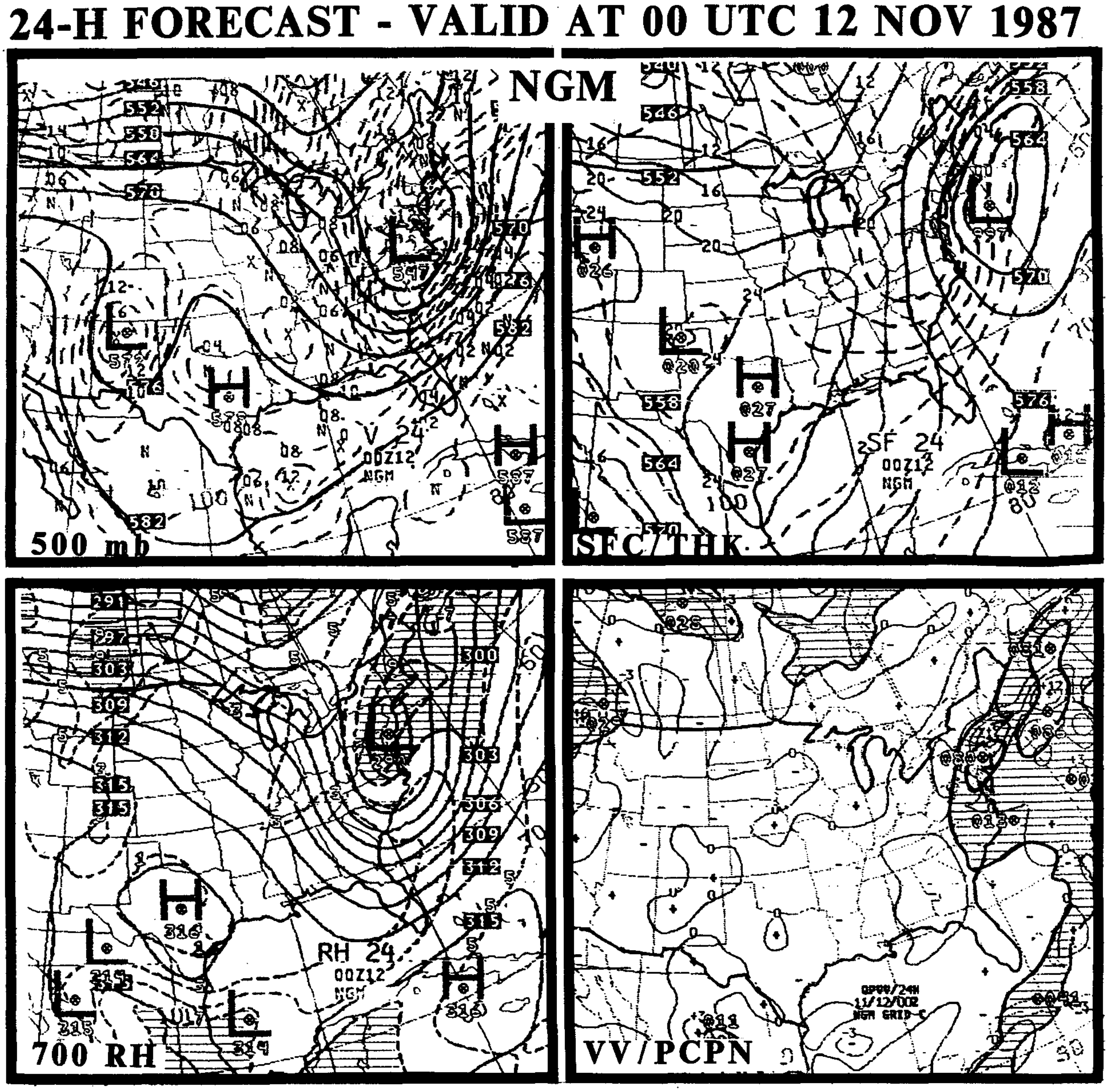

FIG. 5. The 24-h NGM forecast valid 0000 UTC 12 November 1987. The upper-left panel is the forecast 500-mb heights (solid), and vorticity (dashed). The upper-right panel is the MSL pressure (solid), and 1000–500-mb thickness (dashed) forecast. The lower-left panel consists of the 700-mb height (solid), and 1000–500-mb mean relative humidity (dashed). Mean relative humidities greater than 70% are shaded. The lower-right panel is the forecast 700-mb vertical velocities (thin solid), and accumulated precipitation (thick solid) for the 12 h ending at 0000 UTC 12 November.

> slip between the cracks and I am afraid this has been one of them. We missed it and so did the computers. We could only sit here at the Weather Service Office and watch the situation go from bad to worse. We became observers as opposed to forecasters.

As in the Veterans' Day Snowstorm, the heavy snow fell in a band no more than 70 km in width [the width of the 15-cm (6 in.) contour in Fig. 6], with little or no snow reported at either New York City or on eastern Long Island. This heavy snow situation was associated with an advancing upper-level trough, but as shown by the 24-h guidance available from the NGM verifying at 0000 UTC 14 December 1988 (Fig. 7)— the 12-h period in which much of the snow fell across Long Island—the synoptic situation did not resemble any of the classic heavy snow signatures discussed by Kocin and Uccellini (1990). The surface low was forecast to lie several hundred kilometers to the southeast of Long Island, as the primary 500-mb vorticity maximum passed eastward off the North Carolina coastline.

There were some clues in the NGM forecast that suggest the possibility of a forecast problem. While the main cyclone was located well offshore, an inverted trough axis was evident extending from the cyclone center toward southern New England. An elongated region of upward vertical motion associated with this trough axis was also poking northward into southern New England; however, only light amounts of precipitation were forecast across Long Island, as most of the rising motion remained offshore. It should be noted that the Limited-Area Fine Mesh Model (LFM) provided no hint of any inverted trough/ascent feature and generated no precipitation across the affected area.

In actuality, a surface (coastal) front was embedded within the inverted trough and extended northward into eastern Long Island and New England, with temperatures (°F) rising into the 40s (5°–7°C) east of the front across eastern Long Island, while remaining in the 20s and lower 30s (−5°–0°C) across western Long Island (Fig. 8). The heavy snow band occurred to the west of the frontal boundary, very similar to what is observed with coastal fronts. The snow band remained nearly stationary for much of the day on 13 December, with melted precipitation amounts locally exceeding 3.8 cm (1.5 in.).

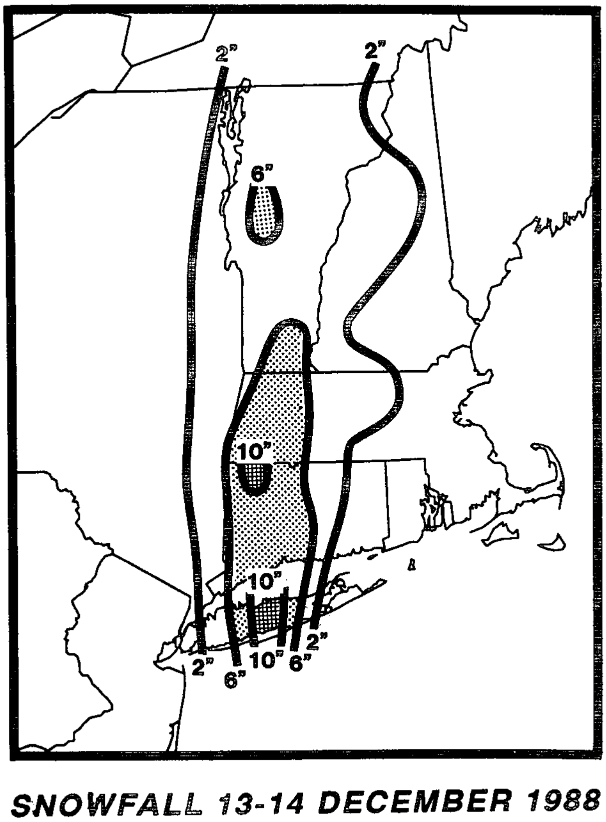

FIG. 6. Observed snowfall (in.) for 13–14 December 1988.

6. Winter weather forecast techniques

To combat the current challenges of forecasting winter weather in the eastern United States, a number of applied forecast techniques have been developed. Much of these efforts are founded on the work of George (1960). Many of these techniques consist of applications of thermal, moisture, and kinematic fields from dynamical models, such as the "Magic Chart" (Sangster and Jagler 1985; Chaston 1989; Evenson 1992), the 850–700-mb thickness field (Naistat 1988), and warm conveyor belt temperatures (Auer 1987). A statistical method for forecasting the probability of precipitation type incorporating the Model Output Statistics technique (Glahn and Lowry 1972) was developed by Bocchieri and Maglaras (1983) and further extended by Ronco (1989). Scofield (1990) described a satellite-based forecast index of 3–12-h heavy precipitation from instability bursts associated with extratropical cyclone systems (ECSs). Finally, the value of applying climatic studies, such as Spar et al. (1969), to winter weather forecast problems was illustrated by Gigi (1989) in an examination of the 24 February 1989 New York City snowstorm that "never was." Unfortunately, space limitations prohibit a detailed description of all of the forecast techniques employed by forecasters in the eastern United States. The reader is encouraged to consult the aforementioned references. Companion papers will present some of the methodologies currently employed by forecasters for diagnosing and predicting cyclogenesis (Gurka et al. 1995), terrain-related winter weather forecast considerations in the southeastern United States (Keeter et al. 1995), and lake effect snow forecasting (Niziol et al. 1995).

7. The potential of new technologies

The two cases presented in section 5 are examples of situations where current operational technology, in terms of observing systems and numerical prediction models, as well as forecasting procedures that rely on these observational data and model output were insufficient to alert forecasters to important meteorological problems that can occur on occasion in the eastern United States. While the more widespread snow situations are better understood and forecast, the region is not immune to events that cry out for observing systems such as Doppler weather radar and wind profilers that can detect small-scale circulations, as well as mesoscale model simulations that can predict small-scale events.

While the past decade has brought a substantial increase to our knowledge of and abilities to forecast eastern United States winter weather systems, a need is evident for further understanding of the roles of sub-

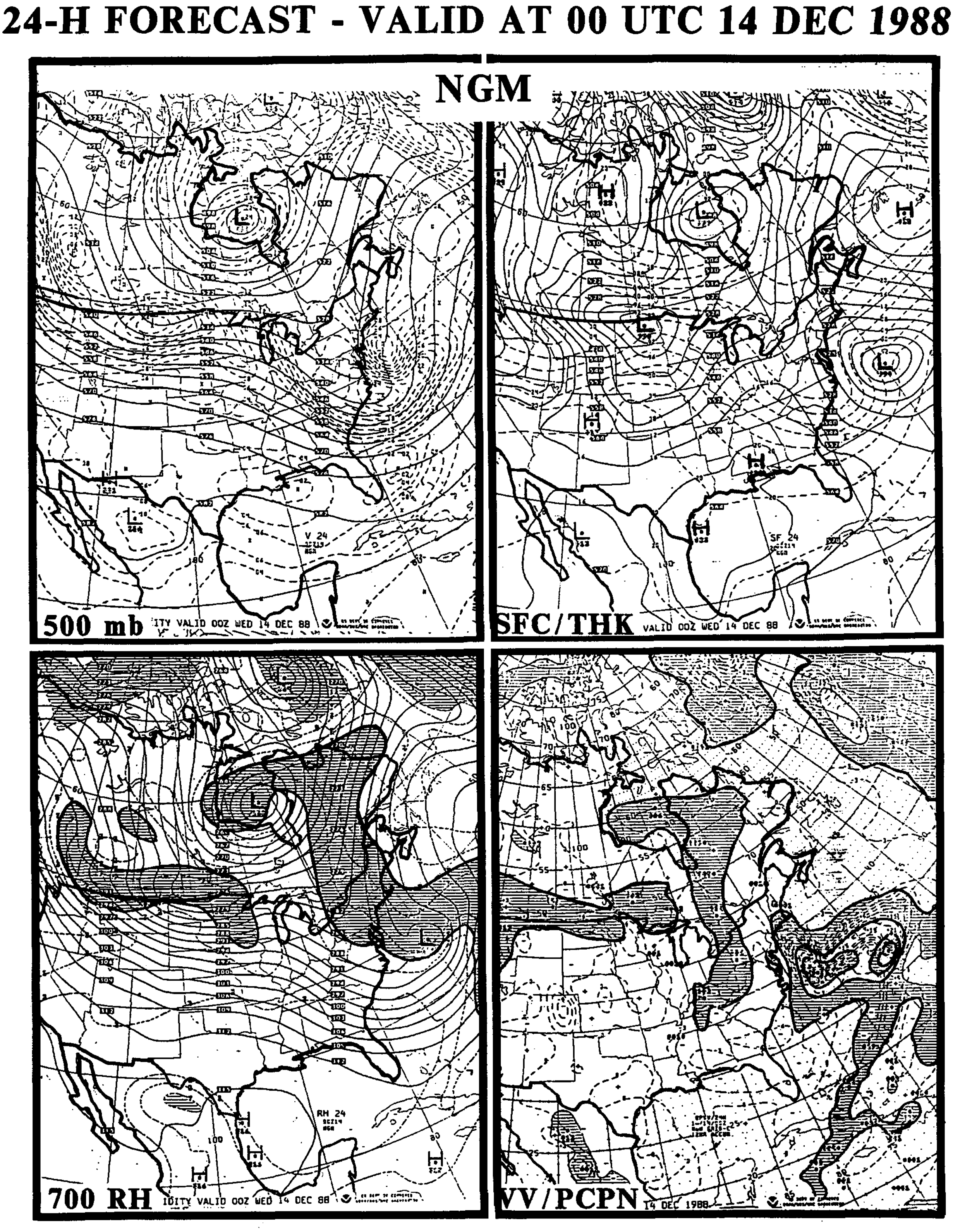

FIG. 7. The 24-h NGM forecast valid 0000 UTC 14 December 1988. The upper-left panel is the forecast 500-mb heights (solid), and vorticity (dashed). The upper-right panel is the MSL pressure (solid), and 1000–500-mb thickness (dashed) forecast. The lower-left panel consists of the 700-mb height (solid), and 1000–500-mb mean relative humidity (dashed). Mean relative humidities greater than 70% are shaded. The lower-right panel is the forecast 700-mb vertical velocities (thin solid), and accumulated precipitation (thick solid) for the 12 h ending at 0000 UTC 14 December.

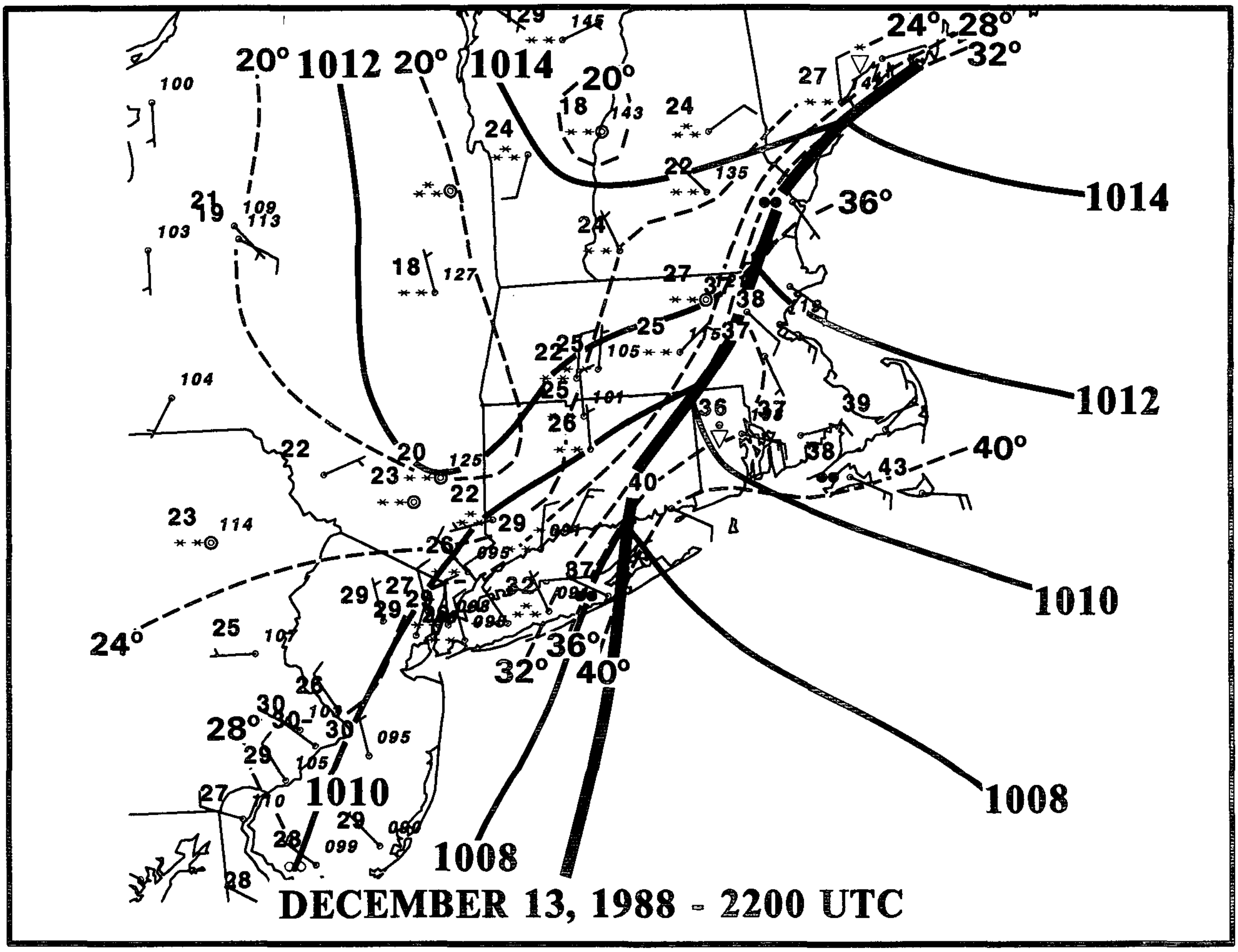

FIG. 8. Surface analysis for 2200 UTC 13 December 1988. The thin solid lines are isobars (2-mb increments), the dashed lines are isotherms (4°F increments), and the heavy solid line is the position of the coastal front.

synoptic-scale features within these systems. To achieve this greater understanding, and to be successful in the application of this knowledge to real-time forecast problems, observing systems with the spatial and temporal resolution necessary to resolve and monitor the mesoscale structure of winter storms are required. Recent field projects have demonstrated the utility of such observing systems. Wakimoto et al. (1991) utilized airborne Doppler radar to examine the mesoscale structure of a rapidly intensifying cyclone during the Experiment on Rapidly Intensifying Cyclones over the Atlantic (ERICA; Hadlock and Kreitzberg 1988), while Martner et al. (1991) used an array of remote sensors to investigate the evolution of a freezing rain event during the Lake Ontario Winter Storms (LOWS) project (Reinking et al. 1990).

During the 1990s the National Weather Service (Department of Commerce), in conjunction with the Departments of Defense and Transportation, will deploy a network of Doppler radars, termed WSR-88D (U.S. Department of Commerce 1990, 1991a,b). It is beyond the scope of this paper to describe the WSR-88D system in detail. For more information, the reader is directed to the referenced papers. The higher-resolution reflectivity data, along with radial velocity data, promises to make the WSR-88D a powerful tool for diagnosing many of the features of eastern winter weather systems discussed earlier.

The utility of Doppler radar for wintertime applications in the eastern United States was first demonstrated during the Boston Area NEXRAD Demonstration (BAND), held during the 1983–1984 winter season (Forsyth et al. 1985). Sanders (1986) and Seltzer et al. (1985) used a Doppler radar located at the Massachusetts Institute of Technology to study mesoscale precipitation bands observed in New England winter storms and related these to the presence of conditional symmetric instability (CSI; Emanuel 1983). Riordan and Anderson (1991) utilized a dual-Doppler analysis to study a coastal front near Cape

Hatteras, North Carolina, during the Genesis of Atlantic Lows Experiment (GALE; Dirks et al. 1988). Additional work has illustrated applications of Doppler radar to short-range snow forecasting in the midwestern United States (Ramamurthy et al. 1991) and northeastern Colorado (e.g., Heckman and Dulong 1989; Szoke and Wiesmueller 1989; Szoke 1991), where topographically forced features, such as cold air damming (Dunn 1987) play important roles in focusing snowfall into mesoscale bands.

In addition to the WSR-88D, Doppler technology is also being applied to ground-based vertically pointing tropospheric profiling radars through the implementation of a Wind Profiler Demonstration Network (WPDN) in the central United States (van de Kamp 1988; Waldstreicher 1990). Cool season application of these data was illustrated by Jewett and Brady (1989) by using a network of wind profilers in eastern Colorado. Farther east, Forbes et al. (1989, 1990) utilized The Pennsylvania State University three-profiler network (Forbes et al. 1985) to study a variety of weather-related phenomena that included jet stream and frontal structures and circulations, warm and cold conveyor belts, meso-β-scale precipitation bands, and several other meso-α-scale atmospheric features. Penc et al. (1991) utilized wind profilers in conjunction with other remote sensors to study lake effect phenomena in the vicinity of Lake Ontario during the LOWS field project, while Eberwine (1990) demonstrated some applications of real-time profiler data to winter weather forecasting.

Finally, while significant improvements have and continue to be made in the skill of operational dynamical models in depicting winter storms (Stokols et al. 1991), there are still areas for improvement. One of the most promising avenues is the development of mesoscale numerical models. During the past few years, the National Meteorological Center has developed and tested versions of a mesoscale model that has horizontal resolutions of 80, 50, and 30 km (Kalnay et al. 1991). This "mesoscale" model uses a vertical "eta" coordinate system (Mesinger 1984), rather than the sigma vertical coordinate system (Phillips 1957) associated with previous operational numerical models such as the LFM and NGM. The eta coordinate system utilizes a "steplike" topography (Janjić 1990), resulting in a more realistic model representation for steep terrain. Initial results have indicated improved quantitative precipitation forecasts, particularly higher amounts and areal distribution in the eta model forecasts compared to the NGM (Black and Mesinger 1989; Kalnay et al. 1991).

In addition to the NMC eta model, joint efforts between The Pennsylvania State University (PSU) and the National Center for Atmospheric Research (NCAR) have resulted in the development of a regional mesoscale model that has been configured so that it can be applied over any geographic area (Warner and Seaman 1990). Anthes (1990) and Warner and Seaman (1990) demonstrated a wide range of applications of the PSU/NCAR Mesoscale Model—Version 4 (MM4). Also, the National Oceanic and Atmospheric Administration's Forecast System Laboratory has developed two mesoscale models that are specifically designed to take advantage of new remote sensing technologies. The Mesoscale Analysis and Prediction System (MAPS; Benjamin et al. 1991; Benjamin 1989) is an isentropic coordinate model with a 60-km horizontal resolution across the continental United States. By using additional data sources, particularly those available at nonsynoptic times such as profiler data, and observations from commercial aircraft relayed through the Aeronautical Radio Inc. (ARINC) Communications, Addressing, and Reporting System (ACARS; Benjamin et al. 1991), MAPS can run on a 3-h update cycle, producing forecasts out to 6 or 12 h. The Local Analysis and Prediction System (LAPS; McGinley 1989; McGinley et al. 1991) uses all available data, including information from Doppler radar, to produce a local (eastern Colorado) finescale (10-km horizontal and 50-mb vertical resolution throughout the troposphere) analysis. LAPS utilizes MAPS as a first guess and is run once every hour. Szoke (1992) demonstrated how forecasters utilized LAPS output to produce short-range forecasts during mesoscale snowfall events across eastern Colorado.

There is an old adage that frequently is used to describe cold season weather in many parts of the eastern United States: "Wait 15 minutes and it will change." While not usually true in the literal sense, it is the premise of this axiom that draws many meteorologists to the tremendous challenges of forecasting winter weather in this part of the country. The unique topography of the east coast of North America results in a number of complex interactions between land, air, and sea that makes the task a difficult one. Many substantial advances have been made during the last decade in our understanding of these systems, yielding a number of innovative techniques and approaches to the forecast problems. However, as we learn more, we also discover more aspects that we do not yet fully understand. The implementation of new remote sensing observing systems like the WSR-88D, and improved numerical modeling capabilities, should provide many answers, result in new techniques and applications, and, ultimately, improve diagnosis and forecasts of winter weather.

Acknowledgments. The authors would like to thank Gary Carter and Paul Stokols of the Scientific Services Division, NWS Eastern Region Headquarters, as well as three anonymous reviewers, for their insightful comments and suggestions.

REFERENCES

Anthes, R. A., 1990: Recent applications of the Penn State/NCAR Mesoscale Model to synoptic, mesoscale, and climate studies. *Bull. Amer. Meteor. Soc.*, **71**, 1610–1629.

Auer, A., 1987: An aid to forecasting heavy snow episodes. Central Region Technical Attachment 87-26, 8 pp. [Available from Scientific Services Division, National Weather Service Central Region Headquarters, Kansas City, MO 64106-2897.]

Bell, G. D., and L. F. Bosart, 1988: Appalachian cold-air damming. *Mon. Wea. Rev.*, **116**, 137–161.

Benjamin, S. G., 1989: An isentropic mesoalpha-scale analysis system and its sensitivity to aircraft and surface observations. *Mon. Wea. Rev.*, **117**, 1586–1605.

——, K. A. Brewster, R. Brummer, B. F. Jewett, T. W. Schlatter, T. L. Smith, and P. A. Stamus, 1991: An isentropic three-hourly data assimilation system using ACARS aircraft observations. *Mon. Wea. Rev.*, **119**, 888–906.

Black, T. L., and F. Mesinger, 1989: Forecast performance of NMC's eta coordinate regional model. Preprints, *12th Conf. on Weather Analysis and Forecasting*, Monterey, CA, Amer. Meteor. Soc., 551–555.

Bocchieri, J. R., and G. J. Maglaras, 1983: An improved operational system for forecasting precipitation type. *Mon. Wea. Rev.*, **111**, 405–419.

Bosart, L. F., 1975: New England coastal frontogenesis. *Quart. J. Roy. Meteor. Soc.*, **101**, 957–978.

——, 1981: The Presidents' Day snowstorm of 18–19 February 1979: A subsynoptic-scale event. *Mon. Wea. Rev.*, **109**, 1542–1566.

——, and F. Sanders, 1986: Mesoscale structure in the megalopolitan snowstorm of 11–12 February 1983. Part III: A large amplitude gravity wave. *J. Atmos. Sci.*, **43**, 924–939.

Businger, S., D. R. Musick, and G. F. Watson, 1992: Case study of a prolonged sleet event over North Carolina. Preprints, *Symp. on Weather Forecasting*, Atlanta, GA, Amer. Meteor. Soc., 139–141.

Chaston, P. R., 1989: The Magic Chart for forecasting snow amounts. *Natl. Wea. Dig.*, **14**, 20–22.

Colucci, S. J., 1976: Winter cyclone frequencies over the eastern United States and adjacent western Atlantic, 1963–1973. *Bull. Amer. Meteor. Soc.*, **57**, 548–553.

Dirks, R. A., J. P. Kuettner, and J. A. Moore, 1988: Genesis of Atlantic Lows Experiment (GALE)—An overview. *Bull. Amer. Meteor. Soc.*, **69**, 148–160.

Dunn, L., 1987: Cold air damming by the Front Range of the Colorado Rockies and its relationship to locally heavy snows. *Wea. Forecasting*, **2**, 177–189.

Eberwine, J. A., 1990: Some local applications of profiler data. Eastern Region Technical Attachment No. 90-10A, 11 pp. [Available from Scientific Services Division, National Weather Service Eastern Region Headquarters, Bohemia, NY 11716.]

Emanuel, K. A., 1983: On assessing local conditional symmetric instability from atmospheric soundings. *Mon. Wea. Rev.*, **111**, 2016–2033.

Environmental Science and Service Administration, 1966a: *Some Outstanding Snowstorms*. Environmental Science Services Administration Environmental Data Series.

——, 1966b: *Some Outstanding Blizzards*. Environmental Science Services Administration Environmental Data Series.

Evenson, E. C., 1992: A case study involving local effects that influence the application of the Magic Chart. Preprints, *Symp. on Weather Forecasting*, Atlanta, GA, Amer. Meteor. Soc., 142–147.

Forbes, G. S., D. W. Thomson, and J. J. Cahir, 1985: Hourly wind profiles in a region of frequent air traffic—The Penn State profiler network. Preprints, *Second Int. Conf. on the Aviation Weather System*, Montreal, Quebec, Canada, Amer. Meteor. Soc., 172–176.

——, R. A. Anthes, and D. W. Thompson, 1987: Synoptic and mesoscale aspects of an Appalachian ice storm associated with cold-air damming. *Mon. Wea. Rev.*, **115**, 564–591.

——, D. W. Thompson, J. J. Cahir, C. A. Carlson, P. J. Neiman, S. R. Williams, and A. A. Person, 1989: Analysis of significant weather on meso-alpha scales using conventional and remotely sensed data. AFGL-TR-89-0179, Air Force Geophysics Laboratory, Hanscom AFB, MA, 224 pp.

——, T. Dye, M.-T. Lee, D. W. Thompson, J. J. Cahir, S. R. Williams, and A. A. Person, 1990: Analysis of significant weather on meso-alpha scales using conventional and remotely sensed data—Further studies. Final Report, Air Force Geophysics Laboratory Contract F19628-86-C-0092, Air Force Geophysics Laboratory, Hanscom AFB, MA, 116 pp.

Forsyth, D. E., M. J. Istok, T. D. O'Bannon, and K. E. Glover, 1985: The Boston Area NEXRAD Demonstration (BAND). AFGL-TR-85-0098, Air Force Geophysics Laboratory, Hanscom AFB, MA, 68 pp.

George, J. J., 1960: *Weather Forecasting for Aeronautics*. Academic Press, 673 pp.

Gigi, A. F., 1989: The New York City snowstorm that never was. Eastern Region Technical Attachment 89-14, 12 pp. [Available from Scientific Services Division, National Weather Service Eastern Region Headquarters, Bohemia, NY 11716.]

Glahn, H. R., and D. A. Lowry, 1972: The use of model output statistics (MOS) in objective weather forecasting. *J. Appl. Meteor.*, **11**, 1203–1211.

Gurka, J. J., E. P. Auciello, A. F. Gigi, J. S. Waldstreicher, K. K. Keeter, S. Businger, and L. G. Lee, 1995: Winter weather forecasting throughout the eastern United States. Part II: An operational perspective of cyclogenesis. *Wea. Forecasting*, **10**, 5–20.

Hadlock, R., and C. W. Kreitzberg, 1988: The Experiment on Rapidly Intensifying Cyclones over the Atlantic (ERICA) field study—Objectives and plans. *Bull. Amer. Meteor. Soc.*, **69**, 1309–1320.

Heckman, B. E., and T. Dulong, 1989: Doppler radar reflectivity bands: Comparison with 500 mb wind patterns and implications for winter nowcasting. Preprints, *Third Int. Conf. on the Aviation Weather System*, Anaheim, CA, Amer. Meteor. Soc., 233–237.

Janjić, Z. I., 1990: The step-mountain coordinate: Physical package. *Mon. Wea. Rev.*, **118**, 1429–1443.

Jewett, B. F., and R. H. Brady, 1989: *Profiler Training Manual #4: Subjective Uses of Wind Profiler Data in Cool Season Analysis and Forecasting*. NOAA/ERL, 92 pp.

Kalnay, E., R. Petersen, M. Kanamitsu, and W. E. Baker, 1991: U.S. Operational Numerical Weather Prediction. *Rev. Geophys.*, 104–114.

Keeter, K. K., S. Businger, L. G. Lee, and J. S. Waldstreicher, 1995: Winter weather forecasting throughout the eastern United States. Part III: The effects of topography and the variability of winter weather in the Southeast. *Wea. Forecasting*, **10**, 42–60.

Kocin, P. J., 1983: An analysis of the "Blizzard of 88." *Bull. Amer. Meteor. Soc.*, **64**, 1258–1272.

——, and L. W. Uccellini, 1990: *Snowstorms along the Northeastern Coast of the United States: 1955–1985. Meteor. Monogr.*, No. 44, Amer. Meteor. Soc., 280 pp.

——, ——, J. W. Zack, and M. L. Kaplan, 1985: A mesoscale numerical forecast of an intense convective snowburst along the East Coast. *Bull. Amer. Meteor. Soc.*, **66**, 1412–1424.

Martner, B. E., R. J. Zamora, J. B. Snider, P. I. Joe, and R. Caiazza, 1991: Evolution of a freezing rain storm. Part II: Remote sensor observations. Preprints, *First Int. Symp. on Winter Storms*, New Orleans, LA, Amer. Meteor. Soc., 264–269.

McGinley, J., 1989: The local analysis and prediction system. Preprints, *12th Conf. on Weather Analysis and Forecasting*, Monterey, CA, Amer. Meteor. Soc., 15–19.

——, S. C. Albers, and P. A. Stamus, 1991: Validation of a composite index as defined by a real-time local analysis system. *Wea. Forecasting*, **6**, 337–356.

Mesinger, F., 1984: A blocking technique for representation of mountains in atmospheric models. *Rev. Meteor. Aeronautica*, **44**, 195–202.

Naistat, R. J., 1988: Using mid-level thickness patterns and warm air advection to forecast heavy snow. Central Region Technical Attachment 88-36, 10 pp. [Available from the Scientific Services Division, National Weather Service Central Region Headquarters, Kansas City, MO 64106-2897.]

National Oceanic and Atmospheric Administration, 1992: Natural disaster survey report: The Halloween Nor'easter of 1991. NOAA/NWS, Silver Spring, MD, 87 pp.

Niziol, T. A., W. R. Snyder, and J. S. Waldstreicher, 1995: Winter weather forecasting throughout the eastern United States. Part IV: Lake effect snow. *Wea. Forecasting,* **10,** 61–77.

Palmén, E., and C. W. Newton, 1969: *Atmospheric Circulation Systems.* Academic Press, 603 pp.

Penc, R. S., S. R. Williams, B. A. Albrecht, R. Caiazza, and R. F. Reinking, 1991: Lake-effect storms east of Lake Ontario: Some preliminary findings from the LOWS field project. Preprints, *First Int. Symp. on Winter Storms,* New Orleans, LA, Amer. Meteor. Soc., 252–257.

Petterrsen, S., 1956: *Weather Analysis and Forecasting.* Vol. 1. McGraw-Hill Inc., 428 pp.

Phillips, N. A., 1957: A coordinate system having some special advantages for numerical forecasting. *J. Meteor.,* **14,** 184–185.

Ramamurthy, M. K., R. M. Rauber, B. P. Collins, M. T. Shields, P. C. Kennedy, and W. C. Clark, 1991: UNIWIPP: A University of Illinois field experiment to investigate the structure of mesoscale precipitation in winter storms. *Bull. Amer. Meteor. Soc.,* **72,** 764–776.

Reinking, R. F., R. A. Kropfli, R. Caiazza, G. P. Byrd, R. Ballentine, A. Stamm, R. S. Penc, T. A. Niziol, and C. Bedford, 1990: The Lake Ontario Winter Storms Project (LOWS). Preprints, *16th Conf. on Severe Local Storms*, Amer. Meteor. Soc., Kananaskis Park, Canada, 613–618.

Reitan, C. H., 1974: Frequencies of cyclones and cyclogenesis for North America, 1951–1970. *Mon. Wea. Rev.,* **102,** 861–868.

Richwein, B. A., 1980: The damming effect of the southern Appalachians. *Natl. Wea. Dig.,* **5,** 2–12.

Riordan, A. J., and J. T. Anderson, 1991: Dual-Doppler analysis of a coastal front near Cape Hatteras, North Carolina. Preprints, *First Int. Symp. on Winter Storms,* New Orleans, LA, Amer. Meteor. Soc., 177–180.

Roebber, P. J., 1984: Statistical analysis and updated climatology of explosive cyclones. *Mon. Wea. Rev.,* **112,** 1577–1589.

Ronco, J. A., Jr., 1989: A procedure for forecasting precipitation type using NGM low level temperatures and LFM MOS frozen precipitation forecasts. NOAA Tech. Memo. NWS ER-82, NOAA/NWS, Bohemia, NY, 113–124. [NTIS PB90-147414/AS.]

Sanders, F., 1986: Frontogenesis and symmetric instability in a major New England snowstorm. *Mon. Wea. Rev.,* **114,** 1847–1862.

——, and J. R. Gyakum, 1980: Synoptic–dynamic climatology of the "bomb." *Mon. Wea. Rev.,* **108,** 1590–1606.

——, and L. F. Bosart, 1985a: Mesoscale structure in the megalopolitan snowstorm of 11–12 February 1983. Part I: Frontogenetical forcing and symmetric instability. *J. Atmos. Sci.,* **42,** 1050–1061.

——, and ——, 1985b: Mesoscale structure in the megalopolitan snowstorm of 11–12 February 1983. Part II: Doppler radar study of the New England snowband. *J. Atmos. Sci.,* **42,** 1398–1407.

Sangster, W., and E. Jagler, 1985: The (7WG, 8WT) "magic" chart. Central Region Technical Attachment 85-1, 5 pp. [Available from Scientific Services Division, National Weather Service Central Region Headquarters, Kansas City, MO 64106-2897.]

Scofield, R. A., 1990: Instability bursts associated with extratropical cyclone systems (ECS's) and a forecast index of 3–12 hour heavy precipitation. NOAA Tech. Memo. NESDIS 30, NOAA/NESDIS, Washington, DC, 77 pp.

Seltzer, M. A., R. E. Passarelli, and K. A. Emanuel, 1985: The possible role of symmetric instability in the formation of precipitation bands. *J. Atmos. Sci.,* **42,** 2207–2219.

Smigielski, F. J., and H. M. Mogil, 1993: A systematic satellite approach for estimating central pressures of mid-latitude ocean storms. NOAA Tech. Rep. NESDIS 63, NOAA/NESDIS, Washington, DC, 64 pp.

Spar, J., F. Zuckerberg, and H. Friedman, 1969: Aircraft reconnaissance of winter coastal cyclones in the northeastern United States. *Bull. Amer. Meteor. Soc.,* **50,** 857–865.

Stokols, P. M., J. P. Gerrity, and P. J. Kocin, 1991: Improvements at NMC in numerical weather prediction and their effect on winter storm forecasts. Preprints, *First Int. Symp. on Winter Storms,* New Orleans, LA, Amer. Meteor. Soc., 15–19.

Szoke, E. J., 1991: The use of Doppler radar in the short-range forecasting of snowfall in northeastern Colorado. Preprints, *25th Int. Conf. on Radar Meteorology,* Paris, France, Amer. Meteor. Soc., 71–74.

——, 1992: The application of new observing systems, a workstation, and a conceptual model to the short-term prediction of snowfall. Preprints, *Fourth AES/CMOS Workshop: Forecasting in the Nineties,* Whistler, Canada, Canadian Meteorological and Oceanographic Society, 205–214.

——, and J. L. Wiesmueller, 1989: Mesoscale structure of winter snowstorms in northeast Colorado as revealed by Doppler radar: Potential for short range forecasting. Preprints, *12th Conf. on Weather Analysis and Forecasting,* Monterey, CA, Amer. Meteor. Soc., 384–389.

Uccellini, L. W., and P. J. Kocin, 1987: An examination of vertical circulations associated with heavy snow events along the East Coast of the United States. *Wea. Forecasting,* **2,** 289–308.

——, ——, R. A. Petersen, C. H. Wash, and K. F. Brill, 1984: The Presidents' Day cyclone of 18–19 February 1979: Synoptic overview and analysis of the subtropical jet streak influencing the precyclogenetic period. *Mon. Wea. Rev.,* **112,** 31–55.

——, D. Keyser, K. F. Brill, and C. H. Wash, 1985: The Presidents' Day cyclone of 18–19 February 1979: Influence of upstream trough amplification and associated tropopause folding on rapid cyclogenesis. *Mon. Wea. Rev.,* **113,** 962–988.

——, R. A. Petersen, K. F. Brill, P. J. Kocin, and J. J. Tuccillo, 1987: Synergistic interactions between an upper-level jet streak and diabatic processes that influence the development of a low-level jet and secondary cyclone. *Mon. Wea. Rev.,* **115,** 2227–2261.

U.S. Department of Commerce, 1962: *Storm Data,* **3**(3).

——, 1977: *Storm Data,* **19**(1).

——, 1978: *Storm Data,* **20**(2).

——, 1983: *Storm Data,* **25**(2).

——, 1990: Doppler radar meteorological observations. Part A: System concepts, responsibilities, and procedures. *Federal Meteorological Handbook No. 11,* NOAA/OFCM, Washington, DC, 56 pp.

——, 1991a: Doppler radar meteorological observations. Part B: Doppler radar theory and meteorology. *Federal Meteorological Handbook No. 11* NOAA/OFCM, Washington, DC, 227 pp.

——, 1991b: Doppler radar meteorological observations. Part C: WSR-88D products and algorithms. *Federal Meteorological Handbook No. 11,* NOAA/OFCM, Washington, DC, 208 pp.

van de Kamp, D. W., 1988: *Profiler Training Manual No. 1: Principles of Wind Profiler Operation.* NOAA/ERL, 49 pp.

Wakimoto, R. M., W. Blier, and C. Liu, 1991: A radar perspective of IOP 4 during ERICA. Preprints, *First Int. Symp. on Winter Storms,* New Orleans, LA, Amer. Meteor. Soc., 124–129.

Waldstreicher, J. S., 1990: An operational guide to the wind profiler network. Eastern Region Technical Attachment 90-1A, 13 pp. [Available from Scientific Services Division, National Weather Service Eastern Region Headquarters, Bohemia, NY 11716.]

Warner, T. T., and N. L. Seaman, 1990: A real-time, mesoscale numerical weather prediction system used for research, training and public service at The Pennsylvania State University. *Bull. Amer. Meteor. Soc.,* **71,** 792–805.

Zimm, A., 1991: Without warning: Storm with no name leaves deep marks on the town. *Marblehead Reporter,* **27,** 1–6.