Winter Icing and Storms Project (WISP)

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Abstract

Field studies in support of the Winter Icing and Storms Project (WISP) were conducted in the Colorado Front Range area from 1 February to 31 March 1990 (WISP90) and from 15 January to 5 April 1991 (WISP91). The main goals of the project are to study the processes leading to the formation and depletion of supercooled liquid water in winter storms and to improve forecasts of aircraft icing. During the two field seasons, 2 research aircraft, 4 Doppler radars, 49 Mesonet stations, 7 CLASS sounding systems, 3 microwave radiometers, and a number of other facilities were deployed in the Front Range area. A comprehensive dataset was obtained on 8 anticyclonic storms, 16 cyclonic storms, and 9 frontal passages.

This paper describes the objectives of the experiment, the facilities employed, the goals and results of a forecasting exercise, and applied research aspects of WISP. Research highlights are presented for several studies under way to illustrate the types of analysis being pursued. The examples chosen include topics on anticyclonic upslope storms, heavy snowfall, large droplets, shallow cold fronts, ice crystal formation and evolution, and numerical model performance.

1. Introduction

Although winter can bring hazardous weather to those living in and flying above Colorado, few coordinated studies have been conducted specifically to investigate winter storms in that area.

During the past two years, the Winter Icing and Storms Project (WISP) has addressed both basic and applied topics in winter storms research. Field studies were conducted along the Front Range of the Colorado Rocky Mountains from 1 February to 31 March 1990 (WISP90) and from 15 January to 5 April 1991 (WISP91). Thirty-six scientists from seven institutions participated in the field program.

WISP was designed to further our understanding of the dynamical and microphysical processes leading to the production and depletion of supercooled liquid water (SLW) in winter storms and to improve forecasts of aircraft icing. In this paper we describe the objectives of the field experiments and the facilities used. We also discuss preliminary analyses to illustrate the types of research being pursued.

The observational strategy utilized for WISP was based on collecting in situ and remotely sensed data that could be used to increase our understanding of the various processes active during winter storm events. One advantage to locating a field study in the Denver, Colorado, area is the abundance of observational facilities already in place as part of experimental networks operated by the National Oceanic and Atmospheric Administration (NOAA) and the National Center for Atmospheric Research (NCAR). To augment these observational platforms, additional instruments were sited at various locations in order to obtain a thorough sampling of storms as they passed through the project area. The facilities available during WISP90 and WISP91 and their locations are shown in Figs. 1 and 2.

Winter storms in the Colorado Front Range area have several unique characteristics that make them interesting candidates for a wide range of studies. The Palmer Divide and Cheyenne Ridge are seemingly minor terrain features, yet they can greatly affect airflow and cloud formation (e.g., the "Denver Cyclone" circulation; Szoke et al. 1984). During the winter, cold fronts with both Pacific and Arctic origins pass through the area. Some fronts produce deep cyclonic storms with locally heavy snowfall, as described by Howard and Tollerud (1988) and Wesley and Pielke (1990). With others, weak, anticyclonic flow around cold high pressure centers in the northern

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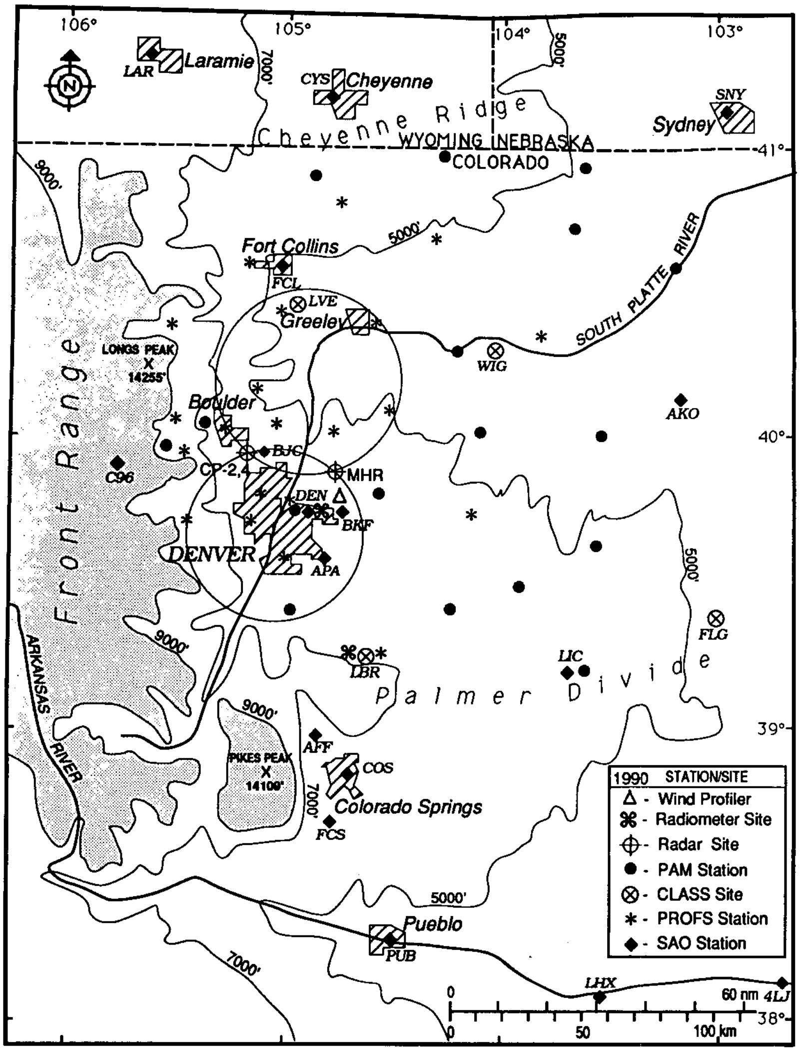


FIG. 1. Winter Icing and Storm Project (WISP90) network of instruments showing the location of the Doppler radars, CLASS stations, PAM and PROFS mesonet stations, radiometer sites, wind profiler sites, and SAO stations. Topographic contours are given every 2000 ft. The shaded region represents terrain above 9000 ft.

Plains can create persistent cloudiness with little precipitation due to weak upslope forcing (as in Reinking and Boatman 1987). Table 1 provides a summary of the various storm events occurring during WISP.

2. Background

a. Aircraft icing

The accretion of supercooled water onto aircraft, or aircraft icing, was either a cause or factor in an average of 30 aircraft accidents per year between 1975 and 1988 (Cole and Sand 1991). General aviation and commuter aircraft often operate in conditions where icing is likely. Many of these aircraft are not certified for flight into known icing conditions and must depend on forecasts to avoid these areas. Aircraft certified for flight in known icing can operate in icing conditions for a limited time; however, they may not be able to cope with prolonged exposure or with extreme encounters. The general aviation community has been particularly vocal in calling for improved icing forecasts and for renewed attention to this hazard.

In recognition of this need, the office of the Federal Coordinator for Meteorological Services and Supporting Research (FCM) issued a document addressing these needs, entitled *The National Aircraft Icing Technology Plan* (FCM 1986a). In this plan, a multiagency effort was proposed that would lead to improvements in the detection and forecasting of icing conditions. A subsequent publication, the *National Plan to Improve Aircraft Icing Forecasts* (FCM 1986b), provided additional delineation of program objectives and design. According to this document:

> This program will provide appropriate data for the study of aircraft icing and the evaluation of existing techniques and will develop improved methods for detecting and forecasting icing conditions. The plan provides for the research needed to determine how the icing hazard depends on microphysical characteristics of the clouds and to relate those characteristics to mesoscale or synoptic-scale characteristics that are readily observable. The approach features the application of modern technology, uses the recent advances in meteorology, and focuses on meeting the operational needs of the aviation community.

In 1988 the Federal Aviation Administration (FAA) funded the NCAR Research Applications Program (RAP) to plan a multiyear program to improve aircraft icing forecasting. Through a series of meetings with investigators interested in icing and other winter storm problems, a comprehensive research plan was formulated that included field research, forecasting exercises, and products and displays concerning testing and evaluation. The FAA Icing Forecasting Improvement Program Experimental Design (Politovich 1989) was completed in fall 1989, and the 6-yr FAA Icing Forecast Improvement Program began in October of that year.

In the past, aircraft icing studies have taken several approaches. Much of the research has been conducted in wind tunnels, where the nature of accreted ice is examined on airfoils. Numerical models have simulated accretion and determined the effects of temperature, liquid water content, droplet size, and other factors (e.g., Shin et al. 1991; Hansman and Kirby 1987). In-flight studies have examined environmental factors and their relation to ice accretion (Hansman 1984; Hoffman 1990) or performance degradation (Cooper et al. 1984). Relatively few studies, however, have been conducted on the relationship of icing-related parameters to observations routinely available to forecasters (Osborne 1989; Sand et al. 1989). The FAA Icing Forecasting Improvement Program is emphasizing the latter types of studies, using the NOAA Forecast Systems Laboratory (FSL) and National Aviation Weather Advisory Unit (NAWAU) as test-beds.

b. Winter storms

Conditions favorable to the occurrence of aircraft icing are found most often in association with winter storms. A number of winter storm projects have taken place in the western United States, focusing primarily on orographic clouds in mountainous regions. Most of these have been weather modification studies, including the San Juan Project (Cooper and Marwitz 1980), the Sierra Cooperative Pilot Project (Reynolds and Dennis 1986), the Colorado Orographic Storms Experiment (Rauber et al. 1986; Rauber and Grant 1986), and the Nevada and Utah programs within the Federal–State Cooperative Weather Modification Program (Warburton and DeFelice 1986; Long et al. 1990; Sassen et al. 1990). These field studies have focused primarily on cloud-seeding objectives, and have yielded much useful information on the production of SLW and precipitation in orographic clouds. Relatively few studies, however, have been conducted on winter storms in the Colorado Front Range. Due to its location in the lee of the Rockies, Front Range winter storms are usually significantly different from the type of storms studied by the weather modification projects mentioned above. A number of limited studies of Front Range winter storms have been made (Whiteman 1973; Weickmann 1981; Boatman and Reinking 1984; Wesley and Pielke 1990; Wesley et al. 1990), which show that the primary storm types affecting the Front Range are anticyclonic and cyclonic storms. Relatively little, however, is known of the dynamical and microphysical structure of these types of storms, especially as influenced by the topography of the Colorado Front Range.

As the Icing Forecasting Improvement Program evolved, it became clear that excellent opportunities existed for collaboration between investigators interested in the applied topic of aircraft icing and those interested in a further understanding of the physical processes active in Front Range winter storms. Some of the local investigators included NOAA scientists interested in testing newly developed instrumentation in a winter storm environment, forecasters at NOAA

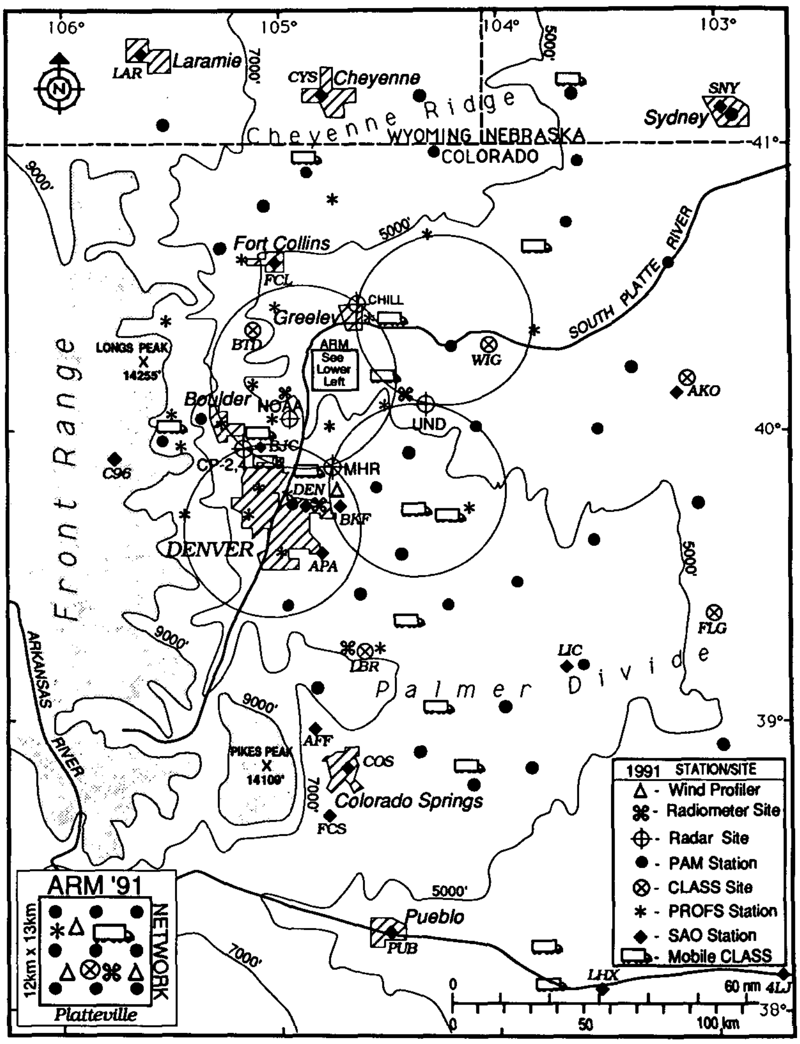


FIG. 2. Same as Fig. 1 except for WISP91.

TABLE 1. Summary of WISP weather events

Date	Storm Type[1]	Comments
2 Feb 1990	IOPC	Snowband, limited aircraft data
8 Feb 1990	IOPA	Shallow cold front, weak upslope
13–15 Feb 1990	IOPA/C	Cold front with associated surges, snowbands, supercooled liquid water
20 Feb 1990	IOPC	Effects of Palmer Ridge on distribution of supercooled liquid water, multiple weak snowbands
27–28 Feb 1990	IOPA	Secondary surge behind cold front, high supercooled liquid water content
5– 7 Mar 1990	IOPD	Blizzard of 1990, barrier, jet, no aircraft, over a foot of snow
13–14 Mar 1990	IOPC	Shallow cold front, overrunning of barrier jet, CSI-type bands
18 Mar 1990	IOPA	Supercooled liquid water, light snow
22–24 Mar 1990	IOPA	Strong cold front, aircraft studies of cold front, snowbands
28–30 Mar 1990	IOPA	Aircraft mapping of supercooled liquid water, snowband
16 Jan 1991	IOPC	Aircraft studies of snowbands in CHILL-UND dual Doppler lobes
19 Jan 1991	IOPC	Snow along cold front, aircraft passes across CHILL, wave clouds, snowband with secondary surge
24–25 Jan 1991	IOPC	Snowbands associated with secondary cold surge behind cold front
28–29 Jan 1991	IOPC	Strong front, widespread snowfall
14–15 Feb 1991	IOPA	Terrain-induced anticyclone with snowband along convergence axis
23–24 Feb 1991	IOPC	Supercooled liquid water flights, aircraft intercomparison with dual-wavelength radar at Erie and cross sections with CP-2 and CHILL
2 Mar 1991	IOPC	Light snowfall, aircraft missed approach flights, some supercooled liquid water found
5– 6 Mar 1991.	Unclassified	Strong moisture advection over Rockies in westerly flow; numerous icing reports, precipitation bands up to 40 dBZ
11–12 Mar 1991	IOPC	Cyclogenesis just east of Rockies thunderstorms, aircraft documentation of Pacific cold-front structure
14 Mar 1991	Denver Cyclone	Special soundings launced to south of Palmer Ridge to document cyclone
15 Mar 1991	IOPA	Mapping of supercooled liquid water, light snowfall
16 Mar 1991	IOPC	Cyclone just east of the WISP area, flights documented structure of thin stratus and vertical structure of wraparound cloud; large drops encountered near Greeley
21–22 Mar 1991	IOPD	Intercomparison flight at Erie with NOAA radar, snowband cross sections, secondary surge
26–27 Mar 1991	IOPD	Heavy snowband east of Stapleton due to strong surface convergence, embedded cells within band
29 Mar 1991	IOPC	Aircraft cross sections of mesoscale snowband, poor numerical forecasts

[1]IOPA: anticyclone; IOPC: shallow cyclone; IOPD: deep cyclone

and the National Weather Service (NWS) interested in obtaining a winter dataset for verification of forecast exercises of snowfall and icing and testing forecast products from automated objective analysis schemes, and NCAR and university scientists interested in basic winter storm research.

It was decided to form a larger research program that would encompass these broader interests around the core provided by the FAA Icing Forecasting Improvement Program. This project became known as WISP, and was designed to address broader issues than aircraft icing. The investigators agreed that the central unifying objective for WISP should be a better understanding of the processes responsible for the production and depletion of SLW, which is of primary concern to both the research and operational communities.

WISP began somewhat modestly, with the WISP90 field effort conducted primarily by NCAR and NOAA. Additional support and participants became available for WISP91 with several universities participating with funds from the National Science Foundation (NSF). WISP91 also collaborated with several programs conducted by the Department of Energy (DOE) in the Denver area (see section 8). The University of North Dakota participated in WISP90 and 91 with funding from the FAA.

3. Scientific objectives

The two main scientific objectives of WISP are to improve our understanding of the dynamical and microphysical processes leading to the production and depletion of supercooled liquid water, and to improve forecasts of aircraft icing in winter storms.

In order to achieve the first objective, research related to the physical processes producing and depleting SLW was planned. Two broad areas, storm dynamics and cloud microphysics, are identified in the following discussion. Studies related to aircraft icing detection and prediction were undertaken to pursue the second objective; these are addressed below as well as in sections 6 and 7.

a. Storm dynamics

Upslope flow in the context of WISP refers to easterly flow of moist air up the gradual slopes of the High Plains leading to the Front Range of the Rocky Mountains. Upslope flow can occur during the passage of both deep cyclonic and shallow anticyclonic storms, and is most common between December and March (Whiteman 1973).

1) Anitcyclonic storms

Anticyclonic upslope events result from a shallow surge of cold continental air that moves southward over the High Plains. As air circulates clockwise around the high pressure center behind the cold front, it rises as it travels westward (upslope). Due to the relatively cold air temperature of the rising air, the SLW of the clouds formed during these events is typically low, usually less than 0.15 g m^{-3} (Reinking and Boatman 1987). Cloud depth is restricted to the depth of the cold air, with average cloud thickness of 2 km based on a 10-yr climatology of anticyclonic storms by Whiteman (1973). Cloud-top temperatures are generally between −8° and −11° C. Although these storms typically do not produce much precipitation, they often create hazardous icing conditions for aircraft due to insufficient concentrations of ice crystals to deplete the SLW. During the two WISP field efforts, eight cases of anticyclonic upslope flow occurred and are currently being analyzed.

2) Cyclonic storms

In contrast to shallow anticyclonic storms, cyclonic storms are characterized by strong dynamic forcing throughout the troposphere. This dynamic support may be enhanced by the effects of the High Plains topography on the flow. Intensification usually occurs as the center of the surface cyclone tracks to the east of the Rocky Mountains and lee cyclogenesis occurs (Fawcett and Saylor 1965; Wesley and Pielke 1990). The circulation around the surface cyclone advects moist air from the High Plains toward the Front Range. The distribution, amount, and intensity of precipitation from these systems principally depends on the location and strength of the surface low pressure center and its track and speed in relation to the upper-air trough (Auer and White 1982; Schlatter et al. 1983; Fawcett and Saylor 1965; Reinking and Boatman 1987). During WISP, 16 cases of cyclonic upslope flow occurred.

3) Local topographic forcing

The Colorado Front Range area includes two east–west ridges: the Cheyenne Ridge to the north and the Palmer Divide to the south (see Fig. 1). As airflow interacts with these ridges, local circulations may develop. When the airflow has a southerly component, the so-called Denver Cyclone forms on the northern side of the Palmer Divide. This mesoscale vortex circulation, with a horizontal scale of ~100 km, can form both in summer and winter and is often associated with the formation of snowbands in the Denver area. A number of mechanisms have been proposed to explain the formation of this vortex, including lee vortex formation during the flow of strongly stratified flow air past three-dimensional obstacles (Smolarkiewicz and Rotunno 1989; Crook et al. 1990), blocking of the flow by the Front Range (Crook et al. 1990), and vorticity production during the flow of a well-mixed layer over the Palmer Divide (Wilczak and Glendening 1988). On 14 March 1991, an excellent dataset was collected on the upstream conditions associated with a Denver Cyclone using multiple aircraft and a mobile CLASS sounding system. These data are currently being used in a study that is attempting to evaluate the relative importance of the various proposed mechanisms on Denver Cyclone formation.

There is also evidence for SLW enhancement over the Palmer Divide as vertical motions are enhanced by terrain. Flight patterns were devised for the field studies in order to study this effect; preliminary modeling studies suggest that this is strongly influenced by wind direction and stability.

Although we experienced a variety of storm types during the WISP field efforts, in nearly every case we observed significant local topographic effects on airflow, cloud formation, or snow accumulation.

4) Conditional symmetric instability (CSI)

Snowbands are a persistent feature in many Front Range snowstorms and are often correlated with heavy snowfall (Lilly 1981; Dunn 1988; Wesley and Pielke 1990). Quasi-stationary and propagating bands both occur, with various orientations. Many of these bands cannot be explained by orographic mechanisms or atmospheric boundaries such as cold fronts. The theoretical work of Bennetts and Hoskins (1979) and Emanuel (1979) shows that CSI can lead to mesoscale bands with many of the observed features. Dunn (1988) showed that CSI may have played a role in determining the location of the heaviest snowfall during the Front Range storm of 28–29 September 1985. Howard and Tollerud (1988) show in their composite of 63 cyclonic storms that the environment over the Front Range area was conducive to moist slantwise convection in the baroclinic ascent region of the composite storm.

During WISP90 and WISP91, only one case was identified as being forced primarily by CSI (Snook 1991), although a number of other cases showed snowband structures and environmental conditions consistent with a CSI-type mechanism during particular stages of their evolution. Further work in this area using a larger dataset is required before the relative importance of CSI to band formation in Front Range winter storms is determined.

5) Cold-air damming/barrier jets

As discussed in Wesley and Pielke (1990), cold-air damming is an accentuated form of topographical blocking in which easterly (upslope) low-level flow overruns a stable cold pool. The cold pool typically is confined to the foothills and immediately adjacent plains; the cause of the presence of the cold pool may be due to adiabatic cooling (Dunn 1987), diabatic cooling (Marwitz and Day 1991), cold advection from the north (Schultz et al. 1985), or a combination of these features. If the easterly flow over the plains is supported for several hours by a cyclonic circulation associated with the approach of a disturbance aloft, a quasi-steady convergence line or "mesofront" can form upstream of the foothills. This leads to locally enhanced low-level ascent, with intensified snowfall just to the west of the convergence line as the easterly flow is lifted over the cold pool. This line has been observed in several cases to be oriented approximately north–south.

The development of a northerly barrier jet along the Front Range is closely related to blocking. On occasion, the low-level flow along the foothills accelerates toward the south due to a geostrophic adjustment of the decelerated or blocked easterly flow.

The accurate assessment and prediction of the type and extent of cold-air damming is critical both to the survival of layers of SLW and to the resulting snowfall distributions. During WISP, several cases of cold-air damming/blocking were documented. The 6 March 1990 case, described further in section 9b and by Marwitz and Day (1991) and Toth (1991), was a particularly intense example of a barrier jet.

6) Synoptic and mesoscale fronts

Propagating atmospheric boundaries are well-known producers of low-level convergence and upward motion. A cold front often propagates as a density current (Carbone 1982) and produces significant lifting at its leading edge. All the frontal passages during WISP were cold fronts occurring primarily in near-saturated conditions. Supercooled liquid water was usually found at the leading edge of the front in association with the strong updrafts, with snowbands in the postfrontal air. During WISP90 and WISP91, nine cold-frontal passages were documented.

7) Diabatic processes

Recent studies by Stewart and MacPherson (1989) and Szeto et al. (1988) showed that mesoscale circulations can result from diabatic cooling during the melting of snow. If synoptic-scale horizontal temperature gradients exist, there will also be horizontal variations in the melting rate of snow (and thus cooling), which may lead to organized circulations. Stewart and King (1987) showed that mesoscale precipitation bands oriented along rain/snow boundaries may be produced by these circulations. Diabatic cooling due to melting can also have a significant effect on cold-air damming/barrier jet formation, as shown by Marwitz (1983). The 6 March 1990 case was a particularly well-defined case of the effects of melting on storm dynamics and is discussed further in section 9b.

b. Cloud microphysics

1) Formation of ice crystals

The dominant precipitation process in Front Range winter storms is the growth of ice crystals by deposition and riming; it is also the main factor in liquid water depletion. Studies by Cooper and Marwitz (1980) and others have described the role of ice crystals in depleting liquid water. The ice crystal concentration in a cloud has been shown in many cases to be strongly temperature dependent when the concentration can be attributed to primary nucleation (as in Cooper 1986). Wide variability at a given temperature also exists due to natural and anthropogenic variations in the concentration of ice nuclei present (Bowdle et al. 1985). During WISP, numerous aircraft flights were conducted near cloud top to document this behavior and to establish whether ice crystal concentrations could be correlated with temperature in Front Range winter storms.

An important factor that may complicate such relations is the production of ice crystals by processes other than primary nucleation. In particular, secondary ice crystal production processes, such as the Hallett–Mossop process (Hallett and Mossop 1974) or enhancements due to crystal collisions followed by breakup, may be operating. Preliminary analysis of aircraft measurements during WISP, however, suggests that the conditions considered necessary for the Hallett–Mossop process (such as riming ice crystals at –5°C) are generally not present in Front Range winter storms (most of the clouds were at temperatures less than –5°C).

2) Depletion of SLC

Relatively few studies have been conducted on the precipitation processes active in Front Range winter storms. Boatman and Reinking (1984) investigated the precipitation processes active during anticyclonic upslope storms and found that diffusional growth was the dominant mechanism due to the low condensate supply rates in these types of storms. The diffusion process was relatively efficient at depleting liquid water, with some aggregation and riming. Wesley (1991) reported a predominance of heavily rimed and aggregated dendrites during several Front Range storms in 1988 and 1989. During WISP, a variety of precipitation processes were documented using the aircraft and other observing systems. These data will be used to investigate the dominant mode of SLW depletion in Front Range winter storms, especially in those storms producing significant amounts of SLW.

3) Production of large drops

The presence of large supercooled water droplets (50 to several hundred micrometers in diameter) in supercooled clouds can create extremely hazardous aircraft-icing conditions (Cooper et al. 1984; Sand 1985; Politovich 1989). These droplets can impact well away from the leading edge of the wing in areas typically unprotected by deice or anti-ice equipment. Such surfaces are particularly sensitive to small changes in surface roughness likely to occur during encounters with large droplets. Large increases in drag have been recorded from relatively small amounts of accreted ice on the wing's underside.

The afore-mentioned effects of large droplets are strongly enhanced in the presence of freezing rain or drizzle due to the combination of large droplet sizes and high liquid water contents. Freezing rain often results in clear-glaze ice accretions with significant runback icing, and is considered an extremely hazardous condition (Hansman 1989).

Although the effect of large droplet accretion on flight has been well documented, the conditions contributing to the formation of these regions are not yet completely understood. A recent study by Cooper (1989) suggested that regions near cloud top may produce conditions favorable to the production of large drops via an inhomogeneous mixing process. During WISP, a number of cases with large droplets were encountered; section 9c presents some preliminary analyses of these cases.

4. Facilities

To achieve the above objectives, an array of instruments was deployed as listed in Table 2. Figures 1 and 2 show the location of the facilities available for WISP field studies.

a. Research aircraft

The two research aircraft used during the field research were the University of Wyoming King Air and the University of North Dakota Citation II. Both aircraft are fully instrumented for cloud physics, thermodynamic, and air-motion measurements, and are certified for flight into known icing conditions.

For WISP90, the propeller spinners of the King Air were painted black and images of the accreted ice were recorded with a video camera. For several flights during WISP91 a continuous cloud condensation nuclei (CCN) counter was flown on this aircraft.

Research missions conducted in northeast Colorado were controlled and monitored from the WISP Operations Center (see section 4i). Flight levels ranged from minimum vectoring altitude to 25 000 ft (7 km) MSL. Vertical profiles of the atmosphere were obtained by flying approaches and missed approaches to local airports.

Although the effect of large droplet accretion on flight has been well documented, the conditions contributing to the formation of these regions are not yet completely understood.

Priority was given to regions of heavy snowfall and to areas of known or suspected SLW. Because of the possibility of extreme icing hazard, procedures were developed to minimize the risk to the aircraft and crew and yet allow the collection of important in situ data. For example, the aircraft coordinator had immediate access to weather reports for all possible alternate airports.

b. Radars

Two radars were used during WISP90, the NCAR CP-4 C-band radar and the S-band Mile High Radar (MHR). Two additional radars, the CSU/CHILL S-band radar and the UND C-band radar, were available during WISP91. The NCAR CP-2 radar participated on an as-available basis during WISP91, and was used primarily as a multiparameter radar providing differential reflectivity (ZDR) as well as linear depolarization (LDR) measurements in coordination with the CSU/CHILL radar, also a multiparameter radar. MHR was operated in conjunction with the Denver NWS. Radar locations are depicted in Figs. 1 and 2. These loca-

TABLE 2. WISP observing systems

System	Agency/system type	#	Measurements	Comments
Aircraft				
King Air	Univ. of Wyoming N2UW	1	Air motion, thermodynamics, microphysics	Vertical soundings, horizontal mapping
Citation	Univ. of North Dakota	1	Same as UW King Air	Same as UW King Air
Radars				
C-band Doppler	UND (1991)	1	Reflectivity, Doppler velocity	Located at S. Roggen
	NCAR CP-3 (1990)	1	Same as UND	Located at Marshall
	NCAR CP-4 (1991)	1	Same as UND	Same as CP-3
S/X-band Doppler	CSU-CHILL (1991)	1	Reflectivity, Doppler velocity, differential reflectivity (ZDR), linear depolarization ratio (LDR)	Located N of Greeley
	NCAR CP-2 (1991)	1	Same as CSU-CHILL	Located at Marshall
S-band Doppler	Mile-High Radar	1	Same as UND	Located NE of Denver
X-band Doppler	NOAA (1991)	1	Differential attenuation for measurement of cloud LW content	Located at Erie, radars "slaved" together
Surface				
PAM Mesonet	NCAR, PAMII (1990)	19	State param., peak wind, accum.	One collocated with Stapleton PROFS site
PAM Mesonet	NCAR, PAMII (1991)	49	Rainfall and snowfall	10 PAM concentrated at Platteville
PROFS Mesonet	NOAA, PROFS	22	State param., peak wind, accum. rainfall, solar insolation, visibility	Uneven spacing, 4 mountain sites

tions provided WISP91 with a large area of at least dual-Doppler coverage, and provided some flexibility in scan choices in that radars could be operated as independent pairs.

Theoretically, it is possible to utilize the differential attenuation between X-band and K-band radars to measure the SLW content of a cloud based on knowledge of the attenuation characteristics of these two wavelengths and the temperature in cloud.

A suite of scans was developed for WISP90 and WISP91, providing an efficient method to call out scans during operations. Scans were divided into low (extending up to 3 km AGL, 15 km from the radar), medium (6 km AGL), and high (9 km AGL) regimes to cover shallow upslope, developing deep upslope, and mature deep upslope storms, respectively. All scans were designed to maintain approximately 500-m vertical spacing at 60-km range. Using this technique, a high-resolution dual-Doppler dataset for a variety of winter storms has been acquired.

Theoretically, it is possible to utilize the differential attenuation between X-band and K-band radars to measure the SLW content of a cloud based on knowledge of the attenuation characteristics of these two wavelengths and the temperature in cloud (Martiner et al. 1991). A test was conducted during WISP91 by the NOAA WPL to verify the feasibility of such an approach. Two radars were slaved together electronically to scan within 0.1 degree of one another. A scanning radiometer was used to simultaneously scan the volume and verify total path-integrated SLW in the radar beams. Occasional aircraft measurements were also used to verify SLW. Preliminary results from this work are promising; the system worked well during the

TABLE 2 (continued). WISP observing systems

System	Agency/System Type	#	Measurements	Comments
Radiometers				
Dual-channel microwave	NOAA/WPL	3	Brightness temperature, integrated liquid water, integrated water vapor	20.6 and 31.65 GHz, located at Platteville, Stapleton, Elbert
Infrared	NOAA/WPL	2	Cloud-base temperature	Located at Stapleton and Elbert
Three-channel steerable	NOAA/WPL (1991)	1	Precipitable water vapor, integrated liquid water along steerable beam	Located at Roggen (1/13–2/13/91), at Erie (2/16–4/2/91)
Soundings				
CLASS System	NCAR Cross-chain LORAN	7	State parameters	Located at Berthoud, Platteville, Wiggins, Akron, Elbert, Flagler. One mobile system.
RASS	NOAA/WPL Radio Acoustic Sounding System	3	Temperature	Located at Platteville, Erie, Stapleton
NWS	NOAA, ART type	N/A	State parameters	Launches every 12 h. Denver and other NWS sites are available.
Wind profilers				
915 MHz	NOAA/WPL	1	Winds	Located at Stapleton
50 MHz	NOAA/AL	1	Winds	Located at Platteville
Satellite				
GOES	NOAA	1	Visible, infrared and water vapor	Geostationary
Other data sources				
Ceilometer	NWS	1	Cloud-base height	Located at Stapleton, lidar-based system
Volunteer snow observations	NOAA/NCAR/CSU	~100	Snowfall depth, rate, crystal type, liquid equivalent	Observers across WISP domain, greater coverage for 1991 season

experiment and sources of error appear to be isolated and correctable. Initial measurements in mixed clouds are producing realistic SLW content values; detailed comparisons with the remote and in situ liquid water measurements are in progress.

c. Radiometers

During WISP90 and WISP91, NOAA WPL operated three ground-based, vertically pointing microwave radiometers at Platteville, Denver, and Elbert. These had wavelengths of 20.6 and 31.65 GHz; the emission at 20.6 GHz is more sensitive to water vapor, whereas the emission at 31.65 GHz responds to liquid water. Precipitable (total path) water vapor and integrated liquid water are derived from the radiometer measurements every 2 min, using a simple retrieval algorithm (Hogg et al. 1983). The estimated absolute accuracy of these instruments in deriving integrated liquid water is 0.03 mm rms; the sensitivity to changes in liquid is 0.005 mm.

The WPL steerable radiometer was deployed during WISP91. Because the radiometer antenna is arranged to be steerable in elevation and azimuth, the system can provide data on the directional distribution of liquid and vapor surrounding the instrument. The steerable-beam system has an additional channel at

90.0 GHz, which is more sensitive to liquid water by a factor of 6 than is the 31.65-GHz channel, giving it a minimum detection limit of 0.03 mm.

d. Wind profilers and RASS

Wind-profiling radars at Platteville (50 MHz) and Denver (915 MHz) provided vertical profiles of horizontal wind velocity. Using the Radio Acoustic Sounding System (RASS) (Westwater and Kropfli 1989), the radars also measured profiles of virtual temperature with the same vertical resolution as the wind profiles. The upper altitude range of the RASS soundings varied from 3 to 5 km AGL for the Platteville system and 1 to 3 km AGL for the Denver system (May et al. 1988).

During storms, wind and RASS temperature profiles were available from the Denver radar every 20 min and from the Platteville radar every hour.

e. Ceilometers and IR radiometers

The new-generation NWS laser ceilometer obtained cloud-base height measurements that were made available in real time to WISP. The ceilometer was located at Denver near the microwave radiometer site.

In addition, at Denver and Elbert, zenith-viewing infrared radiometers were operated during WISP90 for cloud identification and during WISP91 for quantitative measurement of cloud-base temperature. An improvement in the calibration system (Shaw 1991) resulted in accurate cloud-base temperature measurements during 1991. This technique relies on the microwave radiometer to determine that the cloud contains liquid and thus radiates as an infrared blackbody.

f. Surface mesonets

During WISP90, 19 Portable Automated Mesonet (PAM II) weather stations were installed in northeast Colorado to augment the 22 PROFS (Program for Regional Observing and Forecasting Systems) surface stations already in place (Fig. 1). These stations extended from the Palmer Divide northward to the Cheyenne Ridge, and from the Continental Divide to a line 125 km east of Denver.

The PAM II stations reported averaged data every 5 min, including temperature, dewpoint, pressure, wind speed, wind direction, peak wind, and rainfall. Six of the sites were also equipped with R. M. Young snow gauges; 14 sites were additionally equipped with Rotronix humidity sensors. The PROFS stations provided 5-min averages of temperature, dewpoint, pressure, wind speed, wind direction, global sky radiation, and rainfall.

During WISP91, 20 additional PAM II stations were added to the domain to extend the station coverage to the tops of the Cheyenne Ridge and Palmer Divide, 40 km farther east and into the foothills (Fig. 2). Of these, four were placed on the south side of the Palmer Divide to document the effect of terrain on fronts and northerly flow events. Data were recorded every 1 min during WISP91.

Fig. 3. Photograph of a Mobile CLASS launch.

In addition, the DOE Atmospheric Radiation Measurement (ARM) test phase ran from 15 February through 15 March and added 10 more PAM II stations in a 15-km-square array centered on the Platteville CLASS site (see section 8).

Both seasons thus have very high resolution and often unique surface weather data to aid in the analyses of these winter events and to initialize and verify supporting modeling efforts.

g. Soundings

A network of four NCAR Cross-chain LORAN (Long-Range Aid to Navigation) Atmospheric Sounding System (CLASS) stations were deployed in northeastern Colorado during WISP90. Two fixed stations and a mobile CLASS van (Fig. 3) were added to the network during WISP91. Soundings were launched on a 3- or 6-h schedule once operations commenced for a given storm. Immediately after each balloon flight was terminated, the sounding data were relayed via modem to the RAP operations center, where the data could be immediately displayed on a skew-T diagram. Pressure, temperature, dewpoint, wind speed, and wind direction were available at 10-s intervals during the ascent.

Wind data were processed over a 1-min period to smooth navigational errors. Since the balloon ascent rates were 5 m s^{-1}, the vertical data resolution for thermodynamic data was 50 m, and for wind data, 300 m. During WISP91, the balloon ascent rate was reduced to 3 m s^{-1} to increase the vertical resolution of the wind data to 180 m.

Prior to the commencement of operations for a given day, a decision was made where to place the mobile CLASS to best supplement the fixed CLASS network. During operations, the mobile CLASS remained in contact with the operations center via radio or telephone and was repositioned as weather conditions changed. Data from the mobile CLASS were transmitted via packet radio when the unit was within radio range. As with the fixed sites, the mobile CLASS generally took soundings every 3 h.

h. Volunteer snow network

Three (two) networks of volunteer snowfall observers were established for the WISP91 (WISP90) field season. Approximately 100 observers recorded surface observations in the Boulder/Denver, Fort Collins/northern Colorado, and the eastern Plains (WISP91 only) portions of the WISP domain. These observations included snow accumulation, snowfall rate, liquid equivalent, crystal habit, degree of riming, aggregate formation and size, and wind speed and direction. Time resolution was variable and ranged from 1 to 6 h, with most observations recorded at 1- to 3-h intervals. Overall storm information was also collected, including total snow accumulation, liquid equivalent, snow start and end times, and additional information about rainfall, lightning, drifting, etc. These supplemental surface data provide critical information for the evaluation of each WISP event, especially in areas not close to PAM sites.

i. Operations center

Field operations were conducted from the RAP operations center in Boulder. The operations center was designed to gather and display information not only from the research instruments described above, but also from operational NWS facilities. The operations center also functioned as the communications center for WISP. Staff used weather data to make decisions on when and where to deploy research aircraft, plan radar scan strategies, and launch soundings.

The positions of the research aircraft were displayed with Mile-High Radar data, and weather conditions at airports in the WISP area were closely monitored. The aircraft coordinator had radio contact with the aircraft crew so that flights could be directed into regions of interest.

Forecasting and nowcasting were conducted from the Operations Center to enable forecasters to take advantage of the combination of research and operational data available in one location. An important component of the forecast exercise (see section 6) was to allow forecasters the opportunity to gain experience with newer technologies not yet deployed operationally, and to learn which observational platforms are critical in preparing accurate forecasts.

Prototype aviation winter weather products such as snowfall rate, icing severity index, and point snow forecasts were prepared at the operations center. These are described in section 7.

Several developments in data ingest and display capability were tested during WISP. One of these was a real-time dual Doppler analysis (Barron et al. 1991; Kessinger and Lee 1991) developed by RAP and the NCAR Atmospheric Technology Division (ATD). Data from Mile-High and CP-3 (or 4) radars were stored, converted to a Cartesian coordinate system, combined to form true horizontal wind fields, and displayed as wind vectors. The display allowed the user to select altitudes and scales to suit the weather feature being examined.

5. Numerical modeling

WISP has included a significant modeling component from the start. During the initial planning, model results were used to help design the appropriate field deployment and sampling strategy. For instance, the locations of the CLASS sounding sites were chosen based on model-determined upstream distances appropriate for model initiation. During the field efforts, modeling was performed in real time to aid in operations. After the field studies, the models will be used as a postanalysis tool for diagnoses of dynamic and microphysical processes in winter storms.

The PSU/NCAR Mesoscale Model, version 4 (MM4), is a hydrostatic primitive equation model that utilizes a terrain-following sigma coordinate system. This model was used during WISP91 to make real-time 36-h forecasts to aid in operational planning. The real-time version of the model was configured with an outer domain of 90-km horizontal resolution, and an inner domain of 30-km horizontal resolution. Prior to each operational period, two separate model runs were made, one using an MM4 initialization scheme, and another using a MAPS initialization scheme (see section 6).

The model was run on the NCAR Cray Y-MP using a special real-time queue, and the output was sent via high-speed link to a color workstation in the operations center, where it was used in conjunction with real-time weather information to make operational decisions. The output for each of the 25 model runs was saved and is being used to evaluate model performance.

Several numerical models will be used for postanalysis, including the Colorado State University

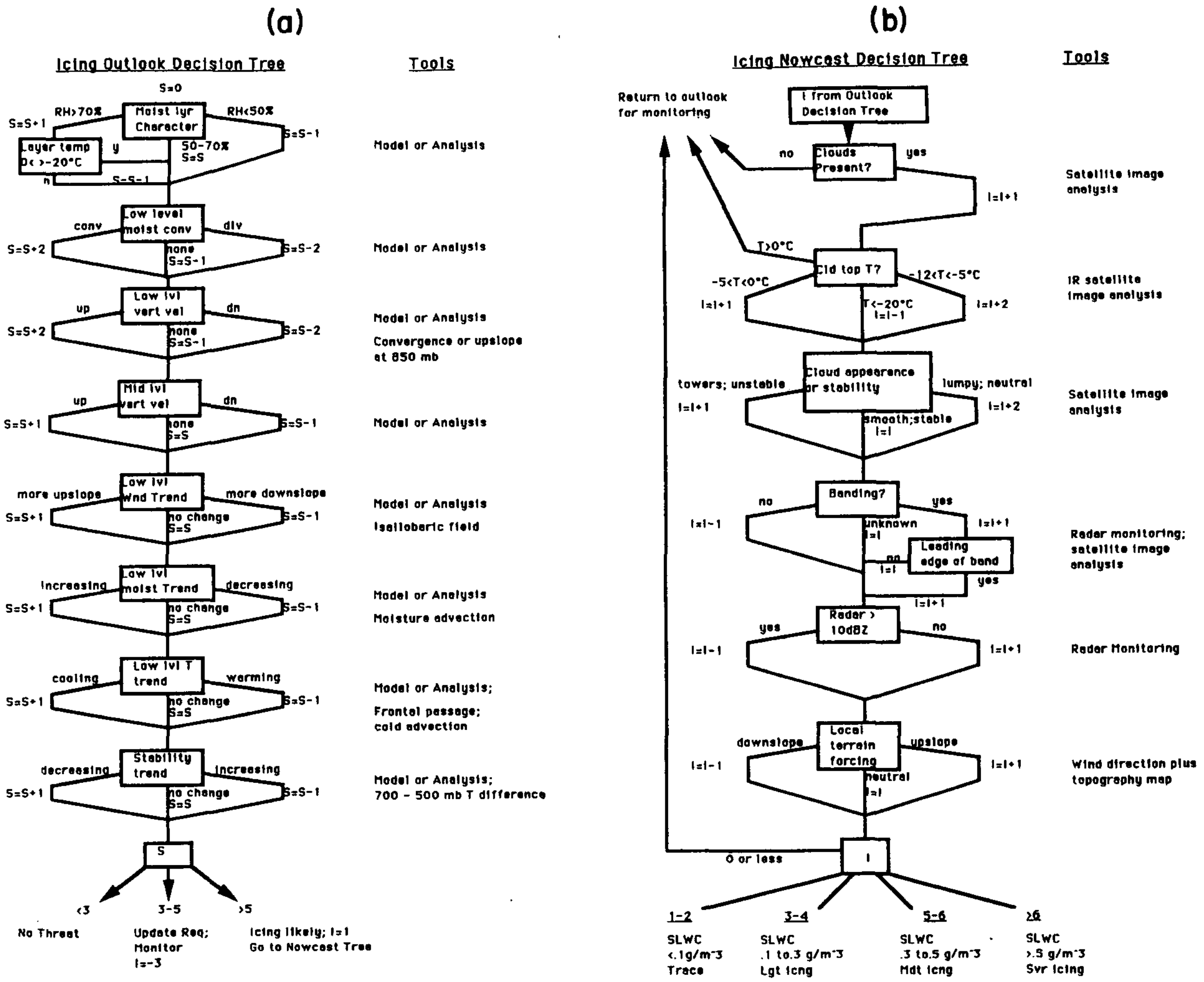


FIG. 4. (a) Icing outlook decision tree developed from experience during WISP project forecasting. The decision method is specific to the eastern plains of Colorado. (b) Nowcasting decision tree developed from experience during WISP project forecasting. The information required to answer decision tree (b) is taken from radar and satellite data imagery displayed on the DARE-II meteorological workstation.

RAMS model (Tripoli and Cotton 1982; Wesley 1991), the CSU kinematic model (Rutledge and Hobbs 1983, 1984), the NCAR Clark model (Clark 1977), the Nickerson model (Nickerson et al. 1986), the UND kinematic model (Burrows 1991), and the PSU/NCAR mesoscale model (Anthes et al. 1987). Some examples of the types of studies being done are given in section 9 of this paper.

6. Forecasting

Forecasting and nowcasting were necessary and important components of both WISP field studies. Although some details of the WISP90 and WISP91 exercises differed, their basic concepts were very similar. Two-day weather outlooks included 24- and 48-h forecasts of SLW and precipitation (both snow depth and liquid equivalent) and were issued daily. In general, the outlooks were probabilistic forecasts for specific categories of SLW and precipitation. The outlook area covered most of eastern Colorado but emphasized the location of intensive data collection as depicted in Figs. 1 and 2. Meteorologists at the NOAA Forecast Systems Laboratory (NOAA/FSL) issued these 24- and 48-h outlooks using the second-generation Denver AWIPS Risk Reduction and Requirements (DARE-II) meteorological workstation (Bullock and Walts 1991). The outlooks were used by project scientists for planning intensive observation periods (IOPs), by United Airlines to help plan their ground deicing fluid tests, and also were recorded for evaluation purposes.

The goals of the forecasting exercise were for meteorologists to gain experience using experimental data, advanced objective analysis techniques, and model output that were available in real time on the DARE-II workstation. Experimental data available on the workstation came from microwave radiometers, wind profilers, PROFS surface mesonet, Mile-High Radar, and RASS. Hourly surface objective analyses came from the Local Analysis and Prediction System (LAPS, McGinley 1989) and the Mesoscale Analysis and Prediction System (MAPS, Benjamin 1989). Upper-air analyses are available every hour from LAPS and every 3 h from MAPS. MAPS also provides isentropic model forecasts at 3-h frequency (Benjamin et al. 1991). Although these tools were used extensively when preparing the outlooks, they are perhaps most useful for preparing the 3-h nowcasts. Post-analysis studies will examine in more detail the value of these data for use in short-term forecasting of conditions associated with aircraft icing and in decision-tree methodologies. Feedback on the use of the experimental as well as conventional data for forecasting SLW is an important WISP-applied research item and is in progress.

One of the unique features of WISP is its direct interaction with the operational aviation weather community. The FAA, NWS, and private agencies have cooperated during both the planning and field portions of the project.

The 3-h nowcasts for SLW and precipitation were prepared when specific 24-h outlook criteria were satisfied (Smart 1990). The exercise was designed so that nowcasts were prepared during storm events and, therefore, were used by the operations directors for specific guidance in coordinating data collection. In addition, 1-h nowcasts of SLW and precipitation were issued for the Denver Stapleton Airport. Details of this component of WISP are further described in the following section. Similar to the outlooks, the nowcasts were recorded during the project and are currently being evaluated using in situ (research aircraft), remote (radiometer and radar), and ground truth (surface weather observations and the volunteer observers) measurements. The evaluation will provide feedback on which measurements, analyses, and model output are needed when forecasting SLW on short time and space scales.

Based on studies to date evaluating forecaster experience, an icing-outlook decision tree has been derived (Fig. 4a). The outlook decision tree can be used both as a diagnostic and prognostic tool depending on whether analyses or model forecasts are used to determine the final score (S). For example, if the method is used diagnostically, information is obtained from hourly and model initial analyses of those quantities. On the other hand, when this decision method is used as a prognostic tool, it requires information from model forecasts. A forecaster can cycle through the decision tree several times to examine different model forecasts. The technology available on the DARE-II meteorological workstation allowed forecasters to readily apply these techniques.

Experience using mesoscale data during the nowcasting portion of the exercise is being summarized in a nowcast decision tree suitable for short-term forecasting of icing (Fig. 4b). The information required for this decision tree is obtained from subjective analysis of satellite and radar imagery, and quantities are either extracted directly or the required information is obtained through subjective interpretation. Both the outlook and nowcast decision tree will be tested during winter 1992.

7. Applied aspects of WISP

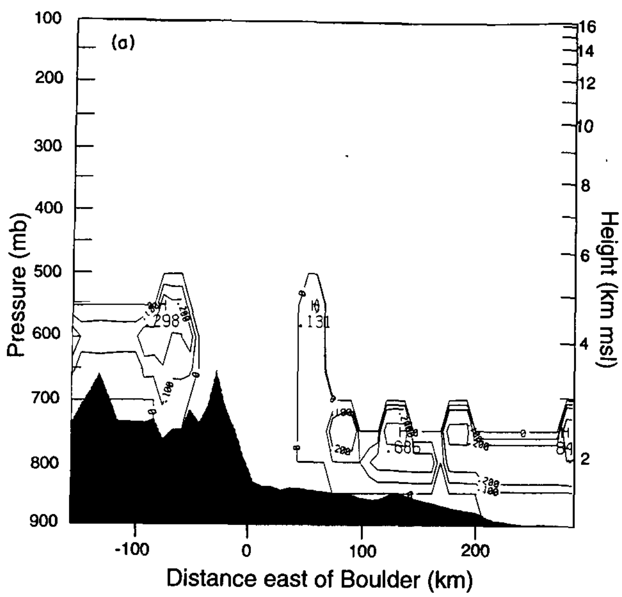
One of the unique features of WISP is its direct interaction with the operational aviation weather community. The FAA, NWS, and private agencies have cooperated during both the planning and field portions of the project.

As mentioned above, the FAA Icing Forecast Improvement Program forms the core of WISP. This program has the following goals:

- to improve icing forecasts on the national, regional, and local scale;
- to develop and test an improved icing severity index based upon meteorology; and
- to develop methods for aiding in ground deicing operations.

NAWAU, located in Kansas City, Missouri, currently issues icing forecasts for the entire continental United States four times daily for time periods of up to 6 h. (See Politovich and Olson 1991 for an analysis of these forecasts.) Since this office will be the eventual recipient of national icing forecast product improvements, WISP is currently working with NAWAU on automating techniques currently used in their icing forecasting, and in developing improvements on these methods based upon research results.

During WISP91, an icing hazard forecast was developed using NGM gridded temperature and humid-



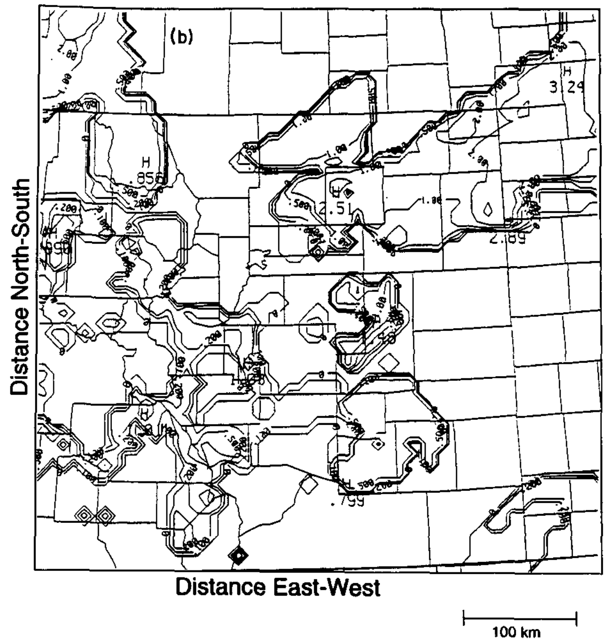


FIG. 5. LAPS model-calculated liquid water content from 6 March 1990: (a) East–west vertical cross section through Boulder at 2300 UTC. Contour interval is 0.1 g m^{-3}. (b) Vertically integrated cloud water in mm at 0100 UTC.

ity data. This product was made available on a DARE workstation, with forecasts from 6 to 36 h at standard pressure levels. Although only modest improvement in forecasting skill over the NAWAU methodology has been demonstrated (Schultz and Politovich 1991), the data links and displays are being established for further development. The NGM Eta model, which should be available in the mid-1990s, will include an explicit cloud liquid water field, which should improve forecast accuracy.

For regional- and local-scale icing diagnoses and forecasting, WISP has been using LAPS, under development by NOAA FSL. LAPS is a data-assimilation and display system that works on a 10-km x 10-km x 50-mb grid, and currently covers most of Colorado (see Fig. 5). Data inputs consist of all measurements currently operationally available, or those being considered for deployment by the NWS. A description of LAPS is contained in McGinley and Albers (1991). A typical cloud water field from LAPS is shown in Fig. 5.

For winter 1992, the LAPS grid will be expanded east and south to include much of the central United States. Much of this domain does not enjoy the data density available in the Colorado Front Range. During winter 1992, a "value-added" experiment is planned for LAPS to evaluate the differences in LAPS performance attributed to the additional data input. At present, LAPS runs only in an hourly, diagnostic mode. Future plans include either a forecast version of the system, or use of LAPS-derived fields to initialize mesoscale models.

For icing forecasts on the regional scale, the MM4 model was tested during WISP91, as described in section 5. The current version of MM4 uses warm-cloud microphysics and does not include an explicit icing forecast; modifications to this model are planned to support winter weather forecasts.

An improved icing severity index is being developed (Politovich and Sand 1991) to replace the current scheme of "trace–light–moderate–severe." Icing severity levels as reported by pilots are based upon the pilot's assessment of how well his or her aircraft can deal with the ice accreting on the airframe. Severity is therefore somewhat subjective, as it depends not only on the aircraft type, but also on the pilot's experience in icing conditions. The more serious problem, however, is that the current index has little basis in meteorology—forecasters thus have little basis for including icing severity in their forecasts.

During WISP91, a preliminary version of this improved icing severity index (ISI) was calculated within LAPS and presented on a display terminal. The display was sent to the Denver Central Weather Service Unit, Air Traffic Control (TRACON), the Flight Service Station Flight Watch Position, and to United Air lines. The users were able to view ISI on selectable flight levels within a 50-km radius of Denver's Stapleton Airport, or view vertical cross sections along the four arrival gates. An example of this ISI product is shown in Fig. 6. The main reason for releasing these products, even though they were considered preliminary versions, was to gain user response to aid in further display development. RAP has found that the means by which weather hazard products are presented are a major factor in their interpretation and use; thus, this work is considered a vital part of the total research package.

User reaction to these products was quite favorable; in future years RAP will be expanding the area displayed as well as allowing more user flexibility in selecting display formats. Verification work is also being conducted to determine the accuracy to which LAPS is diagnosing ISI, and to better define the ISI levels by relating them to the amount of ice accreting on the research aircraft and to the resulting performance loss.

The ground deice problem is essentially one of forecasting snowfall for the short term—for example, several hours or less. Amounts and types of anti- and deicing fluids to be applied to exposed parts of the airframe depend upon temperature, snow crystal type, and snowfall intensity. Thus, if a short-term forecast of these variables could be made accurately, it would greatly increase the efficiency of ground deicing operations.

During WISP91, the program collaborated with United Airlines staff at Stapleton Airport to develop forecast methods and displays for 1-h snow nowcasts, or "snowcasts." Snow amount, type, temperature, liquid equivalent, and winds were forecast hourly during storm events. These are currently being analyzed for accuracy as well as for format and presentation.

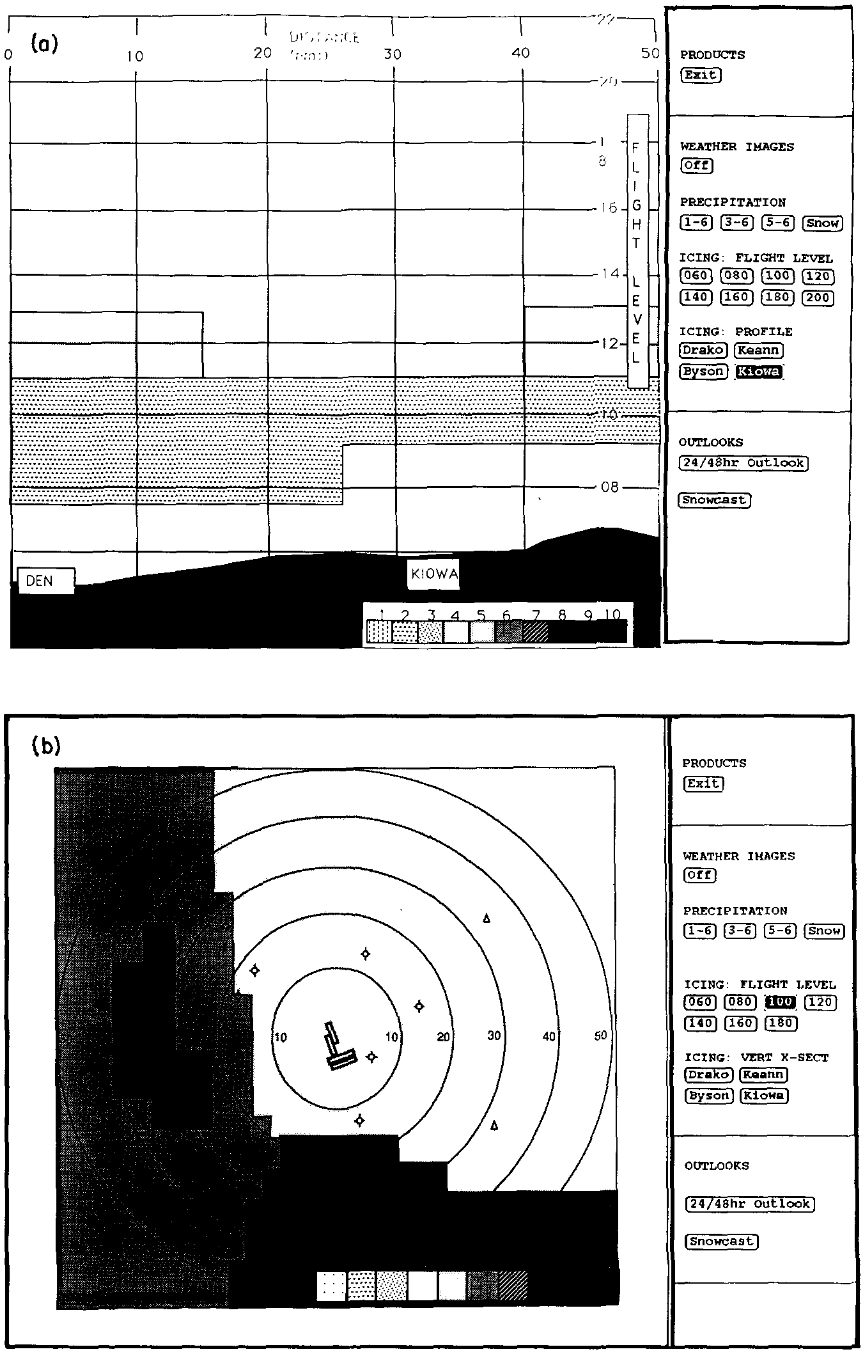


FIG. 6. Example of Icing Severity Index (ISI) product displayed on the GSD during WISP91. (a) Vertical cross section of ISI through the Kiowa arrival gate into Stapleton Airport. ISI is indicated by the shaded regions. (b) ISI at 10 000 ft MSL for a 50-n mi radius around Stapleton Airport in Denver. ISI shading scale is located on the lower right of both panels. Mouse-driven menu is on the right of each display.

8. Collaborative studies

WISP collaborated with several research projects also operating in the Colorado Front Range.

During WISP90 and WISP91, the University of North Dakota participated in the WISP program as part of their ongoing FAA-supported research on the use of NEXRAD-type radars to detect aircraft icing. During WISP90, they provided their Citation II aircraft and crew for research flights, and during WISP91 they

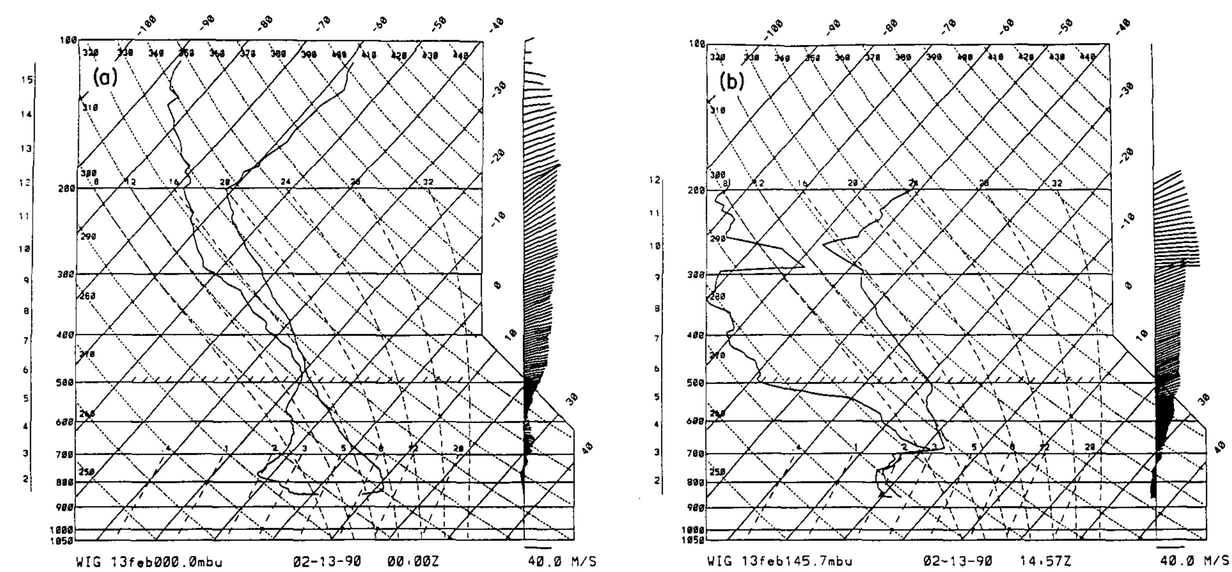


FIG. 7. CLASS sounding taken at Wiggins at (a) 0000 UTC 13 February 1990 (before the cold front) and (b) 1500 UTC 13 February 1990 (after the cold-front passage).

contributed both the aircraft and a 5-cm Doppler radar, as well as supporting personnel. The 5-cm radar (see Fig. 2) served as a dual-Doppler pair for both CHILL and MHR radars.

Another important collaboration during WISP91 involved the DOE's Atmospheric Radiation Measurement (ARM) test phase. Scientists from the Surface Sounding System Facility at NCAR and the Wave Propagation Laboratory at NOAA were the primary participants. During the main period of the test (15 February–15 March 1991), data were collected by a variety of instruments at a number of sites within the WISP domain in order to evaluate their performance as potential components of the ARM Cloud and Radiation Test-bed (CART). At Platteville, three wind profilers were operated (frequencies of 50, 405, and 915 MHz). In addition, CLASS soundings were taken every 90 min during both WISP and ARM IOPs. Ten PAM stations were placed in the vicinity, as well as an atmosphere-surface turbulent-exchange research facility (ASTER) to measure the surface turbulent fluxes. Humidity profilers were also measured at the Platteville site using a High-resolution Interferometer Sounder (HIS) from the University of Wisconsin. At Stapleton and Roggen, wind and temperature were measured with a 915-MHz wind profiler with RASS. Atmospheric radiation was also measured at that site using baseline station pyranometers, pyrgeometers, and a pyrheliometer.

WISP also collaborated with ASCOT91, a project conducted between 28 January and 8 February 1991 in the vicinity of the Rocky Flats nuclear plant (between Denver and Boulder). The main goal of ASCOT91 was to study the effects of local nocturnal flows generated in the canyons and off the slopes of the Front Range on the transport and dispersion fields around Rocky Flats. Data were collected from a variety of instruments, including a network of towers and minisodars, hourly tethersonde flights, two-hourly rawinsondes, Doppler lidar scans of the Rocky Flats area, and occasional tetroon releases.

The various datasets described above are available to scientific investigators participating in WISP.

9. Research highlights

The following provides highlights of ongoing research using WISP90 and WISP91 data.

a. Anticyclonic upslope storms

The Valentine's Day storm, a three-day event during WISP90, was characterized by the invasion of a polar air mass, overrun by southwesterly to southerly flow aloft (Rasmussen et al. 1991; Stankov et al. 1991). CLASS soundings taken before and after the cold-front passage (Fig. 7) show the characteristic shallow depth of these arctic air masses. Most of the Front Range area initially experienced freezing drizzle, followed by light snow after the passage of a secondary shallow cold surge. Ice crystal concentrations measured from the research aircraft were generally low (less than 5 l^{-1}). Vertically integrated SLW as measured by the three radiometers persisted at levels above 0.1 mm for nearly 30 h after initial cloud formation, reflecting relatively inefficient ice crystal production processes. Radar reflectivities were also low (≤15 dBZ) during this initial 30-h period. Locally heavy snowfall, however, was observed in the northwestern portion of the WISP domain during this time.

This enhanced snowfall coincides with periods during which the inversion near cloud top was lifted, as shown in the time series from the Loveland CLASS site (Fig. 8), located 15 km east of the foothills. This agrees with the conclusions of the analysis of the 1–5 February 1989 storm (Wesley et al. 1990), where overrunning was maximized during intensification of upslope flow within the cold air and subsequent "piling up" of cold air over and near the foothills. As expected for both cases, significant surface-pressure rises coincided with snowfall enhancement. Snow crystal observations (refer to section 4h) provide additional data. Predominantly dendritic habits characterized a significant majority of snow reaching the ground in the northern WISP area. Aside from a very shallow layer near the ground, temperatures favoring dendritic growth were confined to altitudes above the capping inversion after 0000 UTC 14 February. Snow of this habit could have originated from a midlevel stratus cloud located over this region, or from enhanced lifting as the upper-level air is lifted over the cold pool. Modeling studies will be conducted to further clarify this issue.

During WISP, a number of anticyclonic upslope storms occurred that exhibited features similar to that described above for the Valentine's Day storm. This case represents a long-lived event, providing an excellent opportunity for detailed studies into the physical processes involved in the production and depletion of SLW in this type of storms. The most hazardous icing environments in anticyclones appear to be early in the storm episode, when clouds are shallow, relatively warm, and are not precipitating heavily. There may be additional times favoring icing later in the storm, associated with additional frontal surges (Politovich 1991).

b. Heavy snowfall

Heavy snowfall of 1- to 2-m depth fell along the Front Range from Cheyenne, Wyoming, to Denver during the deep, cyclonic storm of 6–7 March 1990. Major highways across the Laramie Range were closed for up to a week and a major electrical transmission line along the Colorado/Wyoming border was felled by icing from this storm. The airflow on 6 March was from the south through east at all levels and either warm air or neutral advection was present at all levels. Precipitation began as rain with embedded convection and lightning at around 0000 UTC on the 6th, and quickly changed to snow along a frontal boundary. The frontal boundary developed along the foothills from Ft. Collins, Colorado (FCL), to Denver (DEN). The south end of the boundary moved about 50 km east of DEN at about 3 m s^{-1} while the north end remained near FCL. No cold-air advection was present on 6 March north and east of the front. The frontal boundary and the onset of heavy rain were coincident. Following the onset of rain, the surface temperature decreased to near 0°C and the winds became calm. A strong barrier jet developed from the north over I-25 behind the frontal boundary. Since there was no cold-air advection present, the cold air must have developed through the diabatic processes of melting and evaporation. The evidence that diabatic processes were the primary forcing functions for the development of the frontal boundary and barrier jet is compelling in this case.

c. Large droplets

The hazard posed by SLW droplets with diameters greater than ~50 μm is described in section 3b. Large droplets were encountered on seven research flights during WISP. Most of the encounters took place near the tops of stratiform clouds.

The encounters had several features in common, the most persistent of which was the presence of strong wind shear, either in direction or speed, near the cloud top. Potential temperature increased strongly through the shear layers, which ranged in depth from 22 to 400 m. Diameters of the large droplets varied substantially in the regions, from sizes detectable by an FSSP (≤45 μm), to recognizable circular images from a 2D shadowing probe (≥100 μm). Most cloud-top temperatures were above −10°C, although temperatures down to −16°C were measured.

Figure 9 shows measurements from the Wyoming King Air obtained during vertical soundings through two clouds sampled during WISP90. In one of the clouds sampled, 13 February, a significant number of cloud droplets larger than 25 μm were encountered.

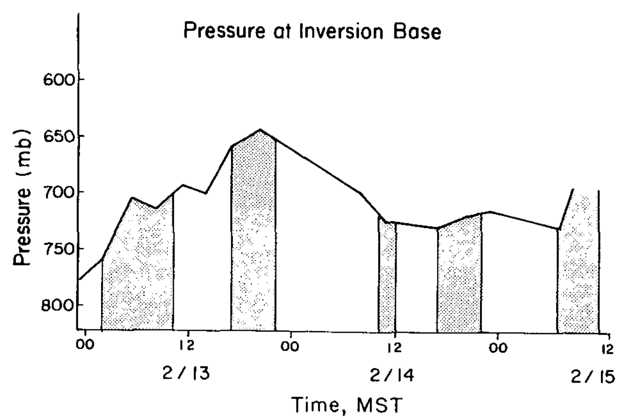


FIG. 8. Time series of the pressure at the base of the inversion from Loveland CLASS. Shaded regions represent periods of enhanced snowfall.

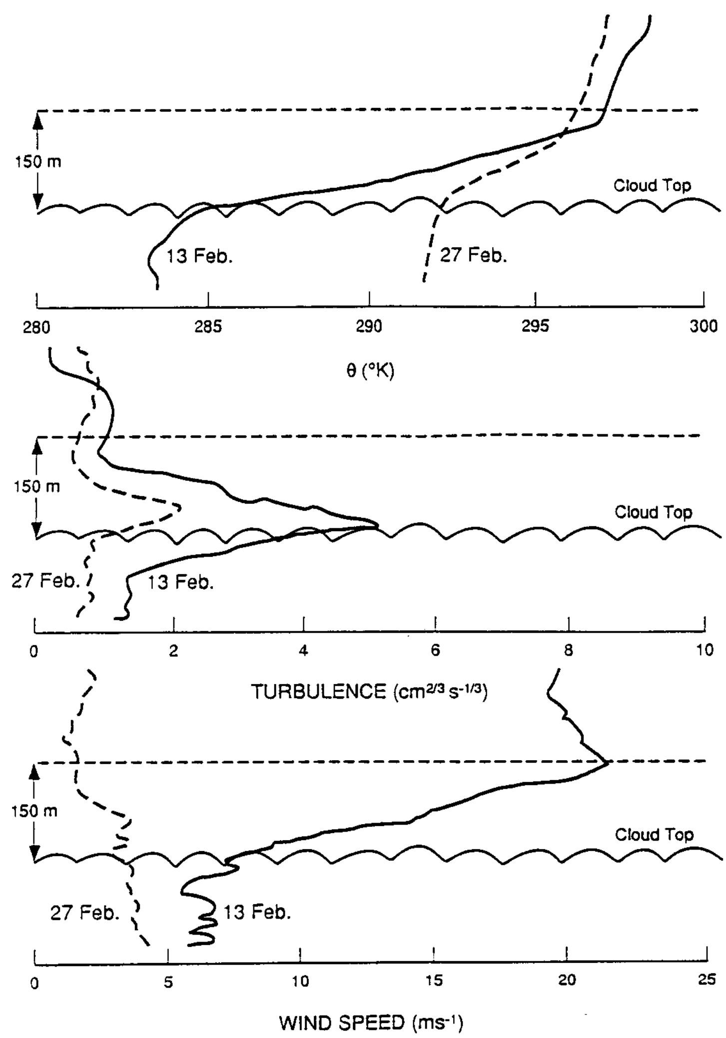


FIG. 9. Data obtained from the University of Wyoming King Air through the tops of two clouds sampled 13 and 27 February 1991. Potential temperature, turbulence, and wind speed are shown. The shear layers just above cloud top are between the dotted lines.

On 27 February, the aircraft measured high SLW, but only a few droplets of greater than 25-μm diameter. Figure 10 illustrates the differences in ice accretion resulting from these conditions.

A stably stratified shear layer was present at the top of the 13 February cloud. The layer was 150 m in depth, was delineated by a sharp increase in wind speed and potential temperature, and had a gradient Richardson number (Ri) of 0.17. By comparison, the 27 February cloud had a distinct stable layer of ~150 m but no shear layer. Ri for 27 February was 2.1. Pobanz (1991) examined these and 27 other cloud-top regions; in 24 of the cases, wind shear and large droplets were present together.

Stankov et al. (1991) discuss the application of microwave radiometers, wind profilers, and RASS to detect shear layers. An analysis of remotely sensed data for the 13 February case indicates a gradient Richardson number below 2.5 at the top of the cloud, while for 27 February the gradient Richardson number was less than 5.0. Due to the relatively coarse vertical resolution of the wind profilers and RASS, the threshold gradient Richardson number is significantly larger than the number calculated from the aircraft data for these cases.

The 150–300-m resolution of the wind profilers and RASS, along with their height ranges of 0.3–6 km AGL, may not resolve all cases. However, the use of these instruments, in concert with microwave radiometers for determining the presence of SLW, could be developed as a powerful tool for the detection of such conditions.

Research continues both in delineating conditions leading to the formation of large supercooled droplets and in their remote detection.

d. Shallow cold fronts

On 19 January 1991, a cold front moved through Colorado during the midmorning and afternoon. The cold-air surge behind the front caused temperatures to drop by more than 10°C over the eastern plains of Colorado between 1800 and 2400 UTC on the 19th. The depth of the cold air was ~3.5 km MSL. A surface low pressure center developed in the southeast corner of the state at 0800 UTC on the 20th and moved southeast during the next 12 h. Aloft, a shortwave trough and vorticity maximum crossed the state from northwest to southeast between 0000 and 1200 UTC, 20 January. This combination of synoptic features led to northeasterly, upslope surface winds over the WISP91 research area. Snow began falling around 1800 UTC and lasted for approximately 18 h, leaving snow depths ranging between 2.5 to over 12 cm and liquid equivalents of 0.1 to over 0.7 cm by 1200 UTC.

Figure 11 shows low-level PPI (Plan Position Indicator) plots of reflectivity and Doppler velocity fields observed by the Mile-High Radar. Well-defined precipitation bands, indicated by reflectivities up to 32 dBZ, were present to the south of the radar. Echo tops were ~6.8 km MSL. Two weaker and less organized bands were situated to the northwest. Periodic changes in the reflectivity along the axes of the major bands located west and southwest of the radar suggest the existence of small-scale transverse waves in that

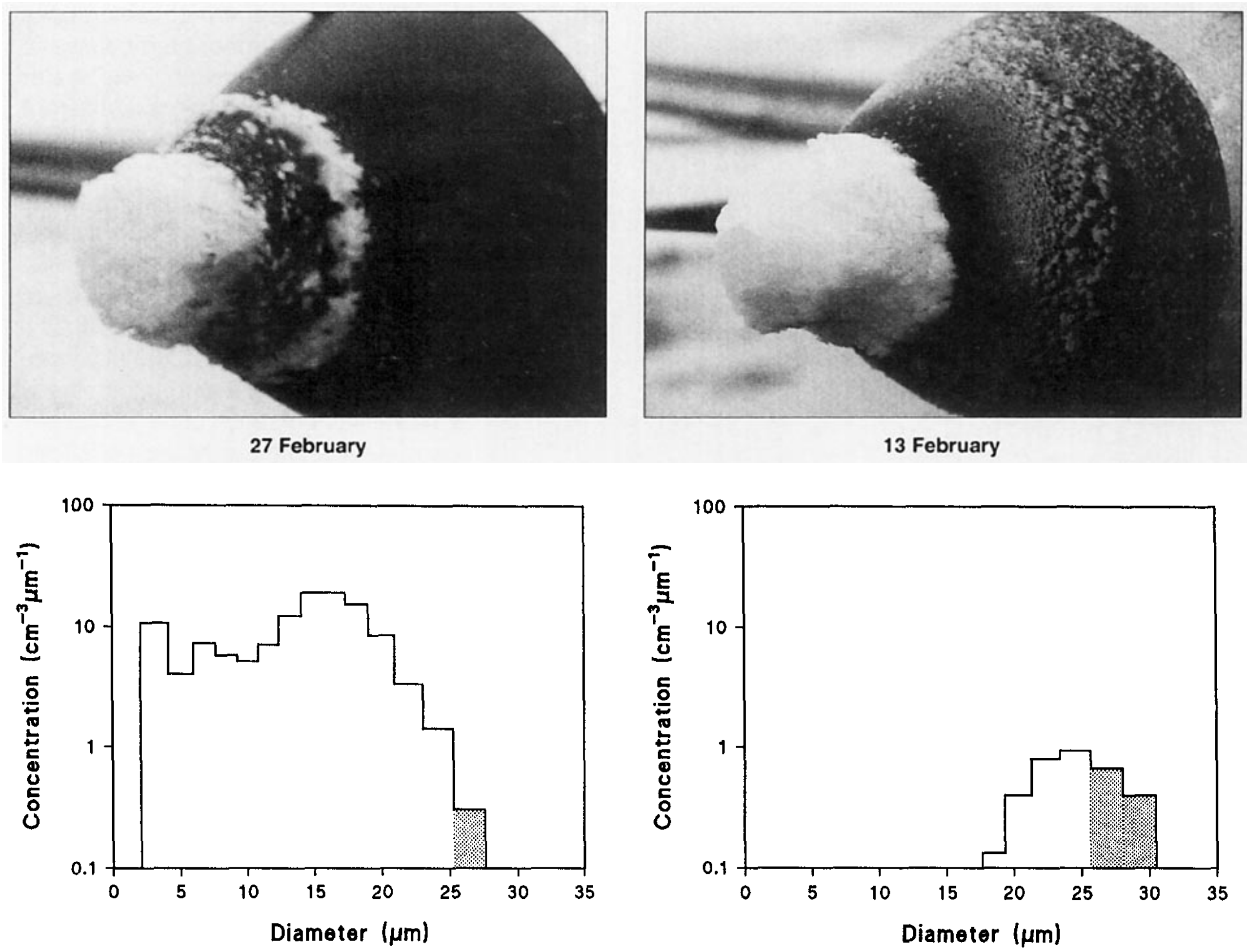


FIG. 10. The photographs and graphs illustrate the effect the size distribution of supercooled water droplets has on the accretion of ice on aircraft. The starboard propellor spinner of the University of Wyoming King Air is shown for two days during WISP, 13 February (upper right panel) and 27 February (upper left panel) 1990, along with representative droplet size distributions measured from a Forward Scattering Spectrometer Probe. The icing for the 13 February case extends farther back on the prop spinner's surface than for 27 February; this represents a more serious icing condition. For 27 February, the aircraft spent 32 min in cloud with an average liquid water content (measured from a King liquid water probe) of 0.29 g m^{-3}; on 13 February, the aircraft spent 51 min in cloud with an average 0.14 g m^{-3} liquid water content.

region. The Doppler velocity (Fig. 11b) shows strong low-level northeasterly upslope winds in excess of 12 m s^{-1} near the surface. Winds backed with height to become west-southwesterly with velocities greater than 24 m s^{-1} as indicated by the blue and red tints near the edge of the radar coverage. Radar scans at higher elevations and CLASS soundings showed winds greater than 40 m s^{-1} aloft, with the strongest winds over the southern portions of the radar coverage. The long axis of the precipitation bands were oriented parallel to this upper-level flow. High reflectivities and zero Doppler velocities in the region beyond 50 km and between the 215° and 325° radials are associated with the Rocky Mountain Front Range clutter pattern.

Shallow cold-frontal passages such as this were fairly common during WISP, and usually resulted in the formation of precipitation and SLW at various stages. Case studies are currently under way in order to determine the role such cold fronts play in the production of SLW. One of the areas to be emphasized is the interaction of shallow fronts with local topographic features such as the Palmer Divide (Fig. 1).

e. Ice crystal formation and evolution

During the Valentine's Day storm (13–15 February 1990) (Rasmussen et al. 1991), a well-defined shallow upslope cloud developed that was sampled by the University of Wyoming aircraft. Missed approaches were made to Greeley Airport (located in the northern portion of the domain) and to Centennial Airport (in the southern portion of the domain). Both missed approaches had significant SLW near cloud top (up to 0.2 g m^{-3} at Greeley and 0.35 g m^{-3} at Centennial) and a relatively warm cloud-top temperature (–16°C at Greeley and –12°C at Centennial). The particle types in the two soundings, however, were completely differ-

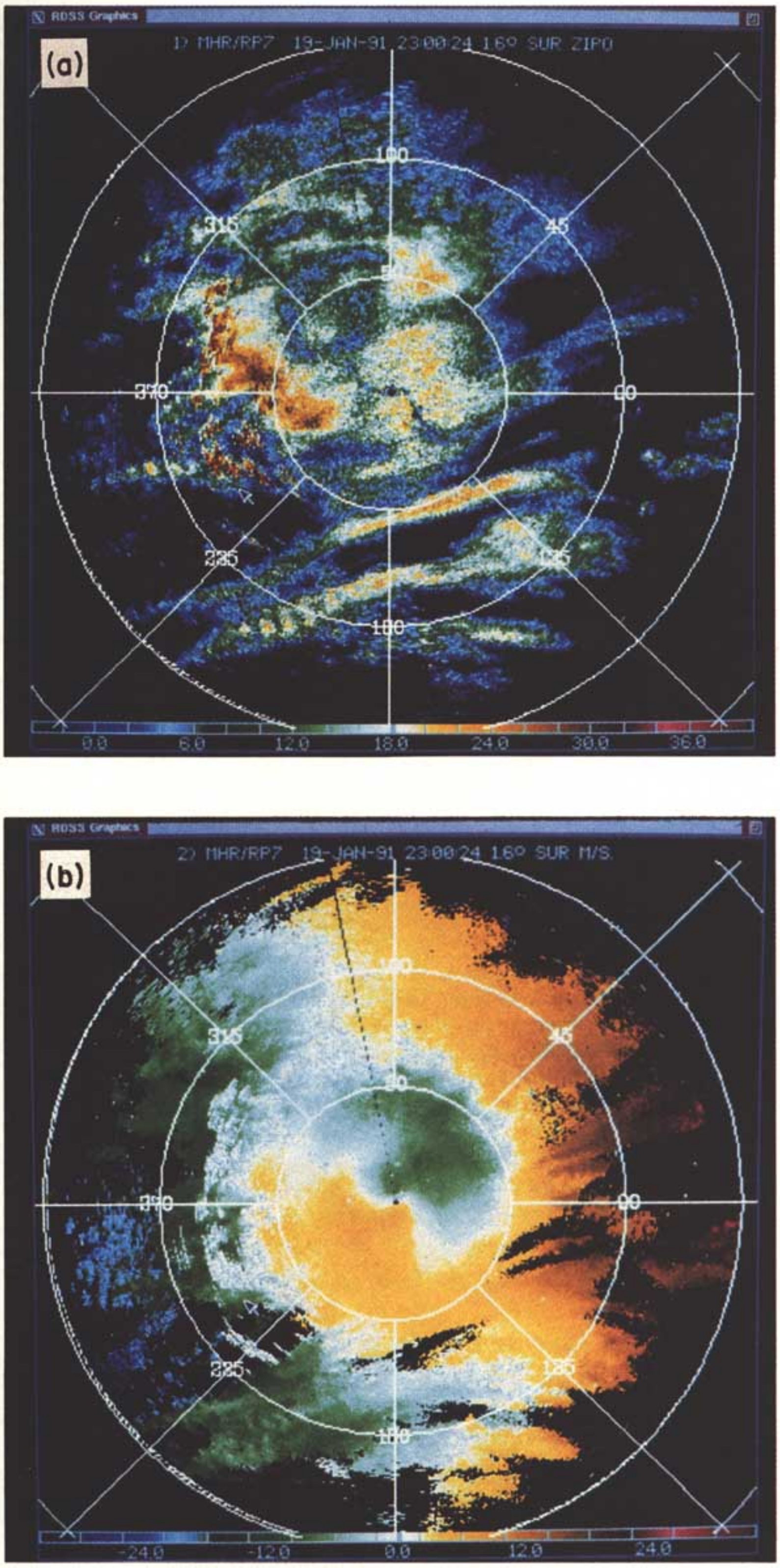


FIG. 11. PPI radar data at 1.6° elevation angle from the Mile-High Radar on 19 January 1991 2300 UTC. (a) Reflectivity (color scale, in dB*Z*, is indicated by the color bar along the bottom of the figure). Range rings are at 50-km intervals. (b) Doppler velocity (velocity color scale, in m s^{-1}, is indicated by the color bar along the bottom of the figure). Positive and negative values indicate motion away from and toward the radar, respectively.

ent. Near Greeley, low concentrations of pristine dendrites existed below the upper-level supercooled liquid water layer. Aggregates of these crystals were found at lower levels of the cloud. At Centennial Airport, water drops of diameter 100–200 μm were observed. No ice crystals were detected by any of the particle probes, nor on an oil slide that was taken during the latter missed approach. These data suggest that a relatively inefficient ice crystal formation process was occurring in these clouds. The presence of large drops is consistent with the presence of strong wind shear near cloud top, as discussed in section 9c. Studies such as these will help to clarify the process of ice formation in winter clouds under conditions that are relatively simple and well defined.

f. Numerical model performance

During the two years of WISP field-data collection, a persistent problem encountered in formulating local nowcasts and forecasts was frequent mediocre and occasionally poor performance of NMC-based models such as the nested-grid model (NGM). An excellent example is the 29–30 March 1991 event, where significant snowfall was predicted by both the NGM and limited fine-mesh (LFM) models associated with an amplifying short wave approaching from the northwest.

Specifically, in the NGM 24-h forecast valid at 0000 UTC 30 March 1991 (Fig. 12a), serious errors occurred in both the placement and strength of the 700-mb low center. The prediction of this low was several hundred kilometers too far north, and approximately 4 dm too deep compared to the analysis (Fig. 12b). Instead of upslope flow extending from the surface to above 700 mb over the Front Range, only northerly flow was observed. The moisture predicted by the model, averaged over the 1000–500-mb layer, was also in serious error at 24 h of simulation. Predicted relative humidities in this layer of 70% to 95% over the area of interest were not observed; only 50% to 75% occurred. In this case, poor model guidance led to an overall false alarm in WISP operations. As part of an effort to analyze the causes of such errors in NMC guidance, researchers at CSU are utilizing RAMS to evaluate the 29–30 March 1991 case. The approach is to run RAMS initially with a similar grid setup as the NGM in order to evaluate the capability of RAMS with a fairly coarse resolution. Subsequently, a fully nested, microphysical simulation will be carried out to help identify the deficiencies in the first experiment, as well as in the NGM.

A well-known shortcoming of the NGM is its inability to accurately predict the evolution of low-level arctic air masses over the High Plains (Junker et al. 1989). This problem was glaringly apparent during the two WISP years of operation and needs to be thoroughly analyzed from a numerical modeling standpoint. Again, the CSU-RAMS model serves as an efficient tool to investigate such pertinent questions as appropriate horizontal and vertical resolution, horizontal and vertical diffusion schemes, surface roughness, radiative effects, etc. A directly related phenomenon, the correlation between inversion height and snowfall intensity during cold outbreaks (see Wesley et al. 1990), is also of primary emphasis in this study.

The 13–15 February 1990 event, along with several other weaker cold intrusions in WISP, will form the database for these numerical experiments. Efforts are also under way to evaluate the performance of the MM4 real-time simulations using the NMC gridded analysis.

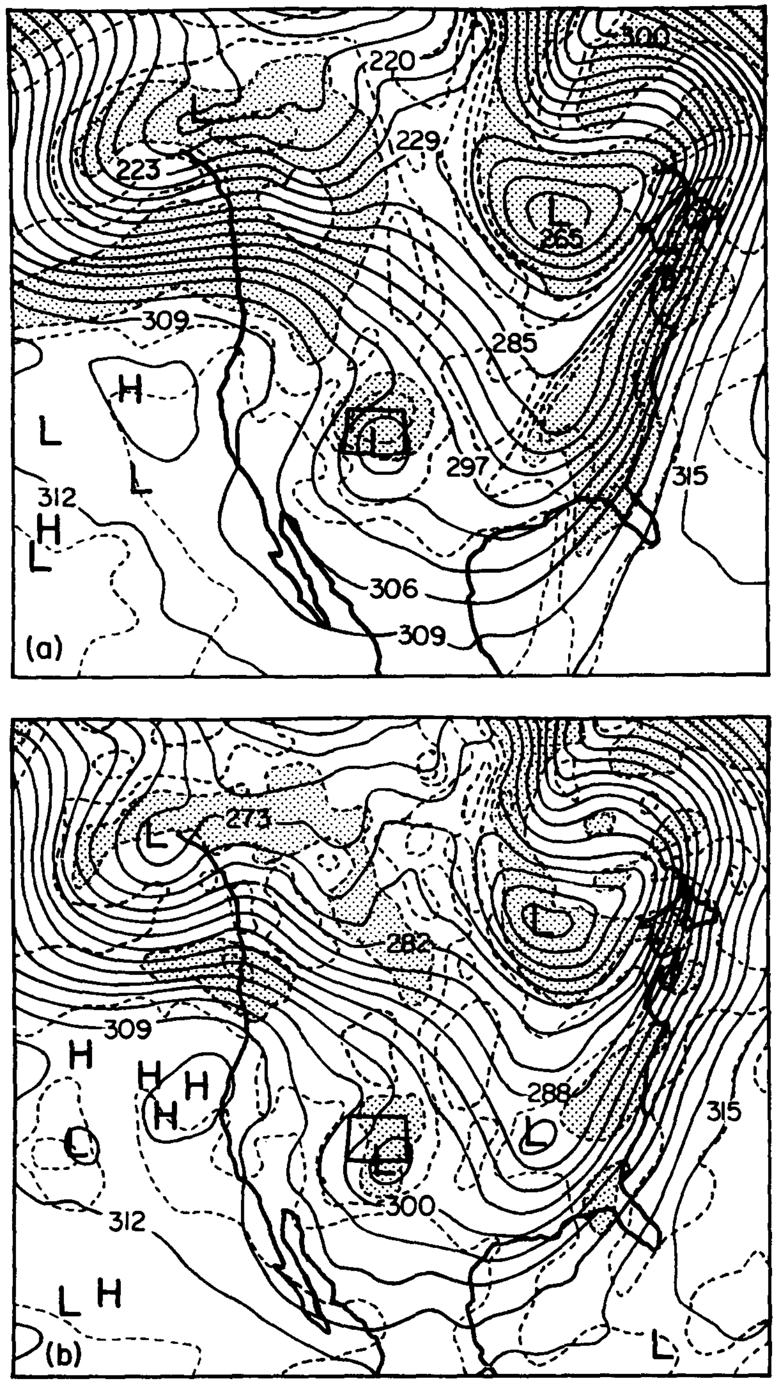


Fig. 12. (a) 700-mb, 24-h NGM forecast valid 0000 UTC 30 March 1991. (b) 700-mb NGM analysis at 0000 UTC 30 March 1991. The dotted lines in both panels indicate contours of relative humidity averaged through the 1000–500-mb layer. Values above 70% are shaded, and the contour interval is 20%.

10. Data availability

Datasets collected during both WISP90 and WISP91 are available to the scientific community. Much of the data is stored on the NCAR Cray Mass Storage System. Inquiries should be directed to Ben Bernstein, WISP Data Manager, RAP, NCAR, P.O. Box 3000, Boulder, CO 80307. Data catalogs for both field seasons are available from the above address. Reimbursement for costs of duplicating and/or processing data may be necessary.

11. Summary

In recognition of the benefits to be gained by both the operational and research communities, the FAA Icing Forecast Improvement Program was expanded to include a substantial research component directed toward the study of dynamical and microphysical processes at work in winter storms. This expanded program, called WISP, has brought increased scientific expertise, a broadening of objectives, and the prospect that both the facilities and datasets will be used in a more comprehensive and efficient manner. The unifying emphasis on the formation and depletion of supercooled water by both the operational and research communities has provided a clear focus for the project that benefits both communities and fosters the desired interaction between them.

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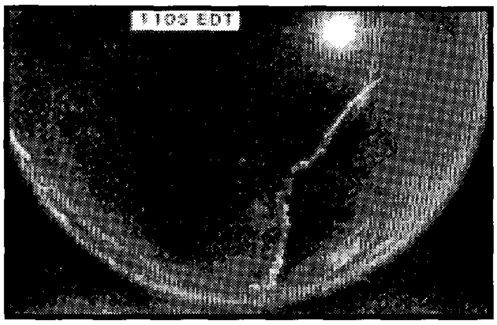

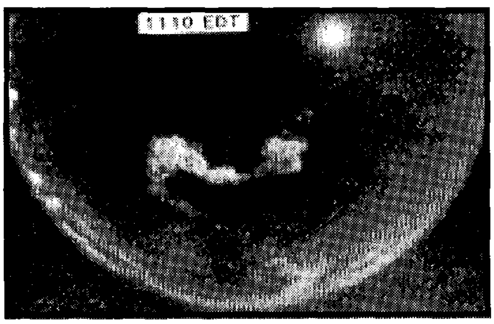

SYMPOSIUM ON WEATHER FORECASTING

NGM Output Error
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Tornado Outbreaks
Doppler Radar
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