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Intelligent and Localized Weather Prediction

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Contents

Acknowledgments iii

Abstract 1

1 Executive Summary 3

2 Proposed Tasks 7

3 System Design and Operation 13
- 3.1 Technological Innovations 13
- 3.2 System Details 15
- 3.3 Operational Procedures 29

4 Field Testing Results 59
- 4.1 General 59
- 4.2 Result Verification 59
- 4.3 Statistical Summary of Results 61
- 4.4 Historic Case Sequence 67

5 Outlook 93

Appendix A Roadweather Pro (Release 1.01) (Beta Test Version) 95

Appendix B Figures 105

Abstract

This report provides details of the design of a 24-hour weather prediction system for snow and ice control operations in road maintenance. The system accounts for detailed terrain effects on weather. Output is provided either in terms of weather maps at 3-hour intervals for meteorological users, or in terms of easy to read icons indicating rain, snow, temperature and wind conditions, laid on top of terrain and road network displays. These icons can be shown as time-lapsed sequences. Graphs of forecasts at specific locations can be manipulated by the user through simple mouse point-and-click actions, thus allowing forecast updates based upon local observations. The system has been tested extensively during the winter of 1991/92 and has performed excellently, providing details that go beyond those issued by the National Weather Service.

1
Executive Summary

This report concludes Phase 2 of a two-year effort to design, develop, and test a local area weather prediction system specifically geared towards providing decision support for highway maintenance operations. Of particular interest were forecasts of precipitation amounts as influenced by complex terrains, temperatures, and wind conditions. Such predictions can usually be obtained from the National Weather Service (NWS) only in general, "generic" terms without providing the quantitative details in location, timing, and intensity needed for decisionmaking in road maintenance work.

To make such a system applicable to highway operations WELS developed Roadweather Pro, a local area weather forecasting system which produces forecasts on small, affordable computers. The development of the system on a PC platform had but one purpose in mind--facilitate the distribution of the forecasts to the lowest level of operations where immediate, operational decisions have to be made. The system was also designed to function operationally in real time, meaning that predictions had to be ready soon after input data were received. And last but not least, the system incorporated a user-friendly graphical user interface so that complex weather information could be presented to highway operations personnel as intuitive graphic overlays superimposed over the terrain and road networks within the state and over their areas of operations.

As the system completed initial design and development in the fall of 1991, it was activated to accept live sensor data from the National Weather Service, and put its local area weather forecasting models into play. Throughout the winter of 1991, the models produced forecasts for 25 snow events, some of which lasted for three days. By any measure, the models produced extremely accurate and timely forecasts. With the forecasting models validated the system is now ready for full deployment throughout the State of Colorado, and other snow states.

Chapter 2. Proposed Tasks

Chapter 2 of this report describes the hardware and software configuration used in Roadweather Pro. Access to NWS satellite sensor data is through a 6-ft satellite antenna dish. The microwave signal from the antenna is digitized in a data reception unit by

Wegener Communications of Atlanta, Georgia, supplied by Zephyr Weather Information Services. All data manipulation needed in the course of the numerical weather prediction is processed by a WELS-developed Satellite Data Pre-Processor on a 486/25 MHz or 486/33 MHz computer system. Typically, data from NWS radiosonde and surface weather observations made at 5 a.m. or 5 p.m. MST are received by 8 a.m. or 8 p.m. Forecast products can be made available by 9:30 a.m. or 9:30 p.m.

In order to produce and show the interaction between detailed terrain and weather, WELS restructured data from a geographic information system (GIS) into an object-oriented format which allows quick access to elevation, slope and azimuth angle data within user-selectable ranges of values.

Chapter 3. System Design and Operations

Chapter 3 provides a detailed overview of system design and operation. The system finally evolved into a central weather forecasting center located at Boulder, Colorado. The center, which is called WELS Weather Central (WWC), accessed NWS sensor data, ran the models, and produced the forecasts. After completion, the forecasts were distributed via modem and statewide area network to users located at CDOT's Maintenance Section 1 in Greeley, Colorado, and the Senior Maintenance Supervisor at Boulder.

The major components of the fully developed Roadweather Pro system are:

WELS Weather Central
(486/33 PC)

- **Satellite Data Pre-Processor**
- **Portable Interactive Weather Prediction System (PIWPS)**- local area weather forecasting system.

User Sites
(386/20 PC)

- **Graphical User Interface (GUI)** resident on the user's PC to display the terrain, road networks, and weather forecasts emanating from PIWPS.

- **Expert Weather Advisor** which is also resident on the user's PC to enable highway maintenance operators to rapidly and readily correct forecasts based on local observations, and to plan for future weather scenarios.

Technological Breakthroughs. To put such a system through the design and development stages, several technological breakthroughs had to be achieved. First of all, numerical prediction models which customarily ran on Cray or Cyber supercomputers had to be restructured and simplified—without unacceptable losses in reliability—to run on desktop PCs. Raw data received from NWS via satellite communication link had to be decoded, checked for errors, and formatted efficiently on a small computer to be acceptable for the numerical prediction model in real time. The prediction module had to yield results allowing for details in terrain, without excessive use of computer time. Forecast results had to be made available with much higher time resolution than the customary 12-hour intervals of NWS products. The display of these forecast results had to be addressed to highway maintenance operators. This meant that details of terrain, road networks and weather had to be shown simultaneously on the computer screen. The weather development in the course of a day also had to be capable of being viewed as time-lapsed displays. And to further facilitate the use of the interrelated weather and terrain displays there had to be a capability of "zooming in" from statewide displays to specific maintenance management areas.

Portable Interactive Weather Prediction System (PIWPS). This chapter also contains a detailed account of the software modules integrated into **PIWPS**, which is the core of the numerical weather prediction procedure.

Graphical User Interface (GUI). The GUI developed by WELS and running under Windows 3.0 or 3.1 receives detailed attention in Chapter 3, with several screen samples shown. This GUI translates complex weather forecasts into user-friendly graphic overlays which are superimposed over the road network and terrain of the state and user's area of responsibility. The GUI allows the user to choose between a number of display modes. First of all, from a pull-down menu a mouse click will load the appropriate geographic and weather data from hard disk into RAM (random access memory). Once this data transfer is accomplished, displays flash to the screen instantaneously. The user can choose to show a statewide, district-wide, or smaller area, depending on the available databases.

A simple mouse choice from a pull-down menu lets the user superimpose road networks and state boundaries over the terrain display. By similar, simple menu choices, rain, snow, temperatures, and wind can be superimposed over terrain and roads, either individually or together. Weather characteristics are presented as icons (rectangles) which change color and/or shading, depending on the numerical values of displayed parameters. Each parameter display can be "toggled on" or "off" at will to suit the user. Precipitation can be viewed as 3-hourly increments, or as cumulative sums out to 24 hours. Choosing "Play" from a pull-down menu, the 3-hourly weather patterns will cycle automatically through a 24-hour prediction as a time-lapsed display.

Expert Weather Advisor. This artificial-intelligence-based expert system is the object-oriented user-interactive part of Roadweather Pro which allows manipulation of forecasts by the user through insertion of locally available sensor data or observations. With this software program forecast results for specific locations can be called to the computer screen in the form of graphs showing the time history of precipitation, temperature and wind conditions. Consulting fly-up menus, the user can choose a conversion factor that translates liquid water-equivalent precipitation (delivered by the numerical weather forecast) into snow depth, depending on atmospheric and ground temperatures, or on the user's own experience. Displayed forecasts can be altered to adjust for timing and intensity of predicted phenomena. The user will be prompted to carry out such adjustments using locally available data either from roadway sensors or from human observers. Simple mouse point-and-click actions will insert new data values and upgrade the forecast for the remainder of the prediction period. These upgrades are saved in memory and can be recalled for further adjustments. However, they can also be used in the form of a "what-if" planning scenario which can be abandoned after appropriate results have been viewed. The user can fall back on the original forecast. The **Expert Weather Advisor** will also display the results of repeated plowing actions at user-specified times, giving indications for optimum spacing of such operations.

A detailed description of operational procedures is contained in Chapter 3.3. It recounts step by step what must be done to proceed from data reception to the finished forecast products.

Chapter 4. Field Testing Results

Chapter 4 examines the operational results obtained during the past winter in 25 snow storm events. In addition to the summaries and details of each snow event, the chapter also describes the test methodology WELS formulated for the tests and an overall review and analysis of the forecasts conducted by WELS Weather Central. Highlighted are test results which showed that WELS' forecasts never varied by more than 1 in. of snow observations reported by NWS observers. Temperature was normally forecasted in greater accuracy and detail than the NWS; wind and intensity were forecasted in much greater detail; the onset of storms was forecasted within 30 minutes to two hours of the actual initiation of the storm, and the forecasts provided greater detail in defining the geographical location and distribution of the storm. The accuracy, timeliness, and detail of the forecasts add up to a greater knowledge of the environment by highway maintenance operators which should translate into more cost-effective operations by CDOT.

Chapter 5. Outlook

Chapter 5 presents a brief outlook for full system implementation and operation.

2
Proposed Tasks

Phase 2 Design Tasks

Under Phase 2 of SHRP-IDEA Contract 018 the general design work of a localized, "intelligent" weather prediction system carried out under Phase 1 was targeted for completion and field testing under operational conditions. Throughout the development and testing processes WELS worked closely with personnel from the Colorado Department of Transportation. This interaction resulted in several major revisions in the system design.

Notably, the original concept of deploying data reception facilities together with the numerical weather prediction model in the field was abandoned, because "highway engineers did not want to become meteorologists on top of their current duties."

The current system design allows transmission of weather forecast results from WELS Weather Central to field locations. At these locations software is installed which displays detailed weather forecast results in the form of maps, and also lets the user interact with forecasts by supplying observational data generated locally through simple mouse "point-and-click" actions.

The original map displays of meteorological parameters were also changed drastically. The current graphical user interface (GUI) exhibits meteorological parameters as easy to understand "icons". Variables, such as temperature, rain, snow, moisture, and wind can be overlaid over detailed terrain and road network images in any combination chosen by the user through simple mouse "clicks" on pull-down menus.

Precursor Tasks

Our original Phase 2 research proposal listed several tasks which had to be completed before the weather prediction system could be readied for deployment and operational testing. These tasks, as listed below, had been completed successfully by fall of 1991. Task completion was demonstrated to SHRP personnel during a site visit in Boulder.

- Porting of the numerical weather prediction model from an HP 9000/500 computer system to a 486 PC. The HP system for which the original FORTRAN code was developed proved to be too slow to qualify for real-time, operational use. Two model components had to be ported:

  A limited-area forecasting model (LFM) with approximately 96 km horizontal grid point resolution, covering roughly the area of the contiguous United States;

  A nested grid model with 24 km horizontal grid point spacing, covering an area somewhat larger than the State of Colorado.

- FORTRAN code for both model components had to be optimized to run on the 486-type PC in "protected" mode. (Further details are given in the subsequent section.) Such optimization provided us with a capability of producing 24-hour forecasts in less than 1 hour computer time.

- Decoding and error checking software had to be ported from the HP to the 486 PC.

- Graphical analysis programs producing weather maps, terrain, and road displays had to be ported from the HP to the PC system.

System Configuration

The WELS-designed intelligent and localized weather prediction system called Roadweather Pro consists of four main parts:

- A data reception, decoding, and analysis facility;

- A mesoscale numerical prediction model, the Portable Interactive Weather Prediction System (PIWPS);

- A Graphical User Interface (GUI) designed to display PIWPS forecasts as graphic overlays on digitized Colorado terrain;

- A graphics-based, user-interactive model (Expert Weather Advisor) designed to display received observations. The Expert Weather Advisor makes use of object-oriented intelligence[1].

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[1]Reiter, E.R., 1991: "Hybrid modeling in meteorological applications. Part I: Concepts and approaches." Meteorology and Atmospheric Physics, Vol. 46, pp. 77 - 90.

Hardware Configuration

The project-related hardware at WELS Weather Central consists of the following items:

- A 6-ft diameter satellite dish and antenna for the reception of microwave signals transmitted via communications satellite carrying meteorological observational data. The antenna was installed on the roof of our office building by Wavelength Inc. of Denver, Colorado.

- A data reception unit by Wegener Communications of Atlanta, GA, supplied by Zephyr Weather Information Service. This unit contains computer boards which translate the microwave signals into digital output.

- An AST Premium 486/25 computer with 10 Mbyte RAM and a 150 Mbyte hard disk drive. This computer was used by WELS for operational weather prediction during the past winter season. Another computer (Austin 486/33E with 12 Mbyte RAM and 1 Gbyte hard disk) was used for software development.

- A MultiModem MT932ECB, running QModem software, supplied by the Colorado Department of Transportation to transmit forecast results to field offices in Greeley and Boulder.

- An AMT Accel-535 24-pin dot-matrix printer for hard-copy production of weather maps.

Software

The following software packages have been installed and were used under the current system design:

- WATCOM FORTRAN with required Pharlap DOS Extender is used to run the numerical prediction model components in "protected mode" i.e. in RAM above 1 Mbyte memory. This software configuration essentially eliminates the memory restriction of 640 Kbyte imposed by DOS and allows it to run large programs accessing large databases.

- MS FORTRAN, running under MS-DOS, is used for the decoding and graphics programs.

- Microsoft Windows 3.1 is used to control all other software packages which do not use the Pharlap memory management. Since Windows has become an industry standard, WELS decided to design the graphical user interface (GUI) of the interactive modules of its weather prediction system to conform to Windows standards.

- PROLOG 3.3 for Windows, by the Prolog Development Center, Atlanta, GA, is the main language for the object-oriented GUI design. This language controls the behavior of "meteorological" and "geographic pixel" objects, their display on the computer screen, and their response to user-prompted actions. (More about these issues will be discussed in Section 3.) PROLOG 3.3 also interacts with the Windows programming language which is based on "C". This interaction allows the programmer to define the behavior of windows and their child objects, using PROLOG rather than "C".

- The Resource Workshop by Borland International allows rapid prototyping of menus, buttons, text boxes, etc., and the construction of "resource files" (*.RC and *.RES files) which are linked to the main PROLOG programs, thus providing the interface between messages controlling the behavior of windows and their child objects, and messages prompting computational procedures specified in the PROLOG program and activated by mouse point-and-click actions.

- Qmodem software allows transmission of forecast results to modem-connected field stations, and data receptions from modem-equipped vendors.

- Show Partner F/X software has been used to "grab" pixel-based screen images in the DOS environment containing weather maps produced by the WELS numerical prediction model (the Portable Interactive Weather Prediction Model, PIWPS). Files generated by Show Partner are suffixed by *.GX2, but can be converted to *.PCX files which is a widely used format for pixel-based image files. This software package was used to transmit weather predictions in the form of weather maps to field stations for the sole purpose of viewing forecast results. These transmission procedures have become obsolete with the development of the Windows-based GUI. Show Partner still provides useful support in preparing computerized "slide shows" for demonstration purposes, and for the production of color prints using the *.PCX file structure.

- PKWARE Inc. software, which is in the public domain, was used to pack ("zip") the image files before modem transmission, and to unpack ("unzip") them after reception at field stations. Condensing the files before modem transmission reduces the transmission time by more than a factor of two.

- HiJaak software by Inset Systems Inc. allows the capturing of image screens produced under Windows rather than DOS. HiJaak produces *.PCX files which can be used by editing and printing software. Conversion to *.GX2 files and the use of Show Partner permits the composition of slide shows.

- PB Paintbrush by ZSoft Inc. edits *.PCX files from above described procedures for reproduction on a Howtek Pixelmaster color printer. Printing facilities were made available to WELS by Objective: Inc.

- Central Point Anti-Virus software is used as part of WELS quality control to scan hard and floppy disks for virus infections.

- Microsoft Word for Windows Version 4 is used for the preparation of this report. File copies formatted as WordPerfect 5.1 files were generated using Word for Windows software.

Databases

Roadweather Pro requires the following data:

- North American radiosonde and surface observations received from "synoptic" observation times (i.e. taken at 0000 and 1200 G.M.D.). These data are collected routinely by the National Weather Service (NWS) and disseminated to a small number of vendors, such as Zephyr Weather Information Service. With appropriate hardware and software (as described above) these raw observational data can be received from such vendors under a subscription agreement. Usually data transmission is completed 3 hours after the aforementioned synoptic observation times. Thus, the numerical model can be initialized with observational data by 8 a.m. or 8 p.m. M.S.T.

  We noticed that heavy snowfall occurring during the data reception periods may cover the lower half of the satellite antenna with a layer of snow. Such snow cover interferes with microwave signal reception, causing garbled or missing data streams, hence a deficiency in information from which the numerical prediction model can be initialized. To overcome this problem, several actions can be taken:

    - Personnel can hand-sweep the antenna with a broom whenever snow accumulation occurs.
    - An electric blower unit can be installed to prevent snow from settling on the antenna.
    - The antenna can be heated by a battery of infrared lamps to melt snow before it accumulates in the satellite dish.
    - A larger antenna dish can be installed to provide sufficient signal strength even with partial obscurance by snow.

Our current funding level prevented us from testing any of these options. The second or third options would be our preferential choices.

- Running the numerical prediction model, and displaying the forecast results in the Windows environment under Roadweather Pro requires access to a geographic database with terrain elevations available from grid points spaced 30 arc seconds (ca. 1 km) apart. Such data are available over the United States from the U.S. Geological Survey. As will be discussed below, these geographic data are reformatted into an object-oriented geographical information system for easy access and interactive display processing.

- A road network database contained in CORIS (Colorado Roadway Information System) and structured according to ARCINFO is used to display Federal and State highways together with topographic and weather information.

Roadweather Pro can be run over any locations with sufficient meteorological data coverage and terrain information as specified above. Road network information is not essential to the execution of the forecast procedures, but is needed for highway maintenance applications of weather predictions.

System Integration

We will elaborate further in Section 3 on the various system components and their role in the overall system design. A major concern from the start of this project two years ago was the integration of these components into a shamelessly functioning, user friendly system which can provide weather and ancillary information for highway maintenance operations with heretofore unattainable speed, detail, and reliability. Furthermore, this information needed to be available at locations where tactical maintenance planning was carried out and had to cope with ever-changing environmental conditions.

WELS has succeeded in developing an operational prototype of such an integrated system. This prototype has performed well during an extended test period which captured 25 snowstorm events passing over Colorado. In the course of these real-time, operational tests we also noted that the WELS prediction system handled very well the severe precipitation events which led to extensive and devastating flooding in Texas and California.

3
System Design and Operation

3.1. Technological Innovations

The development of the WELS weather prediction system brought about several major technological innovations. Only through these innovations is it possible to run an objective numerical weather prediction system operationally, in real time, on a relatively inexpensive, high-end PC, and to allow the forecast results to be modified interactively by user input.

3.1.1. Data Reception, Selection and Decoding

Based on market research, WELS has the only **PC-based** system which receives **in real time** and **operationally** the "raw" radiosonde and surface observational data as disseminated by the National Weather Service, decodes these data into ASCII-formatted, alpha-numerical information, and selects automatically those data groups which are germane to the initialization of the numerical prediction model.

An objective analysis program has been implemented which produces displays in the form of weather maps of observed meteorological variables (such as wind, temperature, pressure, humidity, precipitation) and of derived fields (such as vorticity, temperature advection, moisture flux convergence, etc.).

3.1.2. System Architecture

The system architecture of the WELS weather prediction system for the first time realizes at reasonable hardware costs the goal of **distributed** weather prediction, i.e. numerical weather forecasting carried out at field sites rather than at a central, national facility. The concept of "distributed" versus "centralized" weather prediction invites user input of locally generated observational data for the purpose of forecast improvements. Distributed weather prediction also allows for the first time seamless, computerized integration of weather forecasts into tactical decision making processes.

3.1.3. Numerical Forecasting

The numerical weather prediction model underlying the WELS system is a derivative of the well-renowned Anthes model, a forerunner of the highly successful NCAR/Penn-State mesoscale prediction model widely used as a research tool. The WELS system introduced significant innovations in the treatment of terrain details and in the way a high-resolution nested grid domain interacts with a lower resolution limited-area forecasting model. These changes inherent in the WELS system were geared towards high-speed performance on relatively small computers, such as high-end PCs, making real-time, operational use of such models possible.

3.1.4. Geographic Information System (GIS)

The WELS weather prediction system is, to the best of our knowledge, the first PC-based system which is directly linked to a geographic information system (GIS). This system does not use the customary "flat file" structure of topographic information in which, for instance, elevation values for grid points within the area contained in the file have to be read sequentially. The GIS employed by WELS structures the information in the form of "smart geographic pixel objects." Each of these objects contains designated attributes of X- and Y-locations in terms of longitude and latitude, elevation in feet, slope angle, azimuth angle, etc. (Other attributes are not implemented, but could contain information on soil and vegetation conditions, etc.). This rather large database is structured in the form of "B+ trees": Certain index keys are defined (e.g. X-, Y-locations, elevation, slope, azimuth). Within each key the values occurring in the database are sorted in ascending order. (E.g. all elevation values within the area domain to be depicted on the screen are sorted from 0 to 16,000.) A small database is constructed for each sorted key, containing the value (e.g. elevation at one grid point) and a reference number by which the full record can be found in the main database. Using such a sorted binary tree structure makes it possible to retrieve values quickly according to user-specified criteria. For instance, the user can choose to bring to the screen elevation values between 5,200 and 7,300 ft.

Weather information extracted from the numerical modeling results is structured into similar "smart geographic pixels." Thus, the WELS system is able to consider and display interactions between terrain and weather.

Road network data received from the Colorado Department of Transportation can also be segmented into "smart pixel objects," if one wishes to paint small road segments as they fall under the influence of individual geographic and weather pixels. For current applications the road network is not segmented in this manner, as it is displayed only to provide location guidance on the computerized map display.

3.1.5. Graphical User Interface (GUI)

The WELS system uses Microsoft Windows 3.1 to provide a graphical user interface. Terrain, road network and weather information are displayed in movable and adjustable windows. All actions required by the user, such as loading data from databases, choosing appropriate limits for values to be displayed, selecting the weather variables to be shown on the screen, etc., are carried out by simple mouse point-and-click actions involving fly-up menus and buttons. Once the required geographic and weather databases are loaded from hard disk into RAM, displays can be cycled through almost instantaneously. This capability provides the option to view changing weather conditions as a time-lapsed, animated display.

3.2. System Details

3.2.1. The Numerical Prediction System

3.2.1.1. The Basic Meteorological System

The capability of receiving a stream of raw weather data from the GTS (Global Telecommunication System), access to data decoding and analysis procedures, and the ability of quickly displaying the results in the form of weather charts are the primary requirements for an automated meteorological system.

One of our design goals was to have such a system running on a PC. In order to overcome the memory restrictions of the MS-DOS operating system, and keeping system portability in mind, most of the system had to be designed "from scratch," using FORTRAN 77 and following rigid rules for time and memory optimization[2,3]. It also had to be designed to be fully user-interactive and highly portable between different computer systems.

In order to achieve these, a customized FORTRAN library containing a number of subroutines for analysis, diagnosis, interactive user interface and basic meteorological display capabilities was coded[4]. Only basic graphic routines, such as device drivers, line and character drawing, are required from the host computer, in addition to a FORTRAN 77 compiler. Such portability characteristics were fully tested when the original DOS-based package was ported without difficulties to a UNIX environment and, after further developments, back to a DOS environment.

The present operational system is configured as follows: Under the directory "C:\WELS" there is a list of eight subdirectories identified by four-character labels which mnemonically indicate their contents. No subdirectories exist beyond this level. Some of the directories listed below are not used by the Basic Meteorological System, but are

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[2]Roache, P.J., 1982: Computational fluid dynamics. Hermosa Publishers, 446 pp.

[3]Teixeira, L., 1987: Recursos numericos uteis na optimizatiom de modelos iterativos. Technical Report ECA-17/87, Instituto de Atividades Espaciais, Sao Jose dos Campos, 12225, SP, Brazil.

[4]Teixeira, L., and R.L. Guedes, 1989: Bibliotecas FORTRAN para analise, diagnostico e apresentacao grafica de campos meteorologicos. Technical Report ECA-09/89, Instituto de Atividades Expeciais, Sao Jose dos Campos, 12225, SP, Brazil.

mentioned in anticipation of the discussion in Chapter 3.2.1.2. The content of each directory can be summarized as follows:

UTIL	-	batch programs;
TEMP	-	temporary storage;
MAPS	-	terrain elevation, continental and political boundaries, list of synoptic stations, road network files, etc.;
EXEC	-	executable, setup, and some batch files;
RAWD	-	raw weather data as received from the communication satellite;
UDCO	-	weather data files generated by the decoding program;
GRID	-	gridded files for geographic and weather data;
RSLT	-	forecast results (not part of the Basic Meteorological System).

The whole system is composed of five main programs as depicted in Fig. 3.1. Two of them are classified as "support" programs and are used only in the event that modifications are required in the maps or in synoptic station databases. The others are "operational" components of the system. In this figure, all program names are in bold face and framed with thicker-border rectangles, while input/output files and output charts are labeled with normal face fonts and framed with rounded-corner rectangles.

A list of these programs, their function within the system, their input file requirements, generated outputs and location of the input and output files in the file system is given below. Note that not all file names mentioned in the following description are shown in Fig. 3.1 to avoid clutter. All executable and setup files are expected to reside in "C:\WELS\EXEC" directory.

3.2.1.1.1. Support Programs

CABM - (Conversion ASCII to Binary for Maps)
Objective: Conversion of all continental and political boundary files from ASCII to binary code and vice versa.

Input and/or output files "CC?" and "PP?", represented in Fig. 3.1 by "CP ASCII", contain the ASCII coded information for the continental and political boundaries, respectively. Their binary counterparts, represented by "CP Bin" are "C?" and "P?". The wild card "?" represents the earth octant counting eastward from Greenwich such as 1 north, 2 south, 3 next north, 4 next south, etc. (see Footnote 4). All files involved are located in "C:\WELS\MAPS".

HSHT - (HaSH Table)
Objective: This program generates hash indexes for the synoptic station list, which help to speed up the decoding procedure applied to raw data.

Input: By default the program requires the file "SyNA" containing a list of synoptic stations for North America (prepared from file AFDICT.NA - Air

Weather Service Master Station Catalog). It will accept any other file name upon user request. (Such files may contain observation station locations within a special network.) Input files are expected in "C:\WELS\MAPS".

Output: Four output files are generated. Files "IPOINT" and "ICOLS" contain hash indexes and collision indicators (flagging seemingly identical stations with the same symbolic number), respectively. File "SYD" contains a new list of synoptic stations to be used during the search process. File "SYM" relates to stations that report METAR information and are not used in the current system configuration. All files are expected to be in the directory "C:\WELS\MAPS".

3.2.1.1.2. Operational Programs

GTS - (Represented by RCPT in Fig. 3.1).
Objective: The main function of this module is to read from the computer serial port #1 and store the raw data coming through that port in pertinent files.

Input: A satellite dish antenna continuously receives raw data from Zephyr Weather Information Service, Inc., via communication satellite. These data are funneled through a receiver and converter hardware box that will transform the incoming microwave signal into ASCII coded data. This ASCII coded stream of data is then accessible by GTS through the computer serial port #1.

Output: Four files will be available daily. The file name convention is: "MMDD-HH.RAW" where MM and DD are the two-digit representation of month and day. The HH following the hyphen represents the GMT synoptic hour and the suffix ".RAW" indicates the nature of the file contents. These files will be stored in the directory "C:\WELS\RAWD".

DECO - (Decoding program)
Objective: This program accesses the raw data files received by the program above, selects the meteorological messages of interest, strips the data for inconsistent coding and decodes the messages. In the present configuration only surface data reported as SYNOP, and upper air data as TEMP are decoded.

Input: One of the "MMDD-HH.RAW" files described above (output from the GTS program) and all output files from the HSHT program previously described. Also required as input is a setup file, by default named "DECO.SET", that contains required geographic information for the creation of output files suitable for subsequent display. Such a setup file can be created interactively by selecting the appropriate options while running DECO, and can be called as default in the subsequent execution of the program (see Chapter 3.3).

Temporary files: Several temporary files placed under "C:\WELS\RAWD" and "C:\WELS\UDCO", are used in the process of screening the raw data for pertinent information. In the directory "C:\WELS\RAWD" the files "TMPS" and "TMPT" are created to hold temporary information from the SYNOP and TEMP codes. In "C:\WELS\UDCO", temporary files "MTSY", "TTXX", "FTTYY" and "FTTZZ" are created to hold diverse phases of the decoding process.

Output: Several output files, listed below, for surface and upper air data are made available and are stored automatically in the directory "C:\WELS\UDCO".

Surface files (?? represents 00, 06, 12 or 18 synoptic hour):

PM??	-Sea Level Pressure
PS??	-Surface Level Pressure
PP??	-Precipitation
VT??	-Surface Wind
TA??	-Surface Air Temperature
TD??	-Surface Air Dew Point
QS??	-Surface Specific Humidity

Upper Air files (LLL represents standard upper air levels, such as 850, 700 mb, etc.):

PN??.LLL	-Geopotential at level LLL
VT??.LLL	-Wind at level LLL
TA??.LLL	-Air Temperature at level LLL
TD??.LLL	-Air Dew Point at level LLL
QU??.LLL	-Specific Humidity at level LLL

ANLZ - (Analysis program)

Objective: The function of this program is to display meteorological charts with or without political map background on a variety of devices. Basically two run modes are available and can be selected during execution:

- A research mode, represented by an (R) in figure 3.1, guides the user through a wealth of options allowing the creation of data files on the fly or the selection of pre-existing files, such as the ones generated by the program DECO. The data can be displayed on the computer screen or routed to a plotter or printer in a variety of ways such as: with or without base maps, with different isolines spacing and degrees of smoothing, with or without plotting the original data, etc.

- An operational mode, represented by an (O) in figure 3.1, displays on the screen or routes to a plotter or printer, a series of pre-defined surface and upper air charts with pre-set characteristics. The following charts are available in the current, operational version:

At Surface:

Sea Level Pressure / Wind
Air Temperature
Temperature Depression
Moisture Divergence
Temperature Advection
Vorticity

At 850, 700 and 500

Geopotential / Wind / Station indicators
Air Temperature
Temperature Depression
Temperature Advection
Vorticity Advection
Moisture Divergence

Input: In the research mode the program requires as data source for display either a file created on the fly by the user or a pre-existing one upon request. The default location for these files is the "C:\WELS\UDCO" directory, but the user can instruct the program to access a different directory. In the operational mode, the data sources for display are the output files generated by the program DECO and previously stored in the "C:\WELS\UDCO" directory.

In addition to the files to display, the program also requires input data of continental and political boundaries, contained in the files "C?" and "P?" previously described.

Output: Under the research mode the user has the option to create files interactively, containing the information to be displayed. Under the operational mode the setup file can be created. In terms of graphic output, several devices such as CGA, EGA or VGA monitors, HP compatible plotters and Epson compatible printers can be addressed.

3.2.1.2. Weather and Geographic Data Systems

To describe the chart presented in Fig. 3.2, we divide the system into individual subsystems, each one having a particular well-defined function:

The Basic Subsystem handles the data reception, decoding, analysis, and depiction of upper air and surface meteorological charts, as described above. The Geographic

Subsystem processes, as the name indicates, geographic data. In the current implementation the following data are processed:

terrain elevation,
elevation variance,
slope and azimuth angles, and
road network and state boundaries.

Customized geographic files required by both the Prognostic and the Integrated GUI Subsystems are the output from this subsystem.

The Prognostic Subsystem gathers files previously created by the Basic and Geographic Subsystems, generates all required input grids for the prognostic program, processes the forecast, depicts the forecast charts and generates customized weather files for the Integrated GUI Subsystem.

The Integrated GUI Subsystem combines the customized files from the Geographic and Prognostic Subsystems for processing in a Graphic User Interface (GUI) that allows the user to selectively display several combinations of graphically presented data.

All "executable" and "setup" files are expected to reside in the directory "C:\WELS\EXEC".

3.2.1.2.1. The Basic Subsystem

A detailed description of this subsystem was given in the preceding Chapter "Basic Meteorological System." Here its interaction with other subsystems is described.

3.2.1.2.2. The Geographic Subsystem

Geographic data files are available from several sources, e.g. the U.S. Geological Survey, in a wide variety of formats. A dynamic interface was required between such "foreign" files and the standard files acceptable by the subsystem. "Dynamic" means that specific user choices of geographic areas to be displayed need to be accommodated in a highly flexible manner.

The subsystem is composed of four main programs: two for the "dynamic" interface, one for ASCII-to-binary file translation, and one encompassing the customized geographic file builder. These programs should be considered as support programs. Once a user defines the area of interest and the geographic file for that particular area is generated, there is no further need to run this subsystem. Only the resulting files will be used.

A list of the programs, their functions in the system, input file requirements, generated outputs and the location of the input and output files in the file system is given as follows:

Support Programs

SMLF - (Small Files Generator)

Objective: The function of this program function is to split "huge" files (10 to 15 Mbyte each) containing geographic elevation with 30" resolution into easy to handle "small" files (4 degrees of longitude per 1 degree of latitude - 300 Kbyte each) that can be easily processed in a personal computer. An additional advantage of the "small file" concept is processing speed. Only files that contain geographic location coincident with user requirements are considered for further processing.

Input: As mentioned above, "SMLF" uses files of 10 to 15 Mbyte in size as input. Original processing was done in a UNIX environment using large storage media and virtual memory. Only the resulting "small files" were ported back to the PC environment. In the UNIX environment these input files were stored under the directory "?\USER\WELS\MAPS".

Output: The output files ported from the UNIX environment were loaded in "F:\WELS\MAPS". The file nomenclature, used by the "USEF" program to identify the geographic area contained in each individual file is: "HHXXYYY" where HH is replaced by NN for the Northern Hemisphere, and by SS for the Southern Hemisphere, XX denotes the latitude of the "upper" border of the "box" contained in the file, and YYY indicates the longitude of the left border file (longitude is counted eastward from Greenwich in a 360 degree circle). The "small" files available in the present system cover most of the western United States east of the Mississippi river.

CABE - (ASCII-to-Binary Converter)

Objective: Conversion of the terrain elevation data contained in the above described "small" files from ASCII-to-binary coded files. This conversion leads to a reduction in storage requirements by approximately 60%, from the original 302 Kbyte to 116 Kbyte, which translates into more than 24 Mbyte of saved storage space when all 130 existing "small" files are loaded on disk. Unfortunately, in the current system configuration, the ASCII files are still required by the Prognostic Subsystem because of binary incompatibilities between the real mode MS FORTRAN and the protected mode Watcom FORTRAN under which some of the Prognostic Subsystem programs are running.

Input: The input files are the ASCII coded ones named "HHXXYYY" and described above as output from the SMLF program. They must be placed in a directory "?:\WELS\MAPS" where ? denotes the hard drive used for input (which need not necessarily be drive C).

Output: The files generated by this module are binary coded and are also named "HHXXYYY". The program will not proceed unless input and output drivers are chosen by the user to be different. Once this requirement is satisfied, the conversion program will run and the output will be placed in the directory "?:\WELS\MAPS", where the "?" denotes the output hard drive designation.

CNVR - (Subsystem Standard Format Converter)
Objective: Conversion of the road network files from their original format into the standard format recognized by the subsystem. In the current configuration the CORIS format used by the Colorado Department of Transportation was translated by a version of the "CNVR" program named "CDOT".

Input: The input is an ASCII or a binary file containing the highway network information in a certain format and, by default, is expected to be found in the directory "C:\WELS\MAPS".

Output: The output is an ASCII coded file named "??Roads" that will be stored in the default directory "C:\WELS\MAPS". The default for the wild card "??" is NA (North America), but a more meaningful designator such as CO to represent the state of Colorado can be used, either by rejecting the default or by renaming it afterwards. Be aware that the only modification allowed in this file name is the two-character designator.

USEF - (User Customized File Generator)
Objective: This program assembles a customized geographic file, puts together at user request terrain elevation, road network and state boundary information. The user will be required to enter several parameters, such as the maximum and minimum values of latitude and longitude of the area of interest, resolution of the geographic information in terms of EGA reference pixels (the current system requires 6 by 5 pixels), etc. Interactive queries are self explanatory, and in most of the cases the default is to be accepted.

Input: Input files for this program are the "small" elevation files described above, the "??Roads" for the road network, "??Bound" for boundaries and "??Cities" for a list of cities. Files "??Bound" and "??Cities" are hard-coded in the present application. City names are not yet transmitted to the GUI Subsystem because they were found to clutter the display screen. The wild card "??" represents the two-character designator described above for the output section of CNVR. All input files are expected to be in the directory "C:\WELS\MAPS".

Output: The output for this program is, as mentioned above, a file containing all the geographic information requested by the user. This file is now ready to be assimilated by the Integrated GUI Subsystem. It is named "??.USR" where "??" represent the same two letter designator described above for the input files. This file will also reside in "C:\WELS\MAPS".

3.2.1.2.3. The Prognostic Subsystem

As most of the system, the Prognostic Subsystem was designed following a modular approach. This design identified three major processing tasks which are depicted in figure 3.2 as vertically stacked "layers."

The first of these layers is composed of "GRDW", "GRDS" and "GRDZ". The three-letter initial GRD stands for "grid" and identifies the grid generator programs. They are responsible for the pre-processing of the geographic (Z) , sea surface temperature (S) and weather (W) grids required by the prognostic model. Programs "GRDZ" and "GRDS" are considered support programs, but "GRDW" is needed for operational execution.

The second layer contains the heart of the subsystem. It contains the weather forecasting model, represented in figure 3.2 by "PROG & NEST". This module is a major component of the system as it currently operates.

The last layer was designed with three post-processor modules. Programs "CRTS" and "CRTN" are the prognostic counterparts of the "ANLZ". The program "CSTM" is an interface between the "Prognostic" program and the Integrated GUI Subsystems. All programs in this layer are used during present operations.

A list of the programs, their function in the system, input file requirements, generated outputs and the location of the input and output files in the file system follows.

Support Programs

GRDZ - (Grid Generator for Geographic Information)
Objective: Every single program in this subsystem and beyond is dependent on this module. Here the grid structure, dimension, location and resolution for both the coarse and the nested grid are completely defined. All the required data for each individual grid point, such as latitude and longitude, map factor, Coriolis parameter, terrain elevation, slope, azimuth and elevation variance are also computed by this module.

Input: The first source of data for this module is the file "TOPO-10.MIN", resident in directory "C:\WELS\MAPS". This file contains terrain elevation data covering the continental United States from latitude 55 N to 20 N and from longitude 230 E to 295 E, with a 10 arc-minute resolution. Each grid point on the coarse grid receives its elevation value by interpolation from these 10-minute data.

The second set of files required by "GRDZ" is comprised of the "small" files "NNXXYYY", previously described as output from "SMLF" under the Geographic Subsystem. These files, as mentioned earlier, contain elevation data in a much finer resolution of thirty arc seconds and are used to compute terrain elevation and variance for each individual grid point in the model's "nested" grid.

The last file required is a setup file named by default setting as "GRDZ.SET" and resident, as all "*.SET" files, in the "C:\WELS\EXEC" directory. This file can be generated interactively by "GRDZ" following the user selection of <K> KEYBOARD when prompt for SETUP INPUT SOURCE. Basically the "GRDZ.SET" file contains

the grid dimensions,
left and right grid boundaries in degrees of longitude east,
the desired map projection index (0 for Mercator, 1 for Lambert),
latitude of the northern boundary (if Mercator) or latitude of the grid center (if Lambert),
latitude (if Mercator) or latitude north and south (if Lambert) of the intercept of the plane of projection and the earth's surface,
a "Y" or "N" entry indicating the request for computation of the "nest" grid,
first guesses for the left and right nested grid boundaries in degrees of longitude east (if "Y" for nest grid), and
first guesses for the north and south nested grid boundaries in degrees of latitude (if "Y" for nest grid).

The "first guess" mentioned above is required because the program adjusts the nested grid boundaries to make sure all coarse grid points within the nested grid area have counterpart nested nodes.

Output: Two files are the result of this program. The first one is named "GridZZ" and contains all the information related to the coarse grid. The other, called "NestZZ", contains similar information for the nested grid. Both files are generated under the directory "C:\WELS\GRID".

GRDS - (Grid Generator for Sea Surface Temperature)
Objective: The function of this program is to create twelve monthly grids for sea surface temperature (SST), following the geographic definitions for the coarse grids contained in "GridZZ".

Input File: As suggested above, one of the input requirements for this module is the file "GridZZ" encountered in "C:\WELS\GRID" directory. In addition, the program looks for twelve monthly files containing SST data in a form of a list of point values of latitude, longitude and SST. These files, named "SST??", with ?? being a two digits representation of the month, are stored in "C:\WELS\MAPS".

Output Files: The output files are named "SSTG??" and are automatically saved under the directory "C:\WELS\GRID".

Operational Programs

GRDW - (Grid Generator for Weather)
Objective: The function of this program is to create a series of upper air grids containing weather information, following the geographic definitions for the coarse grids contained in "GridZZ".

Input: As suggested above, one of the input requirements for this module is the file "GridZZ" encountered in "C:\WELS\GRID" directory. In addition, the program will search for several weather files in "C:\WELS\UDCO". These files were the output results from "DECO" and were described before.

Output: The output file, called "Grid00", contains all the weather grids required to run the forecast model and is automatically saved under the directory "C:\WELS\GRID".

PROG & NEST - (Prognostic Model including Nest Grid)
Objective: This module will gather information from the Basic and Geographic Subsystems through the first layer of the Prognostic Subsystem described above and will interactively perform 481 time step solutions of the primitive equations of fluid dynamics in order to obtain a 24 hour weather forecast[5]. The actual command to execute this module is "NEST".

Input: This module requires five files to run. All required geographic information is supplied by files "GridZZ" and "NestZZ". The SST is obtained from "SST??" and weather grids from "Grid00". These files were discussed earlier.

In addition to the grid files, a "*.SET" may also be used in the operational mode to avoid the repetitive task of option selection. The file is named by default "NEST.SET" and is expected to be found in the "C:\WELS\EXEC" directory. This file is generated interactively by "NEST" following the user selection of <K> KEYBOARD when prompted for SETUP INPUT SOURCE. Basically, the "NEST.SET" file contains options for data assimilation from the 1000 hPa surface (always set to "1", meaning the 1000 hPa data will not be used), numeric boundary condition options (1 fixed, 0 time-variant), input and output file-name default, toggles on and off output of a particular parameter and, finally, set output intervals for the coarse grid, nested grid and the GUI oriented results, including their default

[5]Tucker, D.F., and E.R. Reiter, 1988: Modeling heavy precipitation in complex terrain. Meteorol. and Atmos. Phys., 39, 119-131.

names. Caution is advised if modifications are done to this setup file because incompatibilities with subsequent programs may arise.

Output: The results of the forecast process are six files meant to be presented in graphical displays. They are named "RZPLT", "ROPLT", "RPPLT", "RNPLT", "RGPLT" and "RTIME". The first character "R" stands for "result." The second character indicates the type of data: Z (terrain elevation), O (observation), P (coarse grid prognoses), N (nest grid prognoses). The PLT that follows stands for plots. TIME in the last file indicates that the contents are temporal variations of some parameters. All files are created and expected to be in the directory "C:\WELS\RSLT".

CRTS - (Coarse Grid Weather Charts)
Objective: This module is responsible for the presentation of several charts and graphic displays involved and/or generated during the forecast process for the coarse grid of the model. The presentation can be done either on the computer screen or routed to a HP-compatible plotter or Epson-compatible printer.

Input: The required input files for this module are: "GRDZZ" found in "C:\WELS\GRIDS", all the "C?" and "P?" files stored in "C:\WELS\MAPS", and the result files "RZPLT", "ROPLT", "RPPLT" and "RTIME" expected to be in "C:\WELS\RSLT".

Output: The program offers a menu with four output options, which can be selected by typing an appropriate character. They are:

1) charts containing the terrain topography, slope, or azimuth;
2) the observed meteorological data fields used to initialize the model arrays;
3) the resulting forecast fields; or
4) a series of graphs depicting the temporal variation of model parameters in the center of the lower sigma level of the model.

CRTN - (Nested Grid Weather Charts)
Objective: This module is responsible for the presentation of several charts generated during the forecast process for the nested grid part of the model. The presentation can be made either on the computer screen or can be routed to an HP-compatible plotter or Epson-compatible printer.

Input - The required input files for this module are: "NESTZZ" found in "C:\WELS\GRID", all the "C?" and "P?" files stored in "C:\WELS\MAPS" and "RNPLT" expected to be in "C:\WELS\RSLT".

Output: The program offers a selectable (by typing) menu with two output options. They are:

1) a chart containing the terrain topography, or
2) the resulting forecast fields for the nested grid.

CSTM - (Customized Weather File Generator)
Objective: The function of this module is to assemble a customized weather file compatible with the customized geographic data file "??.USR" discussed earlier as the output from the USEF.

Input: Three input files are required by this program. File "RGPLT", from the prognostic run, contains the nested grid results for wind, air temperature and dew point depression for the lowest sigma level of the model for each 3-hour interval during the 24-hour run. The next requirement is "NestZZ", which contains all the data for the correct interpretation of the "RGPLT" contents. Finally, "??.USR" from the Geographic Subsystem is needed as the supplier of data required to create a geography-compatible weather file.

Output: The results from this module are nine files named ??.N??. The first wild card "??" represents the two-character designator, described before during the discussion of the CNVR output. The second "??" represents the model time in hours, represented by two digits, starting at 00 for the model initialization fields, up to 24 forecast fields. Note that in figure 3.2 these files are represented by the generic "??.NST" label. This is a mask file, used by CSTM to query the user. Internally, the two-character "ST" ending the file name will be replaced by the two-digit model time steps.

3.2.1.2.4. The Integrated GUI Subsystem

Up to this point most of the programs described were written in FORTRAN, with the unique exception of the data reception program GTS coded in PROLOG. The GUI subsystem is totally coded in PROLOG.

There are advantages and disadvantages in using PROLOG for the GUI. PROLOG is a high-level, fifth generation language set apart from the traditional procedural approach of Basic, FORTRAN or C familiar to most programmers. The declarative nature of PROLOG needs to be gotten used to. This perceived disadvantage, at the same time, turns into a decided advantage: As a declarative, rule-based language, PROLOG is ideally suited for demanding database applications, such as the development of knowledge bases, expert systems, natural language interfaces and management systems. It has a very powerful, built-in database management capability. Such databases store data items in chains, rather than individually, so that related items can be stored together. In addition, it incorporates a "B+ trees" data structure that allows for very quick data retrieval[6]. The Integrated GUI Subsystem is making extensive and successful use of this database tool, as will be shown below.

Another positive aspect of PROLOG is the ease of implementation of rule-based concepts that will be extremely useful for future artificial intelligence-based expansions of the system. With such implementations the user will be able to interact with the predicted weather fields by imposing corrective measures at certain points or areas, and by selecting rules by which the program will try to distribute the prescribed corrections in space and time.

As coded in the present version, there are three modules: "DBGIS" and "DBWIS" are the geographic and weather database generators, and "WGIS" is the actual Integrated GUI. Modules "DBWIS" and "WGIS" are part of the operational path, while "DBGIS" is a support program.

Future versions of this subsystem will integrate those three modules into a single one, named Weather plus Geography GUI as depicted in Figure 3.2. Such integration will save computer time. As a three-module system, both weather and geographic databases are created in memory, then copied onto files by the database generators, and copied back from the files to memory by the "WGIS". Such arrangement was convenient during the development stage of the system. Under operational conditions an integrated module will be more efficient.

A list of the programs, their function in the system, input file requirements, generated outputs and the location of the input and output files in the file system follows.

Support Programs

DBGIS - (Geographic Database Generator)

Objective: This program reads data from a sequential geographic, ASCII-coded file and simultaneously creates efficient PROLOG databases which use B+ trees as retrieval technique and operate from a fast XMS (Extended) or EMS (Expanded) memory.

Input: The ASCII file required by this module is the "??.USR", created by USEF mentioned earlier.

Output: Three database files are generated by this module. All information related to the "geographic pixels," such as: X and Y (location of the upper-left corner of the geographic pixel), terrain elevation, slope and azimuth, plus three storage areas for elevation-, slope- and azimuth-related B+ trees are saved in the "??.GEO" database. A fourth B+ tree, indexed by X and Y is saved in a companion database named "??.XgY".

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[6] Prolog Development Center, 1986, 1992: PDC PROLOG user's guide, 503 pp. PDC PROLOG reference guide, 478 pp. Prolog Development Center, Copenhagen, Denmark.

Another database, "??.RDS", is used to store road network, state boundaries and eventually city information.

Operational Program

DBWIS - (Weather Database Generator)
Objective: This program is the weather counterpart of the previously described DBGIS. Here ASCII files containing weather information are read in a sequential fashion and PROLOG databases are created.

Input: The input requirements for this module are the nine ASCII files "??.N??" created by CSTM discussed earlier.

Output: Two database files are generated by this module. The first, named "??.WTR", contains all information related to the "weather pixels" (X and Y pixel locations of the upper-left corner of a weather pixel, wind components, air temperature, dew point depression, 3-hour rain accumulation, 3-hour snow accumulation, and total accumulation of water liquid equivalent after each 3-hour time step). A second companion database named "??.XgY" contains a B+ tree indexed by X and Y locations.

WGIS - (Integrated Weather + Geography GUI)
Objective: The main goal of this module is to integrate into a single, graphical, user-friendly interface all geographic and meteorological information required for a particular application. The user is empowered to easily maneuver through the computer screen, selecting at will any desired combination of information.

Input: Input for WGIS are three geographic ("??.GEO", "??.XgY", "??.RDS") and two weather ("??.WTR", "??.XwY") databases described under the discussion of DBGIS and DBWIS.

Output: The product of this last module is a menu-driven, interactive graphic user interface controlled by mouse point-and-click actions and running under the Windows 3.0 or 3.1 environment.

3.3. Operational Procedures

The procedures outlined below describe the operational use of the WELS system under its current setup. It should be emphasized that the system, while it was under development, needed a good deal of flexibility to accommodate research needs as well. This fact is reflected in the many user choices that are required during the initialization steps of the system. Most of these steps will be eliminated in a "turnkey" system design, thus providing a more or less uninterrupted flow of the program with only a few check points to assure smooth functioning of the prediction model under a sufficiently dense stream of observational data.

3.3.1. Data Reception

At WELS Weather Central procedures have been established which facilitate the preparation of weather forecasts following the steps outlined in Section 3.2.

When the computer used for data reception is booted up (either by powering it up or by pressing simultaneously <CONTR> <ALT> <DEL>), a batch program automatically sets the system to **data reception** mode. In this mode, the computer receives data from the Wegener Communications reception unit and stores them in files under the directory

\WELS\RAWD

The clock in this computer is set to Greenwich time. Under operational conditions the computer is running constantly, and so is a backup unit in case the primary unit should fail. Data reception is activated every six hours, at 0000, 0600, 1200, 1800 and 2400 GMT.

Reception is enabled at each of these times for a period of three hours. Data received during these time slots is sent to files which are automatically labeled as MMDD-HH.RAW, where MM indicates the month, DD the day, and HH the starting time of reception. These values are provided automatically by the computer clock.

Under this "robotic" data reception procedure the computer system can run unattended. (As was mentioned in Section 2.1.5, snow accumulation on the satellite antenna dish can lead to a deterioration of the microwave signal, hence to a loss of data. Under inclement winter weather the dish will have to be kept free of snow.)

Each of the raw data files contains approximately 1.7 Mbyte of information. Thus, one day's data reception requires hard-disk storage space of approximately 7 Mbyte. With a sufficiently large hard disk, data from several days can be stored. Presently the system is configured so that if disk space becomes insufficient because old files have not been deleted by the user, data reception stops. Old files are not over-written automatically. Therefore, the user should clear out old files after forecasts have been prepared successfully: While in the \WELS\RAWD directory, type

del *.*

to get rid of all old data files. Then re-boot to prepare the computer for reception of new data.

3.3.2. Data Decoding

To take the computer out of data reception mode one has to interrupt the batch process during boot-up by typing

<CONTR> <C>

until the screen exhibits the DOS prompt

C:\>

To check if observational data have been received properly, change from the root directory by typing

cd \WELS\RAWD <ENTER>

and then

DIR <ENTER>.

The files listed after this command should be named according to the above described convention and should contain significantly more than 1 Mbyte of data, especially for the main synoptic observation times of 0000 and 1200 GMT when radiosonde and surface observations are essential for the running of the numerical prediction model. After satisfactory reception of the 0000 or 1200 GMT data the decoding process can begin. While in the directory \WELS\RAWD type

DECO

to activate the decoding program.

Anticipating future research and development needs, the decoding, analysis, grid generation and forecasting modules of PIWPS contain a number of options which are exhibited on the computer screen, prompting the user for appropriate input. In "turnkey" operational systems these queries for option choices can be eliminated to simplify procedures.

Under the present setup the user is first asked for the input source of data:

<K> KEYBOARD <F> FILE

The query is answered by typing

F <ENTER>

since the required data reside in the aforementioned files. (The keyboard option provides the capability of entering data for special studies via keyboard.)

Next, the user is asked to choose from the starting file options

<Y> KEEP DEFAULT <N> NEW FILE

Type

Y <ENTER>

to have the suggested default files generated by the program

C:\WELS\EXEC\DCUS.SET

which sets up the forecast region for the United States. Other options, not appropriate for operational use, would let the user specify other regions by latitude and longitude for which the received data should be analyzed.

The user is now prompted to enter sequentially the MONTH (01 to 12), DAY (01 to 31), YEAR (00 to 99), and HOUR (00 or 06 or 12 or 18) by which the data files to be decoded can be identified. The user input has to conform to the file names which have been generated automatically by the computer clock, as described above. As an example, the user may supply the values 03 for the month (March), 07 for the day, 92 for the year, and 12 for the 1200 GMT observation time. In this case the computer confirms the choice by displaying:

DEFAULT FOR RAW DATA TO DECODE IS C:\WELS\RAWD\0307-12.RAW

which is the name of the file that had been generated during automatic data reception and is now being decoded.

The decoding process takes approximately 2 to 3 minutes. From the vast amount of data received it searches for only those data which are needed to initialize the numerical prediction model. While the program is running the screen displays a rather long sequence of files generated by the decoding procedure. Meteorological variables (actual temperature, dew point temperature, specific humidity, wind, and geopotential height) at a number of constant pressure surfaces (100, 200, 300, 500, 700, and 850 mb) are stored in separate files, identified by appropriate file names.

----- DONE -----

signals the end of the decoding process.

At WELS Weather Central raw data are received simultaneously on a second, backup computer (a 286 AT clone). Should the main system fail, raw data can be retrieved from this computer. Such data could be accessed directly by other computers if a LAN (Local Area Network) were installed. Lacking such a facility, data would have to be transferred between computers by floppy disk. Since the raw data files are too large to fit on one disk, they have to be compressed first.

Compression and decompression programs are available on a floppy disk, to be inserted into drive A. They are found in a directory

A:\UTIL

When in this directory, type

pack a MMDD-HH <ENTER>

where MM stands for month (01 to 12), DD for day (01 to 31) and HH for hour (00, 06, 12, or 18). The packing program automatically adds the suffix .RAW to the appropriate data file. The user is prompted to insert a new, **formatted** disk into drive A. After <ENTER> the packed file is transferred from the hard disk C to the floppy disk in A. If data from more than one observation time need to be transferred to the main computer, the procedure has to be repeated, one observation period at a time.

Note: Only **one** observation time (e.g 0000 or 1200 GMT) can be handled by the decoding, analysis, and forecasting programs in the main computer. Therefore, data for more than one observation time extracted from the receiving computer should be retained on floppy disks until the main computer is ready to handle them.

In this manner, WELS Research Corporation has retained on floppy disks the raw data for all snowstorm cases investigated during the past winter season. There were 25 such cases, some of them lasting for several days (see Section 4). We, thus, have accumulated a sizable archive of meteorological data which can be used in future studies.

When the main computer is ready to receive data from the auxiliary unit, the floppy disk containing compression and decompression programs is inserted in drive A of the main computer. The decompression program is found in the directory

A:\UTIL

and is activated by typing

inst a MMDD-HH <ENTER>

when in that directory. MM, DD and HH values have to be identical to those provided in the compression procedure described above.

The user is now prompted to insert the disk containing the compressed data into drive A. Upon <ENTER> the decompression process writes the raw data to appropriate files. The decoding program can now proceed as described earlier in this Section.

3.3.3. Data Analysis

When in the directory C:\WELS\RAWD, type

ANLZ <ENTER>

to activate the data analysis program. This program interpolates observational data from irregularly spaced radiosonde and surface observation stations, stored in files generated during the decoding process, to regularly spaced grid points. It then generates contour lines (iso-lines) for a number of meteorological variables, as well as wind vectors at each grid point location. The analysis results can be displayed on the computer screen as overlays over a map of the United States with political boundaries. The results can also be directed to a printer or plotter.

First, the user has to enter an appropriate choice number:

<0> TO QUIT
<1> TO RESEARCH MODE (ANALYSIS)
<2> TO OPERATIONAL MODE (DIAGNOSTICS>

Typing

<2> <ENTER>

sets the program up for operational use. Under these conditions the analyses produced by the program are used mainly for diagnostic purposes:

- to check if sufficient data have been received to produce a reasonable forecast;

- to see if any coding or transmission errors produce awkward and inconsistent "bulls eyes" in the analyzed data.

If the latter were the case, an experienced user can access the original, decoded data files and change the offending numerical values. The analysis program can then be run again, based on these altered files.

Next the user is prompted to enter month, day, year, and hour in the familiar manner described earlier. A question concerning the DIRECTORY FOR INPUT (UDCO SUGGESTED) should be answered by typing

udco <ENTER>

After these entries, a choice has to be made from a variety of display and printer options:

PC >>	<0> CRT	<1> DOT-MTX-PRT	<2> LSR-JET
HP7585	<3> WITH A3	<4> WITH A4	
HP7550	<5> WITH A3	<6> WITH A4	
HP >>	<7> CRT	<8> HP-2397	<9> 7550
	<999> TO ESCAPE		

Selecting

0 <ENTER>

requests a choice of graphics card options:

<0> CGA B/W
<1> EGA 16 COLORS
<2> VGA 16 COLORS
<999> TO ESCAPE

Our present system requires choice <2>.

Under operational conditions there should be no need to save the files for deferred plotting. Hence, the next question pertaining to this issue should be answered with <N> for "No."

Contour lines drawn by the analysis program use a spline function. The user is given a choice to determine the degree of smoothing such a function should exercise in connecting data points. The query

----- SMOOTHING (SUGGESTION 2, MAX 20) -----
<0> NONE <+INT> (+TENSION >-> -SMOOTH)

asks the user to provide a value for the "tension" of the spline function that "stretches" a line between unevenly spaced data points[7]. The simple example of Fig. 3.3 shows how these data points determine the position of the iso-line of value "10" as it winds through an array of grid point data. If option "0" is chosen, no smoothing takes place and the line would appear as shown in Fig. 3.3. In this case, the next question will not be asked. If a relatively large number (<20) is chosen, the line between data points will be stretched tautly, i.e. with high tension, again producing a jagged line. The user is advised to choose a value of 2 for optimal results.

[7]see e.g. B. Carnahan, H.A. Luther, and J.O. Wilkes, 1969: "Applied numerical methods." John Wiley & Sons, Inc., New York, 604 pp.

The query

SMOOTH CONTOUR POINTS FACTOR (1 TO 10)

requires input on the number of "dummy" data points to be inserted between those constituting the line (as for instance shown in Fig. 3.3). A relatively high number (e.g. 10) will provide the smoothest appearance of the line.

After this last query the program proceeds to calculate the meteorological variable values, such as sea level pressure, air temperature, dew point temperature depression, etc., for the coordinate positions I and J of all grid points used in the analysis program, using observational values from all stations whose data were captured by the reception unit. The total number of these stations is exhibited on the screen, e.g. as

= 229.

Data analysis will proceed, even if very few stations (as few as 7 over an area the size of the United States) had reported. (To run the numerical prediction model, a much higher density of reporting stations is required. See below.)

The program computes a number of derived fields of interest to a meteorologist, such as vorticity, vorticity advection, temperature advection, moisture divergence, etc.
The final message

----- ATTENTION, CHARTS OUTPUT -----
----- READY TO DISPLAY GRAPHICS -----
_____ Press <ENTER> when ready to continue -----

alerts the user to turn on the printer if a hard-copy output option had been chosen earlier. If the output was directed to the CRT, <ENTER> will set in motion the sequential display of all the calculated data fields. Scalar values (such as temperature, dew point depression, etc.) are shown as contour lines superimposed upon a political map of the United States with continental and state boundaries. Winds are shown as "arrows" originating at each grid point and "flying" with the wind, their length being proportional to wind speed. The wind speed scale is shown near the bottom of the CRT as the length of an arrow labelled with the maximum wind speed encountered within the map boundaries.

Maps displaying upper air wind and geopotential height observations at constant pressure surfaces also show the position of reporting stations. (In non-operational use surface maps, such as sea-level pressure maps, could be forced to exhibit the vast number of reporting surface stations.)

The professional user will view these map displays in order to find out

(1) if observations from stations which might influence the weather patterns in the area of interest, e.g. Colorado, have not been received or have been

lost during the decoding process. If such were the case, the resulting numerical forecasts cannot be deemed reliable;

(2) if "unreasonable" contour patterns (e.g. the appearance of "bull's eyes") suggest faulty observations, miscoded or misinterpreted data. Fortunately, such pattern inconsistencies appear rather infrequently after intensive debugging of the decoding program. In the rare event of questionable data quality, the user can access the decoded data files and alter data values according to experience. This procedure requires considerable expertise and is not recommended under operational conditions. Even if a questionable station report enters into the analysis program, the smoothing involved in the translation of station values to grid point values tends to blunt the effect of such errors on forecasts.

Professional meteorologists will find the displays of derived quantities, such as vorticity advection, moisture flux convergence, etc. very helpful in understanding the predicted weather developments.

3.3.4. Prediction Model Initialization

As involved as the above described steps may sound, a user with minimal practice will complete them in less then 10 minutes. (Foregoing the analysis part explained in Section 3.3.3 will save approximately 5 minutes of this time.) Setting up the numerical prediction process is equally quick. At the C:\WELS\RAWD> prompt, typing

GRDW <ENTER>

activates the process by which meteorological variable values are generated on the grid used in the numerical prediction process. This grid is not necessarily identical to the one used to depict the analyses of data described before. It is determined by the size of the domain to be covered by the forecast and by the number of grid points allowed in the X- and Y-directions. (These parameters were set earlier by the program GRIDZ, see Section 3.2, which interacts with the geographical database.) The domain of the analysis grid is larger than that of the forecast grid, because observed meteorological conditions outside the forecast area are needed to determine conditions at the lateral boundaries of the forecast area.

Under the present system configuration concerned with weather prediction for Colorado the forecast domain extends from the East Pacific off the U.S. West coast to the Alleghenies, and from southern Canada to northern Mexico (see Fig. 3.4). The file in which these grid characteristics are stored is named "GRIDZZ" in the directory C:\WELS\GRID. For operational use, the query

----- FILE FOR GRID CHARACTERISTICS -----
DEFAULT FOR GEOGRAPHIC PARAMETERS IS C:\WELS\GRID\GRIDZZ
<Y> KEEP DEFAULT <N> NEW FILE

should be answered with

```
Y <ENTER>
```

The query

```
----- FILE TO RECEIVE WEATHER GRIDS -----
DEFAULT FOR WEATHER GRIDS IS C:\WELS\GRID\GRID00
<Y> KEEP DEFAULT    <N> NEW FILE
```

should also be answered with

```
Y <ENTER>.
```

Next, the user is asked to provide input for month, day, year, an hour of starting time of the prognostic model. The keyboard input to these questions has to conform exactly to the answers given earlier to similar queries, so that the appropriately named files can be found.

The next question relates to options regarding the origin of soil temperatures needed in the prediction model calculations:

```
----- OPTION F/ UNDER_GROUND TEMPERATURE -----
<0> FROM A FLAT 320_DEG (BAD OPTION)
<1> FROM LAST MODEL OUTPUT
<2> FROM SURFACE OBS (DECO)
<3> FROM (TMAX+TMIN)/2 (ADP ONLY)
```

Option "0" assumes a uniform initial ground temperature of 320 deg Kelvin. This option should not be used in the prediction of winter weather conditions. Option "1" would use the output from prediction model runs of the previous day, if such output had been saved in appropriate files.

Option "2" is used in the current setup. It accesses the 6-hourly surface observations received via satellite and processed by the DECO program described earlier. (The data reception window is "opened" at 00, 06, 12, and 18 hour GMT for 3 hours each time to receive data. During the next 3 hours these data are processed to extract surface temperature and precipitation observations.) The six-hourly surface air temperature observations near the ground are then averaged over a 24-hour period to give an estimate of the ground (soil) surface temperature.

Option "3" estimates soil surface temperatures from the daily maximum and minimum temperatures reported in historic "ADP" data files as, for instance, received from NOAA or NCAR. This option has been used by us to study the predictability of historic blizzards.

After Option "2" is entered, the program processes the four data files containing 6-hourly temperature observations. The next query relates to

----- OPTION FOR PRECIPITATION -----
<0> FROM A FLAT 0 MM (BAD OPTION)
<1> FROM LAST MODEL OUTPUT
<2> FROM SURFACE OBS (DECO)
<3> FROM PP24 REPORT (ADP ONLY)

As before, Option 0 is a gross simplification, assuming that there was no precipitation anywhere in the forecast domain during the 24 hours prior to the present prediction period. Option 1 would access a file in which predicted precipitation from the previous day had been stored, if such had been the case.

The current setup requires Option 2, which accesses the 6-hourly decoded observational data from which precipitation amounts have been accumulated to yield 24-hour totals.

Option "3" would find 24-hour precipitation totals from ADP data files received from NOAA or NCAR to study historic cases.

After choosing

2 <ENTER>

the program starts processing the precipitation values obtained from the program DECO and then generates all other meteorological data fields required by the numerical prediction model. As each data file is accessed, a report such as

= 330

is issued on the screen, showing the user how many reporting stations provided input data. If the number of reporting upper air stations falls below 80, one "beep" alerts the user to that fact, and program execution stops. Two beeps signal fewer than 40 stations, and three beeps fewer than 20 stations transmitted data. The user can override this alert by pressing

<ENTER>

and program execution resumes. In the case of dew point data from stratospheric levels, low numbers of reporting stations are the rule rather than the exception. Also, the number of stations reporting observations at 850 mb may fall below 80 over the United States, because in the Rocky Mountain region this pressure level tends to be located fictitiously under ground, hence has no actual observations. Under normal conditions observational data from the lower troposphere should be available from close to 90 stations over the region used in the present model setup. As has been mentioned before, lacking observations may adversely influence forecast quality. Execution of the analysis program discussed earlier will provide important indications concerning lacking data.

The message

----- DONE -----

signals the completion of data processing into the grid format needed for the numerical prediction model.

3.3.5. Numerical Prediction

At the DOS prompt, type

NEST <ENTER>

to activate the numerical forecasting procedure. From the initial weather conditions provided at 0000 or 1200 GMT in the gridded data format derived above, and from the boundary conditions as specified by the underlying terrain, this procedure integrates a system of hydrodynamic, thermodynamic and continuity differential equations to arrive at "future" weather conditions every three minutes, out to 24 hours.

First, the user is asked to give the

NUMBER OF GRID POINTS IN X (1 to 70)

then the

NUMBER OF GRID POINTS IN Y (1 to 42).

Under current operational conditions, the number of X-direction grid points has to be = **45**, the number of Y-direction grid points = **35**. Entering different numbers causes incompatibilities with earlier decisions of grid generation (program, GRDZ).

The numerical predictions are carried out on six vertically stacked surfaces, the lowest 600 m above the terrain and "warping" with the shape of the terrain. The top of the atmosphere is assumed at the 60-mb level and no longer "warps" with the terrain. Because observational data come from constant pressure surfaces (such as 850 mb, 700 mb, 500 mb, etc.) which do not coincide with the "terrain-following" surfaces of the prediction model, the vertically stacked data set at each grid point location derived from observations has to be translated to the six levels used by the computational model. The user is given choices of interpolation methods used in the transposition of these data:

----- VERTICAL INTERPOLATION OPTIONS ____
<0> LAGRANGE WITHOUT SURFACE OBS
<1> LAGRANGE WITH SURFACE OBS
<2> SPLINE WITH SURFACE OBS

Under current operational conditions the user should pick Option "0". The remaining two options have been used by us during a number of development experiments.

The length of the forecast period is determined by the number of forecasting steps asked for in the next query:

----- ENTER # OF STEPS (121,241,361,481) -----

A 24-hour forecast requires 481 3-minute forecasting steps. The shorter intervals provided in this option had been used under test conditions.

Present operational conditions do not permit other step options, nor do they allow generation of forecasts beyond a 24-hour period. The 24-hour restriction is mainly imposed by our assumption of "fixed" lateral boundary conditions: Observed weather conditions interpolated along the lateral boundaries of the forecast domain shown in Fig. 3.4 are assumed to remain constant during the 24-hour forecast period. This assumption is factually wrong, but is necessitated by the fact that we do not know, without using someone else's predictions, how the weather will develop along these boundaries. This assumption will impact severely on the quality of forecasts beyond 24 hours. (In future developments we plan to use the National Weather Service's 24-and 48-hour predictions from the previous day to estimate weather changes along the lateral boundaries of our model. Such predictions will also contain errors, but hopefully smaller ones than caused by the imposition of "fixed" conditions. These predictions are not received by our present data reception and decoding setup.)

The next query asks for the source of the prognostic setup:

----- PROG SETUP SOURCE -----
<K> KEYBOARD <F> FILE

which is to be answered by

F <ENTER>.

The setup preserved in the appropriate file specifies that output from the nested grid model over Colorado should be saved every 6 hours for the production of weather maps, using analysis procedures identical to the ones described before. Output is saved every three hours, however, to be channelled to the Graphics User Interface (GUI) running under Windows 3.1. It is this output which can be viewed and manipulated by the user in the field under the latest development status of the WELS prediction model.

The keyboard option provided above would allow changes in the frequency of forecast data preservation. Data could, for instance, be saved every hour. Such increased frequency would, however, generate problems with memory capacity and with the menus presently provided by the GUI.

The next query asks for

----- DEFAULT FOR SETUP FILE IS C:\WELS\EXEC\NEST.SET -----
<Y> KEEP DEFAULT <N> NEW FILE

Operationally we recommend to answer

Y <ENTER>

thereby keeping the default settings by which the nested grid model is run. This model produces output of temperature and wind conditions 600 m above terrain and precipitation at the surface over a domain slightly larger than, and centered on, the State of Colorado at 3- or 6-hour time intervals as explained above.

The final query

----- OPTION FOR DEFAULT QUESTIONING -----
<Y> YES <N> NO

should be answered with

N <ENTER>

since we already accepted the default settings we do not wish to waste time being asked about them.

After this last keyboard input the prediction model automatically runs its course. On a 486/25 Mhz computer it takes a little less than one hour to complete the operation, on a 486/33 Mhz machine the required time is proportionally shorter. While the model is running a table is scrolled on the screen showing the number of the current time step being processed, the time in minutes of this step, and values of kinetic, potential, and total energies computed for the whole model domain. (To the experienced user the behavior of these values with time gives indications of the "stability" of the model in the long run, and on the effects of gravity waves shortly after the model is turned on.)

As the program runs, it automatically generates files in which 3-hourly values of parameters, such as temperature, wind, humidity as difference between actual and dew point temperatures, and precipitation are saved for certain city locations (file name RCOST contained in the directory C:\WELS\RSLT). The RCOST file is accessed by the user interactive Roadweather Pro programs which display forecast histories at these specific city locations and permit alterations of the forecast precipitation and temperatures by inserting user-supplied observational data. At the same time, files are generated which contain such forecast histories at 3-hourly time steps for each grid point of the nested grid (ca. 24 km horizontal resolution) overlying Colorado. These files are used by the GUI. The procedures involved in using these files will be described later.

3.3.6. Display of Maps.

Before the development of the user-interactive GUI running under Windows 3.1, forecast data were delivered to users in Greeley and Boulder, CO, in the form of automatically analyzed weather maps. Although this form of data delivery was not considered ideal, it was essential to the testing of forecast quality and timeliness. Here we describe the steps involved in the preparation of CRT and hard-copy outputs.
Hard copies were used in the earliest stages of data transmission. They were sent by FAX to Greeley. Weather maps were also posted on a display board in the WELS offices. Predictions were compared continuously with actual weather development observed in the Boulder/Denver area. Frequent telephone conversations with Colorado Department of Transportation personnel in Greeley provided a good overview of developing weather situations in the northeastern part of the State.

The following, brief description outlines the steps in the now obsolete data transmission to field stations.

At the DOS prompt type

```
CRTN <ENTER>
```

to activate the program module which produces mapped forecast output.

From the options

```
-----------------------------------
<0> TO QUIT
<1> TO CRTZZN (NESTED GRID TOPOGRAPHY)
<2> TO CRTFRN (NESTED GRID PROGNOSES)
```

the operational user picks

```
2 <ENTER>
```

Option 1 would display on the CRT (or print out in hard copy) the topographic elevations used in the nested grid model over Colorado.

Next comes the selection of plotting devices:

```
----- PLOTTING DEVICE SELECTION _____
PC >>      <0> CRT        <1> DOT-MTX-PRT     <2> LSR-JET
HP7585     <3> WITH A3    <4> WITH A4
HP7550     <5> WITH A3    <6> WITH A4
HP >>      <7> CRT        <8>HP-2397          <9>7550
           <999> TO ESCAPE
```

To display maps on the computer screen, the user picks

0 <ENTER>.

Under this option the user chooses from

----- GRAPHIC CARD SELECTION -----
<0> CGA B/W
<1> EGA 16 COLORS
<2> VGA 16 COLORS
<999> TO ESCAPE.

Else, for hard-copy printout one of the printer and/or paper format options is chosen. In our present, operational setup we would pick

1 <ENTER>

to direct the output to our dot-matrix printer. Under this printing option a choice has to be made among communication ports:

----- PORT SELECTION -----
<0> LPT1/LPT2
<1> COM1
<2> COM2
<999> TO ESCAPE

Our operational setup requires

0 <ENTER>.

Further, the user has to make a

----- PRINTER TYPE SELECTION -----
<0> IBM PROPRINTER
<1> EPSON MX
<2> EPSON JX
<999> TO ESCAPE

Our printer emulates

2 <ENTER>.

From here on the hard copy option uses the same queries as the CRT display option, namely

----- ISOLINE SMOOTHING (SUGGESTION 2)----
<0> NONE <+INT> (+ TENSION, - SMOOTH) ?

which has been described earlier as adjusting the "tension" in the spline function which connects data points (see Fig. 3.3), and

----- EXTRA POINTS (1 NO SMOOTHING, 10 MAXIMUM) -----

for which we recommend at least a value of 2, preferably of 10 as input choice.

Next, the user is asked for the

----- DEFAULT FOR GEOGRAPHIC PARAMETERS IS C:\WELS\GRID\NESTZZ
Y> KEEP DEFAULT <N> NEW FILE

Our operational setup requires the response

Y <ENTER>.

The question

----- DEFAULT FOR NESTED GRID PROG. PLOTS IS C:\WELS\RSLT\RNPLT
<Y> KEEP DEFAULT <N> NEW FILE

should also be answered with

Y <ENTER>

The user can now select from various fields to be plotted by answering each of the following questions by either Y or N:

----- DO YOU WANT PLOTS OF WIND FIELDS?
<Y> YES <N> NO
----- TEMPERATURE FIELDS?
<Y> YES <N> NO
----- 6 HR LARGE SCALE PRECIPITATION?
<Y> YES <N> NO
---- 6 HR CONVECTIVE SCALE PRECIPITATION?
<Y> YES <N> NO
----- 24 HR TOTAL PRECIPITATION?
<Y> YES <N> NO

The final question

----- SAVE FILES FOR DEFERRED PLOTTING -----
<Y> YES <N> NO

should be answered with

N <ENTER>.

The program now computes iso-lines. By pressing <ENTER> at the signalled completion of these computations, maps are displayed on the screen. Their sequence can be shown by repeatedly pressing <ENTER>.

Since our present setup plots winds and temperatures on the same map, answering either one of the first two queries will produce such a plot. "Large scale precipitation" is produced by vertical motions and moisture condensation in saturated air computed from the meteorological fields represented by the grid point values. "ConLaserJet VENUSHPLASEII.PRS grid point spacing of the model. Winter blizzards usually are portrayed completely by "large scale" precipitation only, because they are relatively widespread phenomena. As spring approaches, such precipitation events may have embedded thunderstorm or heavy shower activity, which comes to light in the "convective" precipitation calculations. In the choices presented above, 6-hourly accumulations of precipitation are presented. The 24-hour total precipitation combines the "large scale" and "convective" parts of each 6-hour period and sums them up to reach a final 24-hour total.

Providing 6 hour time steps in these display modes was occasioned by the fact that transmission of graphical weather maps to Greeley via a relatively slow, 2400 baud modem took considerable time. (The maps listed above usually took about 20 minutes to transmit.) With the new display configuration running under Windows 3.1 data files can be transmitted much quicker, hence will allow displays at 3-hourly forecast intervals. With the installation of 9600 baud modems the data access time decreases to only a few minutes. For a larger number of end users feeding from the same data source a file server and network (e.g. Novell) arrangement has been proposed to the Colorado Department of Transportation.

The procedures described above pertain to the output display from the nested grid model which covers an area somewhat larger than the State of Colorado (Fig. 3.5). (The domain of these model calculations can be moved to, and customized for, practically any area of the United States where terrain and weather data can be made available.) This area has a horizontal grid resolution of approximately 24 km and is "nested" within a much larger area, roughly the size of the contiguous United States (Fig. 3.4), in which the grid resolution is approximately 96 km. It is in this larger area that meteorological conditions are forecast for 3-minute time intervals, using a limited-area forecasting model (LFM). As discussed earlier, within the nested grid the effects of detailed terrain are estimated. Since forecasts are produced for most of the United States, they can also be displayed, by running the program

CRTS

at the DOS prompt. We were surprised to see how well this LFM predicted the heavy precipitation events of last winter in Texas and California which led to widespread and devastating flooding in these regions. Encouraged by these findings we have teamed with a hydrological engineering company to propose the development of a "hybrid" meteorological-hydrological prediction model for flood warning and control purposes.

Running CRTS brings up the query

<0> TO QUIT
<1> TO CRTZSL (TOPOG./AZIM./ELEVAT.)
<2> TO CRTOBS (PROG. INPUT GRIDS)
<3> TO CRTFRC (PROG PROGNOSES GRIDS)
<4> TO CRTIME (PROG TIME VARIATIONS)

Option "1" displays topographic data (elevation, azimuth angles) in map form. Option "2" allows the user to view the meteorological data fields used to initialize the model. These fields have already been converted to grid point values, hence may differ from the ones described earlier in the "analysis" program which were based on observational data.

3 <ENTER>

is the option to be chosen under operational conditions. Option "4" can display the temporal variation of a number of parameters (geopotential height, temperature, moisture, wind etc.) for a grid point near the center of the forecast area in terms of departures from the 24-hour averages of these parameters at that point. This option proved to be useful during the "shake down" period of the WELS prediction model to check on possible erratic behavior of forecast conditions.

Having made the proper choice, the user is led through queries regarding output devices, graphics cards or printer options, degree of spline function smoothing and default file options very similar to those described earlier.
One additional query

----- HIGHEST LEVEL TO PLOT 1,....6(LOWER) -----

prompts the user to specify the volume of data to be displayed. Choosing

6 <ENTER>

will provide maps for the 850-mb level, together with precipitation at the surface. Choosing the smallest number, "1", will cause all pressure levels and their associated maps to be plotted or displayed. Such an option choice would consume considerable computer time.

It takes only on the order of 5 minutes to produce CRT output of weather maps, after the numerical model has run its course. It may take up to 20 minutes to produce hard-copy printout on our dot-matrix printer.

3.3.7. Communication with Field Stations

As soon as PIWPS was running operationally (end of October, 1991) forecast results were communicated by telephone to key personnel of the Colorado Department of Transportation in Greeley (Maintenance District 1). Recipients of this information were Mr. Mike Anderson and Steve Carlson. Next, a facsimile transmission link was established which allowed us to transmit hard-copy maps in black and white. Together with explanations provided via telephone, this was the mode of operation until the State of Colorado provided us with a dedicated telephone line and a modem link. It was the details of predicted precipitation distribution evident on the FAX maps, and their lack of color differentiation that prompted CDOT personnel to press for the establishment of a more sophisticated communication link.

Going through State bureaucratic channels for telephone and modem installations required considerable time. Finally, by the end of January 1992 these installations were operational. Communications software and procedures had to be developed and installed in Greeley. This was done during the last week in January. Similar software was installed in the Research Division of the Colorado Department of Transportation in Denver on Monday, 3 February, to be ready for a "live" demonstration to CDOT personnel on Tuesday, February 4. With the cooperation of a snowstorm on February 3, this demonstration was very successful. On February 13 the interactive part of Roadweather Pro (discussed in Section 3.3.8) was installed in Greeley and personnel were trained in the use and interpretation of PIWPS-generated map displays and in the handling of Roadweather Pro.

On February 18 similar installation and training work was performed at the Boulder Foreman/Supervisor station.

To prepare weather map presentations for transmission to these outlying field stations, we used Show Partner F/X software. This software runs under DOS and allows the capture of graphics screens generated in a DOS environment. (This software does not work under Windows and had to be replaced by HiJaak distributed by Inset Systems.) Show Partner's screen-grabbing program can be installed as one of the menu options provided by F/X. It is a TSR (terminate and stay resident) program, i.e. it is accessible by pressing

<CONT> <ALT> <->

even when other programs are running, provided that there is enough real-mode memory left in RAM. (The <-> in the above referred key combination has to be entered from the numerical key pad.).

After installation of F/X the user runs CRTN in the fashion described before. As each map to be transmitted to field stations is displayed on the screen,

<CONT> <ALT> <->

is pressed. This action brings up a prompt requesting file name and path information. (In our operational setting we use C:\WELS\RSLT as the storage directory of these files.) After this information is entered and confirmed, the screen contents are transferred to the specified file with a suffix *.GX2. This suffix indicates the format in which color pixel contents is stored in memory. (F/X also provides software translating between *.GX2 and *.PCX files, the latter being a format preferred by many color printers.)

The individual files thus generated are rather voluminous, containing between 25 and 40 Kbytes each. If 12 such files were transmitted, we would have to send approximately 400 Kbyte at a transmission rate of 2400 baud, or bits per second. Since one byte contains 8 bits, it would take approximately 22 minutes to accomplish this transmission task. Using PKZIP software to compress these files before transmission, and decompress them after reception in Greeley, the transmission time requirements were approximately halved. ("Zipping" and "unzipping" these files takes less than one minute.)

Under this operational mode WELS Weather Central operated for the rest of the winter season until the end of March 1992.

With the development of a new graphical user interface (GUI) which runs under Microsoft Windows 3.0 or 3.1 it will no longer be necessary to transmit lengthy graphics files. Instead, all graphics display software requiring Windows will be resident on computers at field stations. WELS only needs to transmit one data file per 24-hour forecast period, containing gridded forecasts for the nested grid domain (e.g. the State of Colorado). Data will be collected for 3-hour intervals rather than the 6-hour intervals dictated by the low transmission rate in the above described setup.

The Colorado Department of Transportation requires display data only for precipitation, temperature, humidity and winds near the surface. Hence, no upper-air forecasts need to be delivered to field sites. The data file containing the required information, in our present setup named RGPLT, has approximately 690 Kbyte of ASCII-type information. The transmission will not use ASCII but binary format, cutting the file sizes by more than 50 percent to about 230 Kbyte. File compression "zipping" will bring the size down to 100 to 150 Kbyte. At 2400 baud the transmission time will be on the order of less than 8 minutes. A 9600-baud modem on dedicated, "clean" telephone lines is expected to cut transmission time to less than two minutes.

Even without investment into a file server and networking hardware/software, one dozen users could be accommodated with only minor delays.

Under the present setup, the operator in Greeley or in the Boulder Foreman's office only has to type

DIAL <ENTER>

to activate the modem connection to the WELS Weather Central, receive and decompress the data and start the screen display of weather maps. If the computer is used for other tasks which require interruption of the weather display, the user only needs to type

VIEW <ENTER>

at the DOS prompt, and the map display will resume.

With the installation of the Windows version of Roadweather Pro we intend to explore an arrangement whereby the computers at field stations are set to modem "receive" mode during anticipated data transmission "windows". WELS would then initiate the calling sequence and transmit the forecast data. An automated calling cycle for all hooked-up field stations could be established. Under such an arrangement one would avoid the possibility of users requesting data but meeting a "busy" signal on the modem line.

3.3.8. Expert Weather Advisor

There will never be such a thing as an absolutely accurate numerical weather forecast. The reasons for this pessimism lie in the facts that

(1) spacing between radiosonde observations is on the order of 300 miles over well-monitored continental regions. There is a dearth of observations over the oceans and in developing countries;
(2) observations are made twice a day.

Even if all meteorological parameters were measured everywhere all the time (consuming a multiple of the global gross economic product, with the total global work force committed to meteorology)

(3) we have an incomplete understanding of atmospheric physics, and the interaction between the atmosphere and the underlying (continental or oceanic) boundary;
(4) these physical processes have to be truncated into tractable computational approaches.

All these shortcomings impact on numerical prediction model accuracy.

Presently lacking in professional weather prediction is a capability to alter forecasts produced by numerical models quickly by user-generated input of local observations. The concept of "hybrid" modeling developed at WELS[8] and using object-oriented approaches to weather prediction addresses this serious flaw. Briefly, under this concept weather phenomena such as blizzards or thunderstorms are treated as objects which follow certain rules of behavior. These rules, or constraints, are based on conditions

[8]Reiter, E.R., 1991, see footnote 1.

which are either delivered from the output of a numerical prediction model or can be supplied by user input.

Under the current operational setup, "snowstorms" or "blizzards" are dealt with as objects existing at specific locations (e.g. a location to be picked from a menu). In future planned developments it will be possible to change the behavior of a snowstorm not only at that specific location chosen by the user, but to effect appropriate changes at neighboring locations which have similar terrain and weather conditions.

Software for user-interactive manipulation of predicted weather has been installed in Greeley, Denver, and Boulder. The written instructions attached in Appendix A have been provided to users.

The prototype version of Expert Weather Advisor has been coded in PROLOG and runs under DOS and has not yet been transferred to Windows. Such a transfer is planned for the near future. The program allows mouse point-and-click access to menus. These menus provide choices of user interaction to change forecasts of precipitation and temperature, based upon certain factual inputs. First of all, the liquid-water precipitation amounts provided by PIWPS and stored in the file C:\WELS\RSLT\RCOST have to be interpreted in terms of accumulating snow depth. The conversion of liquid water to snow has no hard scientific basis, but is based on "rules" developed in concert with the Colorado state climatologist and observations analyzed by WELS. These rules have been inserted into the Expert Weather Advisor as an embedded expert system. Basically, the conversion factor increases with decreasing temperatures. However, it also depends on the state of the ground: deeply frozen soil will accumulate more snow than thawed ground. Accumulation depends on additional factors which are difficult to account for. Compaction by wind and snow drift formation may cause large local departures from any estimates provided by the user's input choice.

User's choices are prompted in the screen shown in Fig. 3.6. The diagram on the screen reflects the conversion algorithms presently contained in the expert system. The user also has the option of choosing a constant factor which is selected by clicking the mouse at an appropriate Y-coordinate level on the screen. This Y-position is interpreted as the conversion factor value given along the ordinate. If the mouse is clicked at values < 1.0 a "beep" alerts the user that an inappropriate choice was attempted. Another choice will have to be made.

From a menu of locations the user chooses by mouse click the one of interest (in the present example "Boulder"). This action brings up a time history of snow (blue) temperature (purple) and wind forecasts (green arrows for 600 m level, yellow for estimated near-surface conditions). Clicking the mouse reveals a menu from which certain corrective actions can be chosen which will modify the forecast. These actions, again, call on embedded expert systems.

As an example, Fig. 3.7 shows a forecast for Boulder, together with the pop-up menu that allows correction of that forecast. Click "Adjust SNOW fcst", and from the next menu "Timing" (Fig. 3.8). (The example is provided by the March 8, 1992 severe blizzard, in which precipitation in the Boulder area, indeed, was delayed until about 2 p.m. as opposed to the original forecast.)

In Fig. 3.9 we re-ran the Boulder scenario, recalling "the last SNOW action". In this blizzard event, by about 9 p.m. more than 8 inches of snow had already accumulated, indicating a much more intense storm than had been anticipated originally in the Boulder area. Choosing from the adjustment menu "Intensity (much)" and clicking on a coordinate position corresponding to 20 h and 8 inches projects the new forecast (white line) to exceed 12 inches by early morning on the next day.

Adjustments to temperature forecasts can be made as well, as described in Appendix A. More about this blizzard case will be discussed in Section 4, and also in the subsequent section describing the Windows GUI.

3.3.9. Windows-Based GUI

The latest development work carried out by WELS was concerned with a graphical user interface (GUI) running under Microsoft Windows 3.0 or 3.1. This interface accesses the file RGPLT transmitted once or twice daily (for forecasts initialized with 0000 and/or 1200 GMT observational data).

The present prototype setup at WELS Weather Central uses 8 Mbyte of RAM in 486/25 MHz or 486/33 MHz computers. With this configuration, topographic and weather information can be loaded into computer memory, hence needs to be accessed from hard disk only once. After the requisite data have been loaded into memory (more details will be given below), switching between displays of different parameters is almost instantaneous. If insufficient RAM is available, the program may seek to access information from virtual (disk) memory, causing significant deterioration in performance.

Installation software for current highway maintenance applications is available on two floppy disks to be inserted into either drive A or B. When the installation disk is in place change the directory to either

A:\UTIL or B:\UTIL,

then type

install ? FileName <ENTER>

where "?" stands for either A or B to be typed, representing the appropriate drive name, and FileName is either CO (for the Colorado geographic database), D1 (for Colorado Maintenance District 1), or BD (for the Boulder/Denver area). These are "zipped" files contained in the root directory of one or the other floppy disks. By executing the "install" command, several directories and files will be created and installed on the hard disk drive C. The executable file WGIS.EXE will be located in the (newly created or pre-existing) directory C:\WELS\EXEC.

To make the GUI responsive to mouse point-and-click access, this executable file should be accessible as an icon in a Windows display. To generate such an icon, return to the root directory

C:\

and type

WIN <ENTER>.

Create a new Program Group by clicking on the menu option "File", then select "New" from the pop-up menu. In the now appearing window click the "Program Group" radio button and type

WELS

into the text box. After clicking the confirmation button, a new, empty program group window will appear, titled "WELS".

From the Main program group window, click the "File Manager" icon twice. (Should the Main group window be obscured by other windows, click on "Window" from the main menu bar, and select "Cascade" from the pop-up menu. This action will "stagger" all available group windows for easy mouse click selection.)

In the File Manager window find the directory WELS and, after clicking, the subdirectory EXEC. Double-clicking will reveal all the files in this directory. Move the cursor to the file WGIS.EXE, click once, and drag (by holding down the mouse button while moving the mouse) the file to the WELS Program Group window. (If this window is not visible, enlarge it first and/or shrink the File Manager Window before attempting to drag the file.) When releasing the mouse button in the WELS window, the WGIS icon should appear there (a "dog-eared" page with WGIS written underneath). To align this icon properly in the WELS window, click on "Window" in the main menu bar, then select "Arrange Icon". (Be sure to "Save the Settings" before exiting windows, so you will find the same screen arrangement when you load windows the next time.)

Double-click on the WGIS icon to run the program. A registration card will appear on the screen which you should fill out, and afterwards ignore by clicking either the "OK" or the "Cancel" button.

The window now appearing is labelled "RoadWeather Pro/Display". Its main menu bar exhibits the options

File
Display
Adjust
Zoom
Help

and the time frame of forecasts in hours

00 (i.e. initial observation time)
03
06
09
12
15
18
21
24

Menu options can be accessed by either clicking the mouse-driven cursor on them, or by pressing simultaneously

<ALT><?>

where "?" stands for the underscored character in the menu.

On the bottom of the screen is a small, oblong window which exhibits the current status of databases and their manipulations.

First of all, the user will have to load the required databases into memory. (For recommended memory configurations see the introductory remarks in this section.) Click on the menu item "File". In the pop-up menu, first choose

"Load Geography..."

The dialogue box provides choices of files to be opened. If the mouse-driven cursor is double-clicked on "co.geo" the topographic database for the whole State of Colorado is loaded into RAM. On the WELS computer systems this process requires less than 30 seconds. Click the "OK" button in the window confirming the loading process to be completed.

Databases for more detailed displays of Maintenance District 1 (northeastern Colorado) and for the Boulder/Denver can be loaded by making the appropriate file choices from the dialogue box. If the display should be changed, e.g. from "Colorado" to

"Boulder/Denver", the user will have to repeat the "File" loading procedures for both geographic and weather data.

From the main menu again choose the "File" option. This time click on "Load Weather...". From the dialogue box choose, by double-clicking, the file with suffix *.wtr whose prefix matches that of the geographic database loaded before, in this case "co.wtr". To load the weather prediction data into RAM takes only a couple of seconds. After acknowledging the loading process by clicking the "OK" button, choose "Display" from the main menu.

From the pop-up menu select "Terrain.." as our first display choice. A pop-up menu provides the display option

Elevation
Slope
Azimuth.

Under normal, operational circumstances the user will pick "Elevation". Of the options in the next pop-up menu, only "Replace" is implemented at this time. The subsequent dialogue box shows the default values of elevations to be displayed to lie between "0" and "16000" ft, typical for Colorado. Other limits (e.g. 5000 to 13500 ft) can be set by clicking on the appropriate text boxes and changing the values therein. Click the "OK" button once the desired values appear on the text input lines. The program takes about 10 seconds to find the requisite data in the database which has been formatted as B+ tree indexed by elevation.

In the current display configuration, using 16-color VGA, the elevation range between sea level (0 ft) and 16,000 ft is divided into 64 shades of "dithering" ranging from white via yellow to black. Thus, elevation "contouring" is achieved at approximately 250 ft intervals. The plains of eastern Colorado show up in yellow. The high ranges of the Rocky Mountains appear in dithered shades of yellowish gray. Note that the message "Elevation" appears in the small window near the bottom of the screen.

Painting slope or azimuth angles to the screen is equally easy, making the appropriate menu choices. Lower and upper limit values in the dialogue box are given in terms of angles in degrees. Note, that with the relatively large geographic pixels of the map of Colorado, an upper limit for slope angles of 10 degrees is quite adequate. If displaying the Boulder/Denver area with higher terrain details, larger slope limits (e.g. 30 degrees) should be set.

One of our 486/33 computers has a Super-VGA graphics card with an additional 1 Mbyte of memory installed. The attached color monitor can handle a resolution of 1024 x 768 pixels with 256 colors. Running the Roadweather Pro installation under this configuration still uses "dithering" to provide elevation differentiation, albeit with more shading intervals, thus giving a somewhat more "plastic" appearance to the terrain display. We do not feel, however, that for operational use the slight gain in display quality is worth the added expense for hardware and software, especially since the larger number of pixels to be displayed slows down noticeably the screen refreshing (re-painting) process under high-resolution Super-VGA.

Road networks can be superimposed upon the terrain displays by clicking on the "Display" menu option, then choosing "road Network", and "Toggles All" from the subsequent pop-up menu. (Separate displays for interstate and state highways have not yet been implemented.) It takes a few seconds to load the database. Repeating these menu procedures will turn the display of roads off. Thus, the display can be toggled at will.

Choosing "Toggles Boundaries" under the "Display" menu option brings up the State boundaries. (Of course, the Boulder/Denver display contains no such boundaries.) Drawing such boundaries to the screen is an instantaneous process. "Toggling" them "off", however (by clicking the same menu choice again) will take a few seconds, because all databases will be re-checked and re-drawn.

To show precipitation, a time value other than 00 will have to clicked, since at the starting time of the forecast period all "rain buckets" would be found empty. Only "temperature" and "wind" choices from the "Display" menu will show data at 00 forecast hours. The values shown are the ones used in initializing the forecast procedure.

Clicking any other forecast time will show data displays on the screen for each choice on the "Display" menu. Clicking on "General (3hP/T/W)" shows all predicted meteorological parameters at the same time. Since the computer screen will appear rather "busy" we do not recommend this option to start out with.

"Toggles 3-hour precip" brings up snow and rain amounts predicted for the 3-hour time interval ending at the time indicated by the menu choice Fig. 3.10).

"Snow" is shown as gray rectangles. Filling up the darkest ones requires 2 inches of snowfall in 3 hours. More snow, in increments of two inches, fills these rectangles with **lighter** shades of gray. White rectangles indicate snowfall in excess of 8 inches within the indicated time frame.

Rain fills up green rectangles in increments of 0.2 inches, proceeding to **darker** shades with each such increment.

The menu choices "Toggles total Rain" and "Toggles total Snow" permit to display rain and snow separately, albeit in terms of total amounts since the begin of the forecast period (i.e. since 00 hours).

Note that the choice of display option, as well as the displayed time frame, are indicated in the small window near the bottom of the screen.

"Toggles Moisture" shows the temperature difference between actual and dew point temperatures at times other than 00. Single-color light-blue rectangles indicate a difference near zero degrees, i.e. saturation. The geographic pixels thus displayed should have fog or clouds 600 m above terrain. The appearance of dark, and subsequently lighter shades of red indicate larger temperature differences, thus increasingly drier conditions. Each change in color signals an increment in such temperature differences by 10 degrees centigrade.

"Toggles Temperatures" fills color into rectangles according to predicted temperatures 600 m above terrain: As the first indication of red appears, temperatures begin to rise above freezing level (Fig. 3.11). A fully dark red box indicates +10 deg C. Lighter colors of red, yellow and white provide incrementation by 10 deg. C. Blue boxes are decremented by 10 deg. C. Thus the first indication of darker blue appearing in a light blue box signals temperatures of < -10 deg. C.

3.3.10. Presentations

In the course of the current project year the concepts and details of the WELS weather prediction system were presented by the Principal Investigator at several project reviews in Washington DC, and at a number of national and international meetings, as well as in special seminars:

Poster presentation at ASCE Highway Division Conference, Denver Marriott City Center, April 8-10, 1991.

Spring 1991, two seminar presentations for scientists in NOAA and the National Center for Atmospheric Research (NCAR).

Presentation of paper "Meteorological Applications of Hybrid Modeling Concepts" in a special workshop chaired by the P.I. during the XX General Assembly of the International Union of Geodesy and Geophysics (IUGG) and its sub-organization, the International Association for Meteorology and Atmospheric Physics (IAMAP). August 12 - 17, 1991 in Vienna, Austria.

Presentation of WELS modeling concepts to representatives of the Department of Highways, Government of Lower Austria, August 1991.

Presentation of WELS development status at the ASCE Conference on "Applications of Advanced Technologies in Transportation Engineering", Minneapolis, August 19-21, 1991.

October 11 - 13, 1991, demonstration and display at AASHTO Technology Transfer Fair, Milwaukee, Wisconsin.

October 24, 1991, presentation at Highway Operations Advisory Committee meeting, Washington, D.C.

October 1991 seminar presentation of WELS concept and results U.S. Air Force Geophysics Directorate, Phillips Laboratory, Hanscom AFB, Bedford, MA.

SHRP-IDEA review presentation, Washington, DC, 4 November, 1991.

Paper on "Mesoscale prediction by an object-oriented approach" presented at the 72nd Annual Meeting of the American Meteorological Society (Symposium on Weather Forecasting), January 7, 1992, Atlanta, GA.

January 14, 1992, seminar presentation on "Object-oriented nowcasting", Department of Meteorology, Florida State University, Tallahassee, FL.

February 3-4, 1992: System demonstration at CDOT, Denver, with live data transmission from WELS office in Boulder.

4
Field Testing Results

4.1. General

WELS Weather Central (WWC) started operations on October 28, 1991 to support highway maintenance operations for two levels of management - CDOT Maintenance Section 1 at Greeley, Colorado, and the Senior Maintenance Supervisor at Boulder.

Original contract specifications called for documented testing operations during at least three snowstorms. Yet a longer than normal snow season in Colorado enabled WELS to participate in the development of forecasts for many more snow events, some of which lasted for periods of several days.

From its first day of operation which was greeted with the first major snow storm of the season to the end of the test on March 20, 1992, WWC covered 25 snow events. This lengthy test period gave the corporation the added opportunity of fine tuning the Satellite Data Pre-Processor, PIWPS model, and Expert Weather Advisor. It also served as an excellent vehicle to develop data communications links with Greeley and Boulder, and refine the Graphical User Interface in concert with the users.

4.2 Result Verification

Since WELS introduced a number of improvements to the PIWPS model during the course of the test, the forecasts (or model outputs) changed in accuracy during the snow season. This was fully anticipated as a test opportunity before the tests ever began. The timing of major changes to the model are noted in the detailed presentation of the test data.

Also WELS was confronted with a major dilemma of using NWS forecasts as a baseline to compare the timing and accuracy of forecasts emanating from WWC. The former are very general in nature, and the latter very specific. The former result in forecasts such as "There is a 40 percent chance of afternoon showers...", meaning that similar predicted weather conditions produced showers in 40 percent of the cases contained in the statistical database which extends over many years of operation. This approach is contained in the NWS Model Output Statistics (MOS) to judge the adequacy of forecasts[9].

WELS' PIWPS model, on the other hand, gives highway maintenance operators and crews the capability to base their snow operations on location-specific weather forecasts which provide details on the geographic location of the storm, and the predicted onset, intensity, and end of the storm.

4.2.1 Test Methodology.

In developing the Roadweather Pro test plan for forecasting last winter's snow storms, WELS sought the most reliable outside source possible of currently available weather forecasts and observations. These forecasts and observations were required to serve as a professionally recognized benchmark against which WELS could compare the results of its own daily forecasts and establish the accuracy and reliability of those forecasts.

As anticipated, that source was the National Weather Service. Daily weather forecasts were acquired from Accu-Weather presentations of NWS forecasts and observations in local newspapers, NWS forecasts and observations as presented by a dial-up weather data service called Weather-Brief, and even TV weather reports of NWS forecasts and advisories.

As noted in paragraph 4.2, NWS forecasts are rather general in nature which made it extremely difficult for WELS to conduct a one-on-one comparison with its location-specific and detailed daily forecast results. In an effort to compensate for this lack of specificity, WELS incorporated NWS daily observations as an added component of the comparison. The observations are reports of readings of ground weather sensors on the day of the forecast taken at various locations throughout the state by NWS volunteers.

Even though these daily observations provide more weather details from more specific locations than the NWS daily forecasts, the readings themselves are sometimes suspect. The number of weather observation stations sited within the state is limited; weather station sensors have built-in accuracy biases, and during severe weather it is not unusual for a number of stations to lose contact with NWS.

Based on the above, and the fact that there are no national standards for determining the adequacy of forecasts we chose to establish a set of measurements which in our view would provide a reasonable basis for comparison with actual observations, and establish if we had performed a successful forecast:

- Precipitation: Within 1" of snow as observed from specific sites.

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[9]H.R. Glahn, and D.A. Lowry, 1972: The use of model output statistics (MOS) in objective weather forecasting. J. Applied Meteorol., Vol. 11, 1203-1211.

- Temperature: Within 10 degrees Fahrenheit of the ground observations.

- Winds: Within 10 MPH of the ground observations.

A review and evaluation of the WWC forecasts conducted for the 25 snow events establishes both the accuracy and timeliness of the PIWPS models. WWC consistently forecast:

- Precipitation within 1" of the reported snow observations, and went beyond those limited number of sites to provide a detailed forecast for any point desired within the state. (In the table which accompanies each snow event in the following section, precipitation is displayed as fractions of an inch which make some comparisons appear to differ percentage-wise, but still only by fractions of an inch.)

- Temperature in the same degree of detail, and with even greater accuracy.

- Wind direction and intensity commensurate with the observations, but available in more detail to forecast strong Chinook wind events, blowing snow, and track major events such as the March 1992 blizzard.

- The onset of a storm within 30 minutes to two hours of the actual storm with one or two exceptions which were two to three hours off the mark (an acceptable margin to the NWS).

- The geographical location and distribution of the storm with great detail.

Even though the quality judgment of weather predictions for test comparison cannot rely on precise test and evaluation engineering standards, WELS is confident that its forecasts during the course of last winter provided immensely greater accuracy and detail than those obtainable by NWS or the media in predicting the onset, end, intensity, and geographical distribution of precipitation.

WELS forecasting summaries, comparisons, and details are found in section 4.3, Statistical Summary of Results.

4.3. Statistical Summary of Results

The following table provides a summary of the snow storm cases which are described in more detail in the subsequent part of this chapter. The first column refers to the storm case number (identical to the last digit in the numbering of subchapters below), the second column indicates the starting date, the third column the starting time of the

WELS forecasts. The fourth column identifies the source of comparison data, and the last column gives a brief evaluation of the forecast results.

No.	Date	MST	Comparison Source	Fcst/Critique
1	10/28/91	5 am	NWS-Accu-Weather in newspaper CDOT Personnel, Greeley	Highly accurate WELS forecast in terms of distribution details, timing, and amounts (down to fractions of an inch). NWS grossly overpredicted Denver/Boulder area and NE Colorado and provided hardly any area differentiation and no timing details.
	10/29/91	5 pm	NWS-Accu-Weather in newspaper CDOT personnel in Greeley	WELS provided good timing and intensity predictions as storm moved from mountains into eastern plains. NWS and news media overpredicted storm effects.
	10/30/91	5 am	NWS-Accu-Weather in newspaper NOAA and TV releases	Generally good forecast by NWS and WELS, but WELS gives more details. Precipitation patterns on this day differ drastically from the previous ones. Heavy accumulation of snow predicted by media did not materialize since roads were still warm.
2	11/6/91	5 am	Newscasts	WELS produced highly reliable wind predictions which was verified in terms of road closures due to blowing snow conditions. Much of this snow was on the ground from previous storm. Additional snowfall was predicted within 25-mile vicinity.
	11/7/91	5 am	Newscasts	Blowing snow caused more havoc on mountain pass roads. Cold front passage and upslope along Front Range south of Boulder caused snow in southeastern Colorado, as also predicted by the media.
3	11/14/91	5 am	NWS-Accu-Weather, News CDOT personnel	Excellent forecast for western Colorado; light precipitation anticipated, but not predicted by the model, near the foothills east of Boulder.

	11/14/91	5 pm	NWS-Accu-Weather, News, local observations	NWS heavily overpredicted the storm for Denver area. WELS forecast shows much better results and greater details which verified with observations.
4	11/18/91	5 am	NWS special update	WELS forecast good during first 12 hours, but then flawed by insufficient input data.
	11/18/91	5 pm	News reports, observations	Excellent timing, location of "freak" snowstorm, hitting Denver area. NWS underpredicted Denver, overpredicted rest of eastern slope.
	11/19/91	5 am	Observations	Excellent WELS prediction of fading storm
5	11/21/92	5 am	Observations, news reports, CDOT personnel	Excellent prediction of high winds and snow (leading to very hazardous driving conditions in the mountains) in terms of timing and location. Many more details made available by WELS than available through NWS and the media.
6	11/22/92	5 am	Observations, news reports	Excellent WELS forecast in terms of trace precipitation, temperature. NWS grossly overpredicted a 4 - 8" snowstorm that did not come.
7	11/27/92	5 pm	Observations, news reports	NWS predicted 1-3" of snow by afternoon of 28th in Denver. Improved version of WELS model, now installed, indicates precipitation south of Denver. Observations show 0.01" in Denver before 5 p.m. Thus, NWS strongly overpredicted, WELS missed the precipitation by about 15 miles.
	11/29/92	5 am	Observations, CDOT personnel	Weak winter storm in the mountains west of Denver; extension into eastern plains predicted very well by WELS model.
	11/30/92	5 am	Observations, news reports	WELS forecast provided reliable prediction of diminished snowstorm activity in the Denver area and to the east, increased activity in the southern part of the State.
8	12/11/91	5 am	Observations, Accu-Weather	Excellent timing and intensity predictions of a storm that started in the southwest, missed the central

				mountains, and extended into the northeastern plains. WELS forecast provided much more detail than NWS and media forecasts.
9	12/19/91	5 am	NWS-Weather Brief, personal observations	Details of WELS weather forecast proved to be highly reliable, as evident from personal trip report. Reliance in WELS forecast rather than NWS forecast prompted the P.I. to choose mountain route to Phoenix, AZ. Excellent forecast of flooding rains in Texas. NWS called for 30% chance of showers late in the day, 3 -5" of snow by evening, which did not materialize.
	12/20/91	5 am	NWS-Weather Brief, personal observations.	Excellent forecast of drizzle and fog along eastern foothills, with rapid clearing to follow. NWS called again for snow today, which did not materialize in the Denver area.
10	12/31/91	5 am	NWS-Weather Brief, newspaper data	WELS caught the first half of a rapidly moving system, with snow in the west/central mountains, but missed the shift to eastern slopes before 5 p.m.
	12/31/91	5 pm	NWS-Weather Brief, newspaper data	WELS now has good precipitation distribution for eastern Colorado between 5 p.m. and 11 p.m. Decay of this weak storm by 11 p.m. also is well predicted. NWS (Weather Brief) delivered good forecast, but lacking details.
11	1/3/92	5 pm		Data collected, but no forecast was prepared, because no impact on Greeley target area was anticipated.
10	1/6/92	5 am		Excellent forecast of snow moving into western and central mountains.
	1/6/92	5 pm	NWS-Weather Brief	Good continuity with previous and subsequent overlapping forecasts.
	1/7/92	5 am	NWS-Weather Brief	Denver snow was underpredicted, but excellent forecast for all surrounding regions.
	1/7/92	5 pm	NWS-Weather Brief	Excellent continuity. Good prediction of storm end. NWS forecasts were generally good, but

				much less detailed, and tended to overpredict snow in lower elevations.
13	1/11/92	5 am	NWS-Weather Brief	WELS forecast not attempted because of insufficient data reception.
	1/12/92	5 am	NWS-Weather Brief	WELS provided excellent prediction of continuing blizzard conditions over eastern plains, heavy snow in mountains. WELS gave more details than NWS, although NWS forecast called generic blizzard conditions correctly. WELS: Very good portrayal of sharp horizontal gradients of precipitation east of Boulder/Denver.
14	1/14/92	5 am	NWS-Weather Brief	Excellent WELS forecast of relatively dry storm with extremely cold temperatures and very strong winds over eastern plains. More details provided than available from NWS. Observations indicate a slightly wider extent of light snow than shown by the forecast.
15	1/17/92	5 am	NWS-Weather Brief	This case confirmed that situations in which nothing much happens could be predicted well.
16	2/3/92	5 am	NWS-Weather Brief	NWS seemed to miss mountain snow predicted by WELS. WELS shows considerable detail, but seemed to over-predict Palmer Ridge and Limon area. Unfortunately, areas with highest predicted precipitation do not have reporting stations.
17	2/10/92	5 am	NWS	Heavy snow advisory issued by NWS did not materialize in WELS forecast. No data were received to verify predictions on this day. Reports from next day make no mention of any previous heavy snowfall.
18	2/11/92	5 am	NWS-Weather Brief	NWS forecast was correct, but very generic with no details. WELS forecast details verified well with data from the few reporting stations in the west.
	2/12/92	5 am	NWS-Weather Brief	Only light snow showers expected in

				mountains. WELS forecast reports light snow in vicinity of stations observing trace amounts.
	2/13/92	5 am	NWS-Weather Brief	Continuing snow in western mountains only generically predicted by NWS, but well placed by WELS.
	2/14/92	5 am	NWS-Weather Brief	WELS calls for more isolated, light snow in the western mountains, partly confirmed by observations, and for showers in eastern Colorado, unconfirmed.
19	2/16/92	5 am		NWS (systems problem). Insufficient data reception, therefore forecast had to be canceled
20	2/23/92	5 am	NWS-Weather Brief	Light precipitation system over Sangre de Cristo Mountains and eastern plains predicted well by WELS model. Only generic prediction with no details available from NWS.
21	2/25/92	5 am	NWS-Weather Brief	WELS provided specific forecast for Front Range. A few isolated traces of precipitation along foothills were missed.
22	3/3/92	5 am	NWS-Weather Brief	NWS provided generic forecast with few details. WELS forecast with much more detail verified well. Missed some of the light shower activity in Boulder, Ft. Collins, Greeley area, although general shower activity in eastern plains was anticipated.
	3/4/92	5 am	NWS-Weather Brief	NWS "generic" forecast without details underpredicted a major spring storm in the Rocky Mountains and eastern plains. This storm was hailed by farmers as a multimillion dollar relief. WELS provided great details which, allowing for terrain effects and shower activity, verified very well.
	3/5/92	5 am	NWS-Weather Brief	NWS generic forecast underestimated major snow storm in mountains. WELS, again provided great detail, but overestimated some mountain valley locations.

	3/6/92	5 am		Clearing predicted
	3/7/92	5 am	NWS-Weather Brief	Major storm predicted by NWS for central and southern mountains, San Luis Valley did not materialize. WELS forecast accurately predicted only light, widely scattered showers.
23	3/8/92	5 am	NWS-Weather Brief	Worst blizzard in several years was predicted very well by WELS in terms of location and intensity, albeit a couple of hours early in the Boulder region. Perhaps slight overprediction for area south of Ft. Morgan. NWS anticipated storm in southeastern Colorado which did not materialize, and underpredicted events elsewhere.
24	3/17/92	5 am	NWS-Weather Brief	Weak storm moves into SW Colorado.
	3/18/92	5 am	NWS-Weather Brief	Precipitation in northern and central mountains and northeastern plains predicted by NWS and WELS.
	3/19/92	5 am	NWS-Weather Brief	Scattered precipitation over central and norther mountains predicted by NWS and WELS.
25	3/24/92	5 am	NWS-Weather Brief	Downgraded, weak snow storm over mountains predicted by WELS and NWS.

4.4. Historic Case Sequence

4.4.1. October 28-31, 1991

This was our first operational forecast period, and also the first major snowstorm of the "winter" season. The storm came in two surges, both predicted well by the WELS model.

The first surge came late on the 27th and continued into the 28th. Our first model run started with the data from 5 a.m. MST on the 28th. NWS predictions telecast by the media called for 7 to 14 inches in the "southern mountains" (presumably the Sangre de Cristo Mountains), 5 to 10 inches in the Denver area and the "northern mountains" by evening, and 1 to 4 inches in northwestern Colorado. (This information is gleaned from diary entries made by the P.I. on that day. Note the wide error margins in the NWS forecasts which are of little use for road maintenance operations; also note the vague geographic location descriptions.)

Our forecast called for a maximum > 30 mm of precipitation accumulation from 5 a.m. to 11 a.m. between Denver and Colorado Springs (the infamous Palmer Divide and Monument Hill area where I-25 quickly becomes impassable in snowstorms), and similar amounts south of Ft. Morgan (Fig. 4.1). This extension of relatively higher snowfall amounts from Monument Hill northeastward into the plains appeared in many of our subsequent forecasts. Checking with CDOT personnel revealed that this phenomenon is well known to them. We found that it is associated with a very low range of hills, evident on a map of Colorado mainly from the diverging pattern of mostly dry creek beds. Along the Front Range from Ft. Collins to Denver (including Longmont and Greeley), our forecast revealed a minimum in predicted precipitation (2 to 3 mm, ca. 0.1 inch). A precipitation maximum (> 20 mm) is indicated west of Pueblo in the Wet Mountains.

Between 11 a.m. and 5 p.m. on the 28th an additional 30 mm of precipitation was predicted for the Monument Hill area and locations south of Ft. Morgan. The Wet Mountains also are expected to receive another 20 mm. The mountains west of Boulder may count on additional 10 mm (Fig. 4.2).

Between 5 p.m. and 11 p.m (Fig. 4.3) no additional accumulation of precipitation is registered in the Colorado Springs and Ft. Morgan areas. Only the Wet Mountains should experience significantly more snow. The mountains west of Boulder show an additional 2 mm of precipitation, but nothing more past 11 p.m.

This early in the season snow tends to be relatively wet as it begins to fall. Rapidly decreasing temperatures (our forecasts called for temperatures in the teens over the northeastern plains) will lead to increasingly dryer snow conditions. A conversion of approximately 1 mm of liquid precipitation to 0.4 or 0.5 inches of snow would be called for under such conditions by empirical rules.

According to Steve Carlson (CDOT Greeley), it started to rain near 2 a.m., turning into snow. By morning there was about 1 inch on the ground. Much of the snow had melted as it hit the ground. (Note in Fig. 4.1 that WELS predicted ca. 3 mm by 11 a.m, and hardly anything thereafter. In Greeley snowfall stopped after 1 p.m. In Boulder, precipitation started around 3 a.m., became lighter around noon, but increased again later. The newspaper reported accumulations between 3 and 5.7 inches, increasing from north Boulder towards south Boulder. Such a gradient is also indicated in our maps (see Fig. 4.1).

Mr. Carlson also obtained information from Estes Park (3 to 4" by late morning, 5 to 10 mm liquid water according to our forecast). The San Luis Valley had hardly any precipitation, as predicted by us. Very little fell on La Veta Pass east of Alamosa, and on Poncho Pass near Salida, in agreement with our forecast. However, on Wolf Creek Pass near Pagosa Springs "it snowed all day", contrary to our predictions. Our forecasts show a precipitation maximum in the San Juan mountains, but ending about 50 miles farther north than indicated by the isolated Wolf Creek pass observation.

The Boulder newspaper on the 29th published the following observations pertaining to the preceding day, which can be compared with WELS predictions:

Station	**precipitation observed**	**(liquid amount, inches) predicted**
Akron	missing	> 1.2
Alamosa	none	none
Colo. Spgs.	0.09	1.1
Denver	0.17	0.2
Eagle	0.01	0.02
Ft.Collins	0.05	0.08
Ft.Morgan	missing	0.8
Glenwood Spgs.	missing	0.02
Grand Junction	0.37	0.2
Gunnison	missing	0.4
La Junta	0.07	0.1
Lamar	0.05	0.12
Pueblo	none	1.2
Salida	missing	0.2
Trinidad	none	none

If these values can be trusted, we slightly over-predicted Colorado Springs, and also Pueblo. (The heavy precipitation on Monument Hill north of Colorado Springs does not appear in any station reports, but was confirmed by news flashes about traffic pileups.) La Junta and Lamar appear with predictions of > 2 mm. It should be noted that Eagle, east of Glenwood Springs, showed a predicted amount on the order of less than 1 mm, whereas Grand Junction appears on our forecast map (Fig. 4.3) with 5 mm or 0.2 inches. Thus, it appears that even some of the detailed differences in precipitation patterns reflected in our forecasts and caused by terrain effects are matched by some of the observations.

The abrupt end of the snowstorm in northeastern Colorado seemed to coincide with a change in wind patterns which went from slight up-slope conditions in the morning (Fig. 4.1) to downslope conditions in the evening (Fig. 4.4). The downslope effects also showed in the appearance of a slightly warmer tongue of air in the Denver - Boulder - Ft. Collins region, as compared to Ft. Morgan in the eastern plains.

The second storm surge started on October 29. The WELS forecast, again, was started with the 5 a.m. MST data. By 5 p.m. no precipitation was indicated anywhere in the State. By 5 a.m. only isolated precipitation appeared in northeastern Colorado. A data check revealed that several key stations from the western U.S. were missing from our records. Therefore, this forecast could not be relied upon.

We started the model again with the data received at 5 p.m. This time, the 6-hour forecast for 11 p.m. showed light snow in the high mountains, ending just east of Greeley - Boulder -Denver (Fig. 4.5). By 5 a.m. (Fig. 4.6) snowfall was supposed to extend to the eastern plains, again with the Monument Hill area being hit hard (> 10 mm). Slight increases in snow amounts were expected in northeastern Colorado and in the high parts of the western mountains by 11 a.m. on the 30th (Fig. 4.7), with practically nothing more thereafter. Temperatures in the eastern plains were expected to drop close to 0 deg F (-17 deg C). Because of a down-slope chinook effect temperatures along the foothills were expected to remain somewhat more moderate.

Our diary notes indicate that very light snow started in Boulder around 4 p.m. on the 29th, becoming moderate around 6 p.m. "Mike" Anderson of the Greeley CDOT was advised that snow was expected before 11 p.m. in the Greeley area, and in the Ft. Morgan area after midnight. According to his inquiries, snow in Greeley started around 6 p.m. Most of the accumulation started after 3 a.m. and amounted to 3 to 8 inches by 9:30 a.m. on the 30th. According to our forecast the amounts expected were on the order of 2 - 5 mm of liquid water, or 2 to 4 inches of snow on well-insulated surfaces, less on still warm road surfaces. Anderson reported about 3" from Netherland and Estes Park in the mountains west of Boulder, in agreement with our predictions. Light snow was experienced near the northeastern border of the State, again in line with our forecast.

The following table provides comparisons between 24-hour precipitation reported by the Boulder Daily Camera and that predicted by 5 p.m. MST on October 30th.

Station	**precipitation (liquid amount, inches)**	
	observed	**predicted**
Akron	0.03	< 0.2
Alamosa	0.50	none; 0.02 within 25 miles
Colo. Spgs.	0.36	< 0.2
Denver	0.11	< 0.2
Eagle	0.07	none
Ft.Collins	0.22	< 0.2
Ft.Morgan	missing	0.3
Glenwood Spgs.	0.05	0.1
Grand Junction	0.1	0.4
Gunnison	missing	none
La Junta	0.16	none
Lamar	0.06	none
Pueblo	missing	0.4
Leadville	missing	trace
Salida	missing	< 0.1
Trinidad	0.19	0.15

In summary, the WELS forecast provided good timing and snowfall amounts, revealing considerably more details than those available from NWS products. Amounts in Greeley, Boulder and Denver might have been underpredicted slightly. The apparent discrepancies between predictions and observations in the region around La Junta and Lamar are resolved by the WELS forecast starting with data from 5 a.m., October 30. On this day, the storm was confined to the southeastern plains and the southwestern mountains of Colorado. By 5 p.m. of that day about 5 mm (0.2") of liquid-water equivalent precipitation was predicted for these two locations, in line with observations.

The NWS forecast of 7:20 a.m. on October 30 called for a "winter storm warning" for the southeastern plains. 4 - 8" of snow were expected "locally" (presumably meaning the

Denver area), 1.5 ft in the foothills, and 1 - 4" on the "northeastern plateau" (wherever that may be). Denver Channel 9 TV at 7 a.m. was more specific by calling for 8 - 12 inches "west of I-25", and 4 - 8 inches "east of I-25".

The media forecasts overestimated the storm system and its effects. It was a very fast moving system. Such systems are notoriously difficult to predict, especially in their up-slope effects on precipitation distributions. To keep track of them it will be necessary to update weather forecasts every 12 hours as new radiosonde data are received.

4.4.2. November 6 - 8, 1991

WELS forecasts show strong northwesterly winds over mountains which should lead to blowing snow. Snowfall in excess of 20 mm (0.8") liquid water, representing approximately 1 ft of snow, was predicted for the western mountains in the Grand Junction - Glenwood Springs - Montrose area, as well as in the mountains between Leadville and Salida. Light isolated rain showers were called for in the eastern plains, in agreement with the Channel 9 forecast. These showers did materialize in Akron, Denver, Ft. Collins, Ft. Morgan, according to Accu-Weather statistics. Glenwood Springs observed 0.05" (predicted <0.1"), and Eagle observed 0.03" (predicted <0.1"). News reports in the evening indicated that I-70 was closed across Vail Pass because of many accidents in blowing snow. This report is consistent with our high wind forecast. Snow has been in this area from the last storm. Light, additional snow should be expected, as it has been forecast for a mountain region only 25 miles to the south. Light snow showers observed in Denver were attributed to a "back door" cold front.

These frontal effects appeared in the WELS forecast initiated with data from 5 a.m. on November 7. While winds were still expected to be strong and from the northwest over the mountains west of Boulder and Denver, winds east of Denver were predicted to be light early in the forecast period, picking up during the afternoon and night. WELS forecast light snow all along the Front Range from Boulder to the New Mexico border. According to morning newscasts, the high wind and drifting snow situation caused closure of Loveland Pass. Hazardous material transports, normally using the pass road, had to be diverted through the Eisenhower/Johnson tunnels. These tunnels, then, had to be closed for other traffic, causing long delays.

4.4.3. November 14 - 17, 1991

The WELS forecast starting with data from 5 a.m., November 14, gave first indications of snow (0.2" to 0.4" liquid, equivalent to 2 to 6 " of snow) between 11 a.m. and 5 p.m. in the mountains from Durango to Steamboat Springs. By 11 p.m. additional snow (equivalent to more than 1 ft in the Telluride region) was expected. Furthermore, the precipitation pattern shifted to the east, now including the foothills west of Boulder/Ft. Collins, and west of Colorado Springs. Dave Fraser (CDOT Denver) was advised in the late morning that with such a pattern usually we can also expect precipitation in the Boulder/Denver area. Because of the relatively warm temperatures in the plains, this precipitation should start out as rain. By 5 a.m. the storm was expected to involve all of

Colorado west of the foothills, with the exception of the Walsenburg/Alamosa area (Fig. 4.8).

Because of the intensity and speed of this fast-moving weather system we also prepared forecasts using the 5 p.m. data of November 14 as input to the WELS model. Fig. 4.9 shows the precipitation predicted in the 12-hour period between 5 p.m. (forecast start) and 5 a.m. on November 15. The intensity of the storm over the western half of Colorado remained similar. The new forecast, however, indicated significant precipitation between Colorado Springs and Trinidad, along the eastern slopes of the Sangre de Cristo Mountains. Alamosa remained in a "dry island."

By 5 p.m. on November 15 the storm was expected to sweep into the northeastern plains (Figs. 4.10 and 4.11), curiously sparing the Denver - Boulder - Longmont area. Significant precipitation (>20 mm or 0.8" liquid, equivalent to approximately 8" of snow) were expected in the Monument Hill area south of Denver and in an area south of Ft. Morgan mentioned before as prone to snowstorms.

According to our diary notes, upslope clouds started to appear in Boulder around 4:30 p.m., and rain started around 6:30 to 7 p.m. According to Steve Carlson (CDOT Greeley) by morning of November 15 Greeley had experienced light rain, turning into light snow. Ft. Collins had about 1" of wet snow, the upper reaches of Poudre Canyon west of Ft. Collins had about 5" of snow, in excellent agreement with our forecast. (Note that we advised CDOT that we expected the precipitation pattern to reach a few miles farther east than indicated in Fig. 4.8).

NWS and the media had predicted up to 1 ft of snow in Denver which, as shown correctly by WELS, did not materialize. The snow stayed in higher elevations, in agreement with the WELS forecast. Vail Pass had to be closed again, as anticipated from Fig. 4.8.

The P.I. had to drive from Boulder to Ft. Collins and back to Boulder in the evening of November 15, relying on the WELS forecast in spite of dire travel advisories issued by the media. Note that this trip coincided with the prediction shown in Fig. 4.10, which shows the Boulder area to lie inside a "dry hole". Other than sporadic light drizzle and patchy fog with a few snow flakes, no adverse weather was encountered.

The following table compares 24-hour precipitation amounts predicted by 5 p.m. on November 5 with statistical data published in the Boulder Daily Camera in the morning of November 16, presumably dating to the evening before.

Station	**precipitation (liquid amount, inches)**	
	observed	**predicted**
Akron	none	0.3
Alamosa	0.1	none; 0.02 within 15 miles
Colo. Spgs.	0.14	0.4
Denver	0.15	Trace
Eagle	0.09	0.4
Ft.Collins	0.31	0.2
Ft.Morgan	0.09	0.4
Glenwood Spgs.	0.12	0.8
Grand Junction	0.6	1.2
Gunnison	missing	1.6
La Junta	0.03	<0.1
Lamar	none	none
Leadville	0.05	0.2
Pueblo	0.04	1.2
Salida	missing	< 0.1
Trinidad	0.14	0.8

Newspaper statistics also show Boulder to have received 1.5" of snow by 6 p.m. on November 15.

The WELS forecast issued from the 5 a.m. data of November 16 showed the snowstorm moved into eastern Colorado, dying out after 11 p.m.

4.4.4. November 18 - 19, 1991

This storm followed on the heels of the previous one. The predictions derived from the 5 a.m. data on November 18 show the storm starting in southwestern Colorado, covering most of western Colorado by 5 p.m., but then breaking up. This fact made us suspicious about our input data. Indeed, several key stations were missing.

NWS issued a special update in the late afternoon, calling for 4 -6" of snow in the Boulder-Denver area within the next few hours. This snow was not evident from the 5 a.m. forecast run, but was excellently revealed in terms of location and timing in the forecast run using the 5 p.m. data.

Precipitation in Boulder started around 4 p.m. Boulder received about 2" until next morning out of this storm. The Denver airport reported 13" on the runways as of 7:30 a.m. North of Boulder there was little snow accumulation. Ft. Collins only had about 1/2 to 1" of snow during the night.

The WELS forecast starting with the 5 a.m. data of November 19 showed continuing light snow in Denver between 5 a.m. and 11 a.m., nothing more thereafter.

4.4.5. November 21, 1991

According to our diary notes, the NWS predicted partly cloudy conditions statewide, except for Trinidad and Glenwood Springs calling for clear skies. Denver was to expect partly cloudy conditions with highs near 45 and a low of 28 degrees. The forecast for the subsequent day called for cloudy, with a high near 44 and a low in the twenties.

The WELS model indicates precipitation in the region of Grand Junction and Glenwood Springs, decreasing during the afternoon, but flaring up again after midnight when snow is also expected over the Continental Divide west of Boulder and in the northern part of the Sangre de Cristo Mountains. From past experience with similar forecast patterns we called for a chance of rain to spill over into the Denver/Boulder region between 5 p.m. and 11 p.m. The model did extremely well in predicting strong Chinook wind conditions along the Front Range between Ft. Collins and Colorado Springs. Strongest winds near 28 m/sec (62 mph) were expected in the Boulder area by 11 a.m., easing back to about 45 mph by evening, but increasing to about 50 mph during the night. In contrast, Greeley was expected to have only light winds, even though it is only about 40 km (25 miles) to the east of the mountains. This wind forecast was confirmed by CDOT personnel in Greeley.

Accu-Weather statistics in the Boulder Daily Camera indicated 0.01" of precipitation in Eagle (east of Glenwood Springs), in agreement with our forecast. Boulder had very light drizzle around 5 p.m. Denver reported very light rain around 10 p.m., which stopped soon after it started. Vail Pass had the chain law in effect. Loveland Pass had to be closed because of a semi-truck accident. According to the WELS forecast, these locations are within the predicted region of heaviest snow fall (>10 mm liquid equivalent, or > 4" snow) and winds near 50 mph near the Continental Divide.

Media forecasts broadcast in the evening expected up to 4" of snow tonight. Snow advisories were issued for I-70 west of Denver. Rain was expected east of Denver.

4.4.6. November 22 - 23, 1991

Recall the NWS and media predictions calling for 4" of snow in the Denver area. None of it came, as anticipated by WELS. The NWS forecast issued this morning, again, calls for snow today and tomorrow. Temperature high in the thirties for today, a low in the twenties, and a high of 35 for tomorrow is expected.

In contrast, the WELS model predicted continuing light snow in the mountains west of Boulder/Denver (ca 5 mm liquid, or 2" of snow in 6 hours). Light snow (< 1" of snow in 6 hours) was also expected in the Sangre de Cristo mountains southwest of Colorado Springs, and in an area between Montrose, Aspen and Glenwood Springs. Snowfall in these areas was expected to diminish into the afternoon and night. WELS temperature predictions call for a decreasing trend, starting in the mid twenties and dropping into the teens, lower than the ones anticipated by NWS.

Our weather diary shows a light snow flurry in Boulder around 1 p.m., but heavier clouds with virga over the foothills, with patches of blue sky off and on appearing over the mountains. In the late afternoon, again a few light snow flurries rendered the streets wet, but caused no accumulation. However, in the Denver area, these light flurries, together with the cold temperature invasion, caused major traffic problems due to ice on I-25. Traces of precipitation were reported by 5 p.m. from Denver, Glenwood Springs, Grand Junction, La Junta, Pueblo, and Trinidad.

Data transmission from the National Meteorological Center (NMC) went down today, therefore no evening data could be received. The NOAA offices in Boulder seemed to have been affected in the same way.

4.4.7. November 27 - December 1, 1991

Beginning with this case a significantly improved version of the nested grid model was put into operation. It mainly affected the way in which solutions were found for the Poisson equation which accounts for the effects of terrain on the wind field.

The WELS forecasts prepared from the data of 27 November, 5 a.m. show a light precipitation system moving into the mountainous areas of northwestern Colorado. Starting the forecasts with the data from 5 p.m. indicate this precipitation system to be even weaker at 5 a.m. on the 28th, with first indications of precipitation by 11 a.m. also appearing west and north of Colorado Springs. By 5 p.m. on November 28 the WELS model predicted snow over most of the central Colorado mountains. The precipitation activity was expected to spill onto the eastern slopes in the Monument Hill area between Denver and Colorado Springs (Fig. 4.12).

The morning forecast on Channel 9 calls for sleet in the afternoon, with snow accumulation from 1 to 3". Weather statistics published in the Boulder Daily Camera for 5 p.m. on the 28th indicate 0.01" of precipitation in Denver and 0.03" in Ft. Collins, much less than what was indicated in the earlier warnings.

The next forecast, prepared from the data of November 29, 5 a.m., shows snow by 11 a.m. in Denver, Boulder, and in the mountains to the west (Fig. 4.13). By 5 p.m. a precipitation tongue was expected to extend into the eastern plains southwest of Denver. Light snow was expected to continue in the region south of Ft. Morgan until morning, while the Denver/Boulder area was expected to clear already after 11 a.m.

Our diary notes indicate snow in Boulder starting around 6 a.m., ending around 11 a.m. with an accumulation of 1 to 2", but melting on road surfaces. (Fig. 4.13 indicates 2 mm of liquid-equivalent precipitation or about 1" of snow for Boulder by 11 a.m., nothing thereafter.). CDOT personnel in Greeley reported that snow was observed south of Ft. Morgan to Last Chance (the limits of their District's responsibility), in excellent agreement with our forecast. News media reported 3" of snow south of Ft. Morgan, as compared to 15 mm (0.6") liquid, or approximately 6" of snow, predicted by WELS as upper limit.

The WELS forecast from data received on November 30, 5 a.m., indicates snow from Boulder to Colorado Springs until 11 a.m., with maximum amounts near 2 mm liquid, or < 1" of snow. Small amounts were also predicted by noon for the areas around Pueblo and Lamar. Data published in the newspaper indicate 0.01" (liquid equivalent) in Pueblo, 0.10 in Denver, traces in Colorado Springs and Ft. Collins, in excellent agreement with the WELS prediction. Boulder reported 3" of snow, quitting around 6 a.m. This snow was missed by a few miles in yesterday's and today's forecast.

Between 5 p.m. on November 30 and 5 a.m. on December 1, WELS predicted significant snow for the Red Mountain Pass area north of Durango and for the eastern foothills between Pueblo and Trinidad. According to observations from Alamosa and Trinidad, some of this storm activity may have arrived already before 5 p.m. on November 30.

4.4.8. December 11 - 12, 1991

This case provides a classic example of a rapidly moving storm, associated with strong Chinook winds over the Continental Divide west of Denver. According to our notes, the NWS forecast in the morning of December 11 called for snow in the Grand Valley (around Grand Junction) and in the southwest corner of the State, possible snow flurries in metropolitan Denver. The Denver forecast advised of a 20% chance of rain mixed with snow, highs in the upper thirties, a 30% chance of snow showers tonight, decreasing after midnight. Lows in the 20 to 25 deg F range. The Channel 9 forecast warned of 8" of snow in the San Juan mountains and in the foothills west of Trinidad.

The WELS forecast showed light snow in the southeastern corner of Utah before 11 a.m. on December 11, none in Colorado. By 5 p.m. (Fig. 4.14) approximately 10 mm (0.4" liquid) were expected in the Grand Junction area, extending all the way to Glenwood Springs. Similar amounts were expected between Durango and Pagosa Springs in the southwestern part of the State. Trinidad, Pueblo, La Junta and Lamar encompassed other regions with predicted precipitation. The following table gives comparisons between these predictions and reports for the 24 hours ending at 5 p.m. published in the Boulder Daily Camera.

Station	**precipitation (liquid amount, inches)**	
	observed	**predicted**
Akron	none	none
Alamosa	missing	none
Colo. Spgs.	0.10	0.04 between 5 p.m. and 11 p.m.
Denver	none	none
Eagle	missing	none
Ft.Collins	none	none
Ft.Morgan	none	none
Glenwood Spgs.	0.06	Trace
Grand Junction	0.13	0.1
Gunnison	missing	none
La Junta	0.07	0.08
Lamar	0.01	Trace
Leadville	missing	none
Pueblo	0.14	Trace; 1.6" in next 6 hours
Salida	missing	none
Trinidad	0.19	0.04

The progression of the storm into the northeastern plains is evident from Figs. 4.15 and 4.16. (Akron observed 0.2' of precipitation by 5 p.m., as compared to 0.2' forecast as of 5 a.m.). The high winds predicted over the mountains were evident from the cloud formations west of Boulder. However, the associated light snowfall escaped our predictions. The reason for this we found to be a shallow moist layer observed by the 5 a.m. radiosonde over Grand Junction. This layer was less than 100 m thick, too small to enter into the forecast calculations, but when forcibly lifted over the mountains to the east, moisture would condense into a shallow cloud layer, producing light snow over the Continental Divide.

4.4.9. December 19 - 20, 1991

As an unanticipated side effect, the WELS LFM (limited-area forecast model) caught the Texas flood disaster perfectly (Fig.s 4.17 and 4.18). In central Texas approximately 70 mm of large-scale precipitation have to be added to 80 mm of "convective" (i.e. local scale) precipitation to yield a total of 150 mm (6") of rain in a 24-hour period. The weak storm in Colorado was of interest only, because the P.I. had the chance to examine its local effects on a trip west on I-70. The NWS forecast of 3 - 5" of snow expected in the Denver area by evening of December 19 almost caused an adjustment in Travel plans. The WELS forecast, however, indicated no problems for driving across the mountains.

By 11 a.m. on December 19 (Fig. 4.19) approximately 5 mm (2" of snow) were expected south of Moab, Utah, to be followed by similar amounts during the following night. Fig. 4.20 (5.p.m.) shows major precipitation along I-25 to the west of Grand Junction and near Glenwood Springs, with dry conditions prevailing east of Grand Junction. Snowfall abated by midnight (Fig. 4.21), but flared up before early morning over Vail Pass (halfway between Boulder and Glenwood Springs in Fig. 4.22). Next morning's forecast (Dec. 20, 11 a.m., Fig. 4.23) showed very light precipitation and temperatures slightly above freezing, extending in a wedge along the foothills to the west of Boulder. No precipitation was predicted for the afternoon.

Departing Boulder around 8 a.m. light drizzle was encountered, turning into fog in the foothills. Clear skies prevailed west of Idaho Springs (9000 ft level), almost precisely where the WELS forecast indicated. There was evidence of snow clearing activity during the preceding night on Vail Pass (estimated at around 3"), although the roads were clear by now. Similar evidence was encountered near Glenwood Springs, tapering off towards Rifle, and again increasing west of Grand Junction. Although almost 2 days had passed since then, there was evidence of plowing south of Moab, Utah, especially in Monticello and Blanding: snow piles in the middle of town roads indicated previous snowfall on the order of 0.5 ft or more.

Weather Brief data for the 24-hour period ending at 5 a.m., December 20 are used in the following comparison:

Station	**precipitation, liquid**	**amount, inches (snow, inches)**
	observed	**predicted**
Akron	none	none
Alamosa	none	none
Boulder	none	Trace
Colo. Spgs.	none	Trace
Denver	0.01	none, but trace nearby
Eagle	missing(1)	Trace
Ft.Collins	0.01	Trace
Ft.Morgan	none	none
Glenwood Spgs.	missing	none, but snow to the west
Grand Junction	0.06(3)	0.06, more to the west
Gunnison	none	none
La Junta	none	none
Lamar	missing	none
Leadville	missing	0.04
Pueblo	missing	none
Salida	missing	0.06
Trinidad	Trace	none, but some to the west

4.4.10. December 31, 1991 - January 1, 1992

A very rapidly moving front and low-pressure system were expected to affect Colorado today and tomorrow. The WELS forecast starting with data from December 31, 5 a.m. showed snow in the central mountains of western Colorado, diminishing by morning of the following day. However, the forecast starting with data from 5 p.m. indicated light precipitation before 11 p.m. in the foothills south and west of Denver, all the way to Trinidad, and also precipitation in eastern Colorado along the Nebraska/Kansas borders. No more precipitation was expected after midnight.

4.4.11. January 3, 1992

According to Weather Brief, snow was expected in mountains near Aspen. Data were received, but no forecast was prepared by WELS, because no impact was anticipated for the Boulder/Greeley area.

4.4.12. January 6 - 8, 1992

NWS (as distributed by Weather Brief) expected snow beginning this afternoon in the mountains of western Colorado. Accumulation in the southwestern mountains was expected to be heavy, 10 - 15". Heavy accumulation expected in northern and central Mountains tomorrow. 2 - 5" in lower elevations tonight, with an additional 1 -4" possible tomorrow. Gusty winds with areas of blowing and drifting snow in the mountains.

The WELS forecast, starting with 5 a.m., January 6, showed strong southwesterly winds of 40 mph over the western mountains. Strong southwesterly to southerly winds were also predicted over the eastern plains. Snow accumulation at the rate of more than 5 mm liquid per hours (1 to 2" per six hours) is predicted until tomorrow morning over the southwestern and western mountains, especially in the Red Mountain area and the mountain regions to the north and south of Glenwood Springs. For the eastern plains isolated shower activity is predicted, mainly centered on the region between Colorado Springs, Pueblo and Limon.

The forecast started at 5 p.m. on January 6 showed similar features in the precipitation distribution, with precipitation also extending into the Steamboat Springs area of northwestern Colorado. According to this forecast sequence, more snowfall was expected in the Red Mountain area north of Durango by 5 a.m.

NWS called for winter storm warning for north central and northeastern Colorado, with blizzard conditions over portions of the Front Range and Palmer Divide. 6 - 14" of snow expected in lower elevations, up to 2 ft in mountains and foothills.

In the forecast starting with 5 a.m. on January 7, snow was expected in the mountains west of Boulder, becoming heavy in the Monument Hill area south and east of Denver (up to 20 mm or 0.8" liquid by 11 a.m., which would translate to about 8" of snow (Fig. 4.24). Strong northerly winds near 30 mph should give rise to blizzard conditions. The region around Boulder was expected to receive only light snow. Snowfall in the Boulder/Denver area was expected to decrease in the afternoon (Fig. 4.25). However, precipitation was expected to continue in eastern Colorado and in the western mountains.

Another forecast run, starting with 5 p.m. on January 7 showed a resurgence of the storm, mainly along the foothills south of Colorado Springs and in the plains east of Denver (Figs. 4.26, 4.27, 4.28). The Sangre de Cristo and San Juan Mountains also were expected to receive significant precipitation.

The forecast starting at 5 a.m. on January 8 finally signalled the end of the storm with no precipitation in sight.

Verification for the forecasts ending on 7 January, 8 a.m.:

Station	precipitation, liquid amount, inches (snow, inches)	
	observed	predicted
Akron	Trace	none, but scattered showers possible
Alamosa	0.08	none, but significant precip starting 10 mi west
Boulder	Trace	none, but showers possible
Colo. Spgs.	Trace	Trace
Craig	0.18	0.04
Denver	0.02	none, but showers possible
Eagle	Trace	Trace
Ft.Collins	none	none
Ft.Morgan	0.02	none, but showers possible
Glenwood Spgs.	missing	0.08
Grand Junction	0.15(2)	0.12
Gunnison	missing	Trace
La Junta	missing	none, but showers possible
Lamar	missing	none, but showers possible
Leadville	missing	Trace, more to the south
Pueblo	missing	none, but showers possible
Salida	missing	Trace
Trinidad	0.2	none, but showers possible

Verification of the forecasts ending January 8, 5 a.m.:

Station	precipitation, liquid amount, inches (snow, inches)	
	observed	predicted
Akron	0.37(8)	0.4 (> 4)
Alamosa	none	none, but precip in near mountains
Boulder	0.03	0.01 - 0.05
Colo. Spgs.	0.03	0.4
Craig	0.01	0.9
Denver	0.68	0.08, but heavy all around (see Ft.Morgan)
Eagle	Trace	Trace
Ft.Collins	0.46	0.04, but heavy to west and northwest
Ft.Morgan	missing	0.6
Glenwood Spgs.	missing	0.2
Grand Junction	Trace	0.1
Gunnison	none	0.15
La Junta	0.03	none
Lamar	missing	none
Leadville	missing	0.2
Pueblo	Trace	0.1
Salida	missing	Trace
Trinidad	none	none, but precip in mountains to west

4.4.13. January 11 - 13, 1992

Under the current testing conditions, WELS was not set up to run 24-hour and weekend shifts. This storm developed over the weekend (Saturday Jan.11, Sunday Jan. 12). As a consequence, a data reception problem, probably due to snow accumulation on the antenna, remained unchecked. Due to poor data quality, the forecast starting with 5 a.m., January 11, showed no precipitation in Colorado, even though light rain showers were observed around 8 p.m. over the southern foothills. By 5:50 a.m. much of eastern Colorado experienced snow. Heavy snow was reported from Limon on south, falling at a rate of 2 - 3" per hour. All roads out of Limon had to be closed. Light snow was reported from western valleys.

The WELS forecast starting at 5 a.m., Sunday January 12 showed strong northerly winds over eastern Colorado in excess of 30 mph, in line with observation. By 11 a.m. Palmer Ridge/Monument Hill show precipitation close to 20 mm (0.8"), and almost 10 mm (0.4") were expected north of Limon. Denver and Boulder were expected to receive 5 mm (0.2"). The mountains west of Boulder were expected to receive in excess of 10 mm (4 to 6" of snow in 6 hours). Precipitation was forecast to extend as far south as Pueblo. By 5 p.m. strong northerly winds, now up to 40 mph, were expected to continue over the plains. Another 10 mm of precipitation were predicted in the Monument Hill area and in the mountains west of Boulder and Denver, as well as in the Wet Mountains and Sangre de Cristo mountains west of Pueblo. The edge of the predicted precipitation line extends from Pueblo to Limon, signalling the end of snowfall there. By 11 p.m. another 10 mm were expected along the whole Front Range of the Rocky Mountains from the Wyoming border to Trinidad. By 5 a.m. light snow is indicated again over most of eastern Colorado, with 6-hour accumulations of more than 10 mm liquid-equivalent (4 - 6" of snow) over Monument Hill and an area between Limon and Fort Morgan.

NWS data received from Weather Brief may serve to verify this forecast.

Station	precipitation, liquid amount, inches (snow, inches)	
	observed	predicted
Akron	0.23(8)	<0.1, much more to south
Alamosa	missing	none, but precip in near mountains
Boulder	0.12	0.16
Colo. Spgs.	0.01	0.8
Craig	none	0.15
Denver	0.18	0.2
Eagle	Trace	Trace
Ft.Collins	0.13	Trace
Ft.Morgan	0.04	none, but heavy a few miles south
Glenwood Springs	missing	none
Grand Junction	Trace	none
Greeley	0.18	none, but snow 20 miles to east
Gunnison	missing	none
La Junta	0.1	0.02
Lamar	missing	0.08
Leadville	missing	none, but heavy a few miles to east
Limon	0.11	0.06
Longmont	0.02	0.04
Pueblo	Trace	0.5
Salida	missing	none
Trinidad	0.07	0.2

4.4.14. January 14 - 15, 1992

The NWS forecast by Weather Brief issued at 3:40 p.m. Tuesday January 14 states: "Turning sharply colder and windy from north to south tonight with snow likely over northeast and a chance of snow southeast. Areas of blowing and drifting snow northeast with extremely cold wind chill temperatures. A chance of light snow early Wednesday in the southeast, otherwise becoming sunny.....Lows tonight 5 below to 10 above zero northeast with 5 to 15 southeast.

The WELS forecast produced with the 5 a.m. data on January 14 indicates northwesterly winds near 50 mph over the eastern plains at 11 a.m., turning into a northerly direction by 5 p.m., and remaining strong all afternoon and night. By 11 a.m. a weak precipitation system appeared in western Colorado, centered between Grand Junction and Montrose. By 5 p.m. the system weakened and became disorganized. By 11 p.m. the area between Boulder and Colorado Springs indicated light precipitation, extending into the eastern plains. (Our weather notes indicated that light snow started in Boulder around 6:30 p.m., in agreement with the forecast.) This pattern weakened by 5 a.m. on January 15. Temperatures in the Boulder/Denver area were predicted to drop from near freezing in the morning of the 14th to near zero F, or slightly below, by 5 a.m. on the 15th, in agreement with observations. The southeastern part of the State was expected to stay warmer by about 10 deg F.

Observations for the 24-hour period ending January 15, 5 a.m. compare as follows:

Station	precipitation, liquid amount, inches (snow, inches) observed	predicted
Akron	Trace	none, but trace possible
Alamosa	missing	none
Boulder	0.01	Trace
Colo. Spgs.	0.02	Trace
Craig	missing	0.04
Denver	0.16	0.12
Eagle	Missing	Trace
Ft.Collins	none	none
Ft.Morgan	none	none, but measurable a few miles south
Glenwood Springs	missing	Trace
Grand Junction	Trace	0.03
Greeley	none	none
Gunnison	missing	none
La Junta	0.07	none
Lamar	missing	none
Leadville	missing	none
Limon	0.01	none, but light 20 mi to NW
Longmont	0.01	none
Pueblo	0.04	none, but more in mountains to W
Salida	missing	none
Trinidad	0.13	none, but more in mountains to NW

4.4.15. January 17, 1992

NWS (Weather Brief) called for widely scattered snow showers mainly over the mountains. This is also what the WELS forecast starting at 5 a.m., January 17, indicates. Winds of >30 mph were predicted for high mountain ranges. Lower elevations were expected to have only light winds.

4.4.16. February 3 - 4, 1992

The NWS forecast for Colorado issued at 3:15 a.m. by Weather Brief for today and tonight calls for "mostly cloudy east and mountains, partly cloudy west. Rain and mixed rain and snow likely eastern border today, and a chance of rain and snow showers elsewhere in the east. Decreasing clouds Tuesday (tomorrow). Colder in the east through Tuesday."

In the WELS forecast issued with 5 a.m. data, February 3, showed major precipitation along the main mountain range west of Boulder and Denver, the Sangre de Cristo Mountains west of Pueblo and Trinidad, the Red Mountain area north of Durango, and the mountains north of Glenwood Springs. Monument Hill south of Denver extended a high precipitation "finger" into the region between Ft. Morgan and Limon. Light precipitation (rain) was also expected along the Kansas border. During the night the precipitation over the eastern plains was expected to let up. Most of the snow was expected to occur during the night along a line from north of Limon, to Colorado

Springs, to Pagosa Springs in the southwestern part of the State. This case was demonstrated in a "live" presentation to personnel of CDOT in Denver.

Comparison values are given below:

Station	**precipitation, liquid observed**	**amount, inches (snow, inches) predicted**
Akron	none	0.3
Alamosa	Trace	0.12
Boulder	none	none
Colo. Spgs.	Trace	1.1
Craig	none	none
Denver	Trace	none, but precip predicted within a few miles
Eagle	none	0.2
Ft.Collins	none	Trace
Ft.Morgan	none	0.6
Glenwood Springs	missing	0.2
Grand Junction	none	Trace
Greeley	none	0.08
Gunnison	none	0.2
La Junta	0.28	none, but more slightly to east
Lamar	missing	0.04
Leadville	0.06	0.1
Limon	Trace	0.3
Longmont	none	none
Pueblo	0.19	Trace, but more to W
Salida	0.04	0.04
Trinidad	0.13	0.08, more to west

4.4.17. February 10 - 11, 1992

NWS issued a heavy snow warning for the southwestern mountains tonight, with accumulations of 6 to 10" there and 4 - 8" of new snow in other mountains tonight. We ran the WELS model with data from 5 a.m., February 10. Light snow appeared first in the border regions with Utah between 11 a.m. and 5 p.m. By 11 p.m. more light snow (2") were expected to accumulate west of Grand Junction. Only between 11 p.m. and 5 a.m. on the 11th was the Red Mountain area north of Durango expected to receive on the order of 2 to 3". Unfortunately, no observational data were received for this day to confirm these predictions which NWS may have grossly overstated. Observational reports from next day make no mention of any previous heavy snowfall.

4.4.18. February 11 - 14, 1992

NWS at 1:05 p.m. on the 11th: "Scattered snow showers will be possible in the mountains and west tonight and Wednesday (tomorrow), while occasional flurries or possible freezing drizzle along with areas of fog will develop over parts of the east. Otherwise mostly cloudy skies will continue nearly statewide tonight and Wednesday."

The WELS forecast showed light precipitation all day in the Grand Junction - Glenwood Springs - Montrose are, becoming heavier between 11 p.m. and 5 a.m on the 12th. The following short listing states 24-hour precipitation ending at 5 a.m. on the 12 in terms of observed (predicted) values:

Eagle	0.07 (Trace, but up to 0.1 in immediate surroundings)
Grd. Jct.	0.04 (>0.2)
Gunnison	0.04 (>0.2)
Hayden	0.07 (0.3)
Rifle	0.23 (0.2)

Denver and Limon reported a trace of precipitation due to fog.

For the 12th NWS called for widely scattered showers over the mountains. The WELS forecast with data from 5 a.m. on the 12th constricts this activity before 5 p.m. to the Glenwood Springs - Montrose region. Craig and Gunnison reported 0.01" of precipitation for the same 24-hour period as our forecast, while Grand Junction reported a trace. Glenwood Springs data were missing.

On the 13th - 14th another incursion of light snow into the western mountain regions was predicted by WELS for the morning and afternoon, diminishing during the night. NWS issued a snow advisory for today and this evening for the southwest and central mountains. Reports (predictions) are summarized as follows:

Alamosa	0.02 (none, but snow within 20 miles to east and west)
Glenw.S.	missing (0.1)
Grd.Jct.	0.20 (0.3)
Gunnison	missing (Trace)
Hayden	0.12 (0.1)
Leadville	none (Trace possible)
Montrose	missing (0.4)
Trinidad	none (none)

From the 14th to the 15th WELS predicted still lingering snow shower activity in the western mountains. Only Eagle reported a trace of precipitation. The WELS forecast also indicated shower activity over eastern Colorado, but no confirmation could be obtained. (Limon reported partly cloudy conditions, but no measured precipitation.)

4.4.19. February 16 -17, 1992

WELS encountered a data reception problem over the weekend, due to insufficient disk space. Therefore, forecasts could not be prepared.

4.4.20. February 23 -24, 1992

The NWS forecast at 1:05 p.m. on the 23rd called for "gusty north winds with snow in the mountains and rain and snow at some lower elevations."

The WELS forecast with 5 a.m. data from the 23rd indicates by 11 a.m. precipitation up to 10 mm over the mountains west of Colorado Springs, extending southward to Trinidad with diminishing amounts. A region between Ft. Morgan and Limon also showed up to 10 mm, mostly as rain. Similar amounts were to be expected during the next 6 hours until 5 p.m., with precipitation spreading to the Kansas border. By 11 p.m. the mountain snows were expected to subside, except for the Monument Hill region. More precipitation was expected in the SW corner of the State. By 5 a.m. only isolated pockets of precipitation were left. A comparison between observed (predicted) precipitation is given as follows:

Akron	0.25 (0.1, but more to south)
Boulder	none (none)
Colo.Sp.	0.02 (0.2)
Denver	none (Trace)
Ft.Morgan	0.01 (<0.1)
La Junta	Trace (none, but more 20 miles to east)
Limon	0.03 (0.1)
Trinidad	Trace (0.2)

4.4.21. February 25 -26, 1992

NWS called for snow to continue in parts of the northern and central mountains. The WELS forecast between 5 a.m. and 11 a.m. showed snow in a narrow band along the whole Front Range between the Wyoming and New Mexico borders. Heaviest accumulations (>10 mm liquid or 6" of snow) were expected west of Boulder and west of Colorado Springs. Snow in the Sangre de Cristo Mountains was forecast to continue into the evening with similar accumulations, but to die out before midnight. Light shower activity emerged from the main precipitation region into the foothills, giving rise to a trace of precipitation in Ft. Collins, Greeley, Denver, Colorado Springs (predicted), Limon, Pueblo and Trinidad. Boulder reported no precipitation (as predicted).

4.4.22. March 3 - 7, 1992

NWS at 1:05 p.m. on the 3rd expected "clouds and scattered precipitation will continue over much of the state....Snow could become heavy on some east facing slopes of the northern mountains late tonight. The snow level is expected quite high, as not much cold air is associated with this system."

The WELS forecast showed a systematic progression of the storm, hitting the Red Mountain area north of Durango by 11 a.m., the area west of Colorado Springs by 5 p.m., working its way to the region north of Glenwood Springs by 11 p.m., and remaining in place over western Colorado until 5 a.m. of the 4th. Scattered rain shower activity was predicted over the eastern plains. The following reports were received from Weather Brief:

Station	precipitation, liquid amount, inches (snow, inches)	
	observed	predicted
Akron	0.1	showers in area
Alamosa	0.49	0.04, but up to 0.8 nearby
Boulder	0.11	none
Colo. Spgs.	0.23	0.2
Craig	missing	Trace
Denver	0.11	none
Eagle	missing	0.2
Ft.Collins	missing	none
Ft.Morgan	0.08	showers in area
Glenwood Springs	missing	0.2
Grand Junction	0.02	0.1
Greeley	0.05	none, shower in area
Gunnison	missing	0.2
La Junta	0.02	none, showers in area
Lamar	missing	none
Leadville	missing	0.2
Limon	0.08	showers nearby
Longmont	0.06	none
Pueblo	missing	none
Salida	missing	0.4
Trinidad	0.16	0.2

At 4:45 AM MST on Wednesday, March 4, NWS (through Weather Brief) issued a "snow advisory for today for the northern and central mountains from the Continental Divide eastward and Sangre de Cristo Mountains." The forecast called for "west and high valleys mostly cloudy with scattered showers except snow likely in the high valleys. Snow decreasing to scattered showers region wide tonight. Partly cloudy Thursday with showers ending.....Mountains, snow likely tonight with accumulations 4 to 8 inches eastern slopes of northern and central mountains and Sangre de Cristo Mountains. Scattered snow showers tonight, except snow continuing east slopes of northern and central mountains. Scattered snow showers Thursday...East, rain with mixed rain and snow above 6500 today...A few thunderstorms southeast this afternoon. Rain continuing in the northeast tonight, scattered showers southeast. Scattered showers Thursday...."

The WELS forecast showed precipitation between 5 a.m. and 11 a.m. over the whole State with the exception of the northwest corner. Greatest amounts (40 mm in 6 hours, approximating 16" of snow) were predicted for the Front Range from Boulder to Trinidad. About 8" of snow were expected in the La Garita Mountains northwest of Alamosa. About 20 mm (0.8") of rain were predicted for the southeastern corner of the State and in the Moab, Utah, area. In the afternoon (11 a.m. to 5 p.m.) convective precipitation was predicted over the northeastern quadrant of Colorado. Snow with diminishing accumulation (less than 8") was anticipated in the central and southwestern mountains. By 11 p.m. the precipitation pattern was predicted to shift to the northern mountains and northeastern plains, fading considerably by 5 a.m.

The following reports were received from Weather Brief:

Station	precipitation, liquid amount, inches (snow, inches) observed	predicted
Akron	0.37	1.2
Alamosa	missing	0.04
Boulder	1.03	0.9
Colo. Spgs.	0.85	1.1
Craig	0.01	0.7
Denver	0.94	0.9
Eagle	0.11	0.2
Ft.Collins	1.62	0.65
Ft.Morgan	0.51	1.4
Glenwood Springs	missing	0.25
Grand Junction	0.08	1.5
Greeley	1.10	0.6
Gunnison	missing	0.25
La Junta	0.07	0.4
Lamar	missing	0.8
Leadville	0.25	0.7
Limon	0.63	0.7
Longmont	0.55	0.5
Pueblo	0.46	0.8
Salida	0.77	0.3
Steambt.Sp.	0.31	0.7
Trinidad	0.10	0.4

Some of the slight disagreements between forecasts and observations can be explained by the shower-type nature of precipitation in the eastern plains. Observation stations in the mountainous regions are all located in valleys within population centers, whereas the forecasts take into account higher elevations nearby where more precipitation tends to fall. The spotty, hence unrepresentative nature of precipitation measurements is exemplified by observation pairs from closely spaced stations:

Leadville A: 0.11"	Leadville B: 0.25"
Trinidad A: None	Trinidad B: 0.1"

It should also be noted that the NWS predictions did not contain detailed quantitative assessments, except for an underprediction of the snowfall along the Front Range.

On Thursday, March 5, 4:50 a.m. the NWS forecast called for "scattered rain or snow showers west and east today with scattered thunderstorms east. Snow showers likely in the northern mountains this morning with scattered snow showers remainder of mountains, partial clearing this afternoon. Clearing statewide tonight. Mostly sunny Friday. Increasing clouds late in the day in the west.

The WELS forecast, using data from 5 a.m., March 5, again called for major snow accumulations in all mountain areas of Colorado, except for the Durango - Pagosa Springs area in the south. Some areas, notably the Red Mountain area north of

Durango, could expect up to 40 mm (liquid) precipitation or 16" of new snow. That area had witnessed avalanches which cost the life of one highway maintenance person.

Station	precipitation, liquid observed	amount,inches (snow, inches) predicted
Akron	0	none, trace possible
Alamosa	Trace	none, but precip within 20 miles
Boulder	none	none
Colo. Spgs.	none	0.3
Craig	0.08	0.8
Denver	0.08	none, but precip 20 mi to south
Eagle	Trace	Trace
Ft.Collins	0.01	none to Trace
Ft.Morgan	0.01	none to Trace
Glenwood Springs	missing	0.05
Grand Junction	0.3	0.8
Greeley	0.02	none
Gunnison	none	0.8
La Junta	0.03	none, showers in area
Lamar	missing	none, showers in area
Leadville	missing	0.6
Limon	Trace	0.04
Longmont	none	none
Pueblo	0.03	Trace
Salida	missing	0.2
Trinidad	none	none

The WELS forecast from 5 a.m. data, March 6, confirmed the clearing trend predicted by NWS, with the potential of just a few showers lingering on over the State.

NWS issued a winter storm watch effective the evening of Saturday, March 7, to Sunday, March 8, for the central and southern mountains, the Four Corners and the San Luis Valley.

The WELS forecast for this period indicated only widely scattered, isolated light precipitation activity in the State. Weather Brief confirms a few scattered showers.

4.4.23. March 8 - 9, 1992, the "Blizzard of 1992"

The NWS forecast issued at 6:30 a.m. MDT, Sunday March 8, and received through Weather Brief stated: "The winter storm will continue to develop today and should bring precipitation to all of Colorado by this afternoon. A heavy snow warning has been issued for some of the mountain areas of Colorado today and tonight, and snow advisories have been issued for much of the rest of the State." At 5:30 a.m. some details were given as follows: "Periods of snow today mountains and west. Accumulations of 6 to 12 inches San Juan and central mountains south of Aspen today, 3 to 6 inches possible lower elevations of southwest. Increasing clouds with scattered showers and a few thunderstorms east. Turning windy and colder afternoon with rain changing to snow.

Periods of snow tonight mountains and east, decreasing west. Scattered snow showers Monday mountains and east, decreasing late. Partly cloudy west."

The news media predicted anywhere from 1 to 8" for this storm before it hit, focussing on the Denver area. While the storm was in progress, advisories were upgraded to snow from 8 to 16 inches, which still underestimated the strength of this blizzard, the worst in several years. The media dubbed it "the Blizzard of 1992."

The WELS forecast started with 5 a.m. data of Sunday, March 8. By 11 a.m. strong winds from the northeast were expected over the northeastern plains, with temperatures near freezing at 600 m above terrain (in the lower 40s near the ground) in the Denver/Boulder area (Fig. 4.29). Precipitation was expected by this time mainly in the mountains to the west and north of Boulder (Fig. 4.30), in strong contrast to the NWS prediction which expected the storm to hit the southwestern parts of the State. Convective (shower and thunderstorm-type) precipitation was predicted by 11 a.m. for the region between Denver and Colorado Springs, and also over the northeastern plains (Fig. 4.31). The P.I. recalls threatening skies to the west and south of Boulder, starting around 10 a.m., with ceilings dropping below the peaks of the Flatiron Mountains. A strong thunderstorm hit Boulder a little after 2 p.m. Thus, the WELS forecast was "premature" by a few hours, but from thereon beautifully matched the sequence of events. By 5 p.m. 30 mm more liquid water (ca. 1 ft of snow) were expected in the mountains west of Boulder, and heavy rain turning into snow is indicated to the southeast of Ft. Morgan (Fig.4.32). Although predicted temperatures remained near freezing in the northeastern plains, the heavy snow itself produced enough cooling (not accounted for in the prediction model) to make it stick to the ground. By Monday morning WELS forecast more than 100 mm (40" of snow) in the foothills and mountains west of Boulder. Near 90 mm (ca. 2 ft of snow, taking into account early rain and high moisture content) were expected in the region between Ft. Morgan and Limon (Fig. 4.33).

The P.I.'s notes indicate that in Boulder (eastern suburb) intermittent heavy showers, some with hail 1/4 to 1/2" in diameter, turned into snow by about 6 p.m. By 10 p.m. snow accumulation amounted to about 9" on driveways, more on grass. Winds were gusty with a northerly component. There were numerous, short power outages. Trees suffered heavily under the burden of wet snow. By 8 a.m. on Monday, March 9, 21" were measured on driveways east of Boulder. The snow was heavy, wet, and melting near the bottom, but light and dry in the upper 2/3. Mr. Steven Carlson (CDOT Greeley) confirmed heavy blizzard conditions. He mentioned that several snow plows got lost in the blizzard and were stuck out on the roads mainly south of Ft. Morgan. Many road closures were in effect. Highway 36 between Denver and Boulder iced over in the evening of the 8th and turned into a gigantic parking lot for hundreds of abandoned cars. Many businesses in Boulder were shut down Monday, and even on Tuesday. On Monday unplowed streets could be negotiated only in four-wheel drive vehicles. Fortunately, snow removal was aided by rapidly clearing weather in the afternoon of Monday, and by warm weather following the blizzard. Unfortunately, heavy snow accumulation on the satellite antenna prevented data reception on Monday morning. Therefore WELS could not follow the aftermath of the storm with a prediction.

The difficulties of verifying the storm effects become apparent from the inconsistencies between observations: Ft. Collins, for instance, reported 1.18" of liquid water turning into 13" of snow, whereas Boulder received 20" of snow out of 0.74" of liquid water (from a report not contained in Weather Brief). According to Fig. 4.33, Ft. Collins lies on a line indicating 30 mm (1.2") of liquid-equivalent precipitation, while Boulder and Denver predictions were in excess of 40 mm (1.6") which would be more in line with 20" of snow. However, the Denver observer only reported 11" of snow (0.67" liquid). Wheat Ridge on the west side of Denver reported 1.86" of liquid (15" of snow). In good agreement, our forecast would place this latter location at somewhat less than 50 mm (ca. 1.9") of liquid precipitation.

There is no doubt that the "southern" storm predicted by NWS did not materialize: Alamosa in the San Luis Valley went from a 6" snow cover on the day before the alleged storm to a 4" cover after the storm. Trinidad reported only a trace of precipitation. The Weather Brief report, unfortunately, shows lots of "missing" data.

Station	**precipitation, liquid amount, inches (snow, inches)**	
	observed	**predicted**
Akron	0.60	2.0
Alamosa	missing	none
Boulder	missing	1.8
Colo. Spgs.	1.07	1.6
Craig	0.06	0.8
Denver	0.67	1.8
Eagle	0.12	0.1
Ft.Collins	1.18	1.2
Ft.Morgan	missing	1.2
Glenwood Springs	missing	Trace
Grand Junction	0.08	0.08
Greeley	missing	0.8
Gunnison	missing	0.1
La Junta	0.14	none, showers in area
Lamar	missing	none, showers in area
Leadville	missing	0.8
Limon	0.32	0.4
Longmont	missing	1.2
Pueblo	0.02	none, precip 10 miles to west
Salida	missing	0.1
Trinidad	Trace	none

4.4.24. March 17 - 20, 1992

The WELS forecast starting with 5 a.m., March 17, anticipated precipitation in the mountains north of Durango and between Grand Junction and Gunnison between 5 p.m. and 5 a.m. Accumulations of up to 20 mm (0.8") liquid-equivalent were expected. Grand Junction, at the very edge of the predicted precipitation area, reported a trace.

At 6:30 a.m. NWS (Weather Brief) predicted "scattered rain and snow showers will be over the west and southeast today and tonight with rain and snow likely from the Palmer

Divide region (south of Denver) into the northeast. Periods of snow will continue over the mountains with 2 to 5 inches of new snow possible over the northern and central mountains...."

The WELS forecast agrees with this rather generic prediction, and provides additional detail.

NWS and WELS forecasts for March 19/20 also are in general agreement. Light precipitation is anticipated over the mountains.

4.4.25. March 24 - 25, 1992

At 6:30 p.m. on the 23rd NWS (Weather Brief) issued the following prediction: "A fast moving storm in southern California early this morning will move to the Four Corners by sunset today. As of 5 a.m. light rain showers had already started at Grand Junction." (Note: This rain was predicted by WELS, and was expected to extend into the mesa to the east as snow.) At 3:55 a.m. on the 24th NWS downgraded this forecast to: "Partly cloudy statewide with widely scattered showers and thunderstorms this afternoon in the east and snow showers likely in the northern mountains. The WELS forecast, issued with 5 a.m. data on the 24th, agreed very well with this "generic" forecast, but provided additional details, especially over the mountains.

5 Outlook

Roadweather Pro is now proven and ready for deployment throughout the State of Colorado, and to be customized for deployment and operational use by the other snow states.

(1). State of Colorado. CDOT has requested that WELS prepare a proposal to implement Roadweather Pro statewide. As a result of the SHRP-IDEA contract, and the concurrent contract with CDOT, WELS Weather Central is in place, and digitized terrain and road networks for the state are in place. To fully deploy Roadweather Pro, the following requirements will have to be satisfied:

- Man and operate WWC on a 24 hours a day, seven days a week schedule.
- Upgrade PIWPS, and the GUI to accommodate all maintenance sections and senior highway maintenance supervisors.
- Establish a communications switch at WWC to distribute the periodic forecasts (data) to the users, and handle the volume of customer service calls (voice and data) anticipated.
- Deploy the appropriate computers and modems to the users (if 386/20 type computers with 9600 Baud modems are already on-site, WELS or the state can configure the computers to share current applications with Roadweather Pro's GUI).
- Contract with the state run WAN (Wide Area Network) for voice and data connectivity between WWC and the users.
- Establish a service and maintenance contract with CDOT.
- Establish on-site system training and installation for highway maintenance operators.

(2) Other Snow States. Because of WELS experience with the State of Colorado, it anticipates that it could implement Roadweather Pro within three months from the signing of a contract. In addition to those issues noted for the State of Colorado, pre-contract negotiations with other snow states will have to include:

- A decision by the state if they desire to contract for WWC services, or opt for a "turnkey" system which includes data reception, decoding, analysis and numerical prediction. In most highway maintenance scenarios contracting for services will be much less expensive than running a meteorological shift operation 24 hours a day and 7 days a week, and making a new capital investment in computer and communications hardware and software.

- Identify the source of a state approved GIS. If the state already owns a GIS, WELS can include access to it as no-cost GFE. As with the State of Colorado, WELS will have to prepare topographic and road networks for each region of the state as an important customization step.

- Included in system development and deployment must be time to test new locations, using historical situations, to insure that each system component works properly, especially with the linkage to new terrain backgrounds.

- And as with the State of Colorado, access to state-run and -operated voice and data communications networks will have to be resolved to establish communications between WWC and the state users.

Appendix A

Roadweather Pro

Roadweather Pro (Release 1.01) (Beta Test Version)

1. System Requirements

Computer based on Intel 386 or 486 chip, with at least 10MB hard disk space available.

VGA monitor
MS-DOS 3.0 or higher
Microsoft mouse installed with appropriate driver

The system may run with other configurations as well, but has not yet been tested out.

Note: This is a Beta Release that still may contain "bugs". If any are found, please contact us with a description of reproducible procedures that caused the undesired performance. We appreciate your help and cooperation.

2. Program Installation

Place the "INSTALL" diskette in Drive B.

When in the root directory of Drive C, at the DOS prompt C:> type

b:install then hit **<ENTER>**.

The program will automatically generate directories C:\WELS\EXEC and C:\WELS\DATA needed for program execution and data manipulation. If such directories already exist, they will not be affected by the installation procedure. Then several executable files are automatically transferred to the directory C:\WELS\EXEC, and an experimental data file (FILE.DAT) is copied to the directory C:\WELS\DATA.

The installation procedure automatically executes the file ROADPRO.EXE which now resides in the directory C:\WELS\EXEC, allowing you to manipulate the experimental data file. If you wish to run the Roadweather Pro program again after having exited it, move to the directory C:\WELS\EXEC. (While in the root directory C:>, type **CD \WELS\EXEC.**) Then type **ROADPRO <ENTER>** to execute the program.

3. Program Features

Roadweather Pro allows you to access forecasts for specific locations which have been generated by a numerical weather prediction system, PIWPS (Portable, Interactive Weather Prediction System). Normally, these data would already reside on the hard disk of your computer, having been sent there on a daily basis via modem from WELS Weather Central. Alternatively, these data may be supplied via "sneaker net", i.e. on a floppy disk fitting either Drive A or Drive B. In the latter case, these data will first have to be loaded into the computer. Depending on the choice of disk, when in the directory C:\WELS\EXEC type either

load_a or **load_b**, then hit **<ENTER>**.

The installation program already provided you with executable files which contain everything to load the appropriate data from a floppy disk to the hard disk Drive C and, in that process, convert the data generated by PIWPS to the format used by Roadweather Pro.

Executing ROADPRO.EXE (by typing **roadpro <ENTER>** at the C:\WELS\EXEC> prompt), brings up a screen with the WELS logo. You should see a mouse cursor on the screen. If not, the proper mouse driver has not been installed. Please, check your mouse installation or activation procedures.

At the bottom of the screen you should note a "Help" instruction line, telling you what to do: Click a mouse button. A menu appears, giving you choices:

Set Conditions
Run
Exit from program

If you work with a new data set, or if you wish to start anew with an already loaded set, first choose "**Set Conditions**". This option provides you with choices of forecast time and date to be displayed on subsequent screens. It also allows you to choose options in converting liquid water precipitation, as delivered by the PIWPS prediction, to snow depth as needed for road maintenance. Click the mouse cursor on this option. The menu will disappear. Click a mouse button again. Now the options

5 a.m. M.S.T
5 p.m. M.S.T

are open for choice. These options pertain to the **starting time** of the forecast period, i.e. the time for which PIWPS has been fed with observations. (If data are received in mid-morning, the choice would be "5 a.m. M.S.T." Data received in late evening would require the choice "5 p.m. M.S.T.")

As instructed by the "Help" message, make the appropriate choice by clicking the mouse. Immediately a text window appears, prompting you to enter the date at which the forecast period started. The date can be entered in any format containing numbers, letters, or printable symbols. Hit **<ENTER>** when the entered date looks correct.

A graph appears which instructs you on possible consequences of snow/liquid-water ratio choices. The graph contains values of such ratios along the (vertical) Y-axis, and air temperatures, as provided by the PIWPS forecast, along the (horizontal) X-axis. Generally, the warmer the air, the wetter the snow, hence the less snow depth per inch of forecast liquid water. However, the amount of snow accumulation not only depends on the wetness of snow as it falls, but also on the state of the ground. The green lines in the graph illustrate the assumed relationships between the snow/liquid-water ratio and air temperature, depending on the ground being "deeply frozen," "lightly frozen," or "thawed." The colder the ground, the more snow will stay on it.

The "Help" line instructs you to click the mouse. Doing so brings up a menu, letting you choose between

Deep Frozen Grd
Only Top Frozen
Thawed
Choose A Ratio
Default

If you choose "**Default**" and no conversion values have been placed into computer memory by previous actions, the "Help" line will tell you so. If the current forecast data set has been manipulated before, choosing "Run" after the next mouse click will continue with the settings chosen during the previous manipulation, as displayed on the "Help" line. If you don't like these default values, go through the "Set Conditions" procedure again and make a different selection for the snow/liquid-water ratio.

Our observations show that snow/liquid-water ratios vary widely from location to location, even in the same snowstorm and on the same day. Local factors, wind packing, etc. produce uncontrollable effects. Therefore, we caution against "fine tuning" these ratios.

Making one of the first three choices in the menu shown above will indicate the relationship between snow, air and ground temperatures by high-lighting in red the appropriate lines on the graph. The "Help" line also will tell you what you did. If you don't like your choice, you can "bow out" at the next step by selecting "Set Conditions" again.

The option "Choose A Ratio" in the above menu lets you override any of the relationships suggested by the green lines in the graph, and lets you pick a constant ratio which will hold regardless of temperature or ground state. As you click this option the menu disappears. Be careful what you do with the mouse cursor. Wherever you click the mouse, the vertical coordinate of your cursor position will be memorized as your chosen value for the snow/liquid-water ratio. This choice will also be communicated to you on the "Help" line. (If you made a mistake, back out again by choosing "Set Conditions" at the next step.

Having made the correct choice for snow/liquid-water conversion, click the mouse again. From the menu that appears, choose "RUN". As the "Help" line instructs you, click the mouse. A new menu appears, containing the names of locations for which the snow and temperature forecasts can be manipulated. If the weather prediction currently resident in the computer as delivered by PIWPS does not contain any precipitation of significance, you may wish to play with the FCST.DAT file provided on the installation disk. Either go though the installation procedure again or, with the installation disk in drive B, at the C:> prompt, type

copy b:\fcst.dat c:\wels\data*.*

This procedure will place the demo file at your disposal again. However, the current PIWPS forecast file will be lost. If you wish to avoid this loss, first copy the FCST.DAT file from directory C:\WELS\DATA to another location or to a floppy disk, before you load from the installation disk as described above. You can later copy the temporarily stored file to its original location in C:\WELS\DATA. In that demo file only the first four locations in the menu contain interesting data.

Choose a station, e.g. "Akron", and click the mouse. A graph appears which shows inches of predicted snow (in yellow) and predicted air temperatures at 600 m above ground (in magenta) along the Y-axis, and time (in M.S.T. according to your previous choice) along the X-axis. The data entered by you earlier appears in the lower left corner of the graph. Snow predictions are indicated in the graph by blue circles, connected by blue lines, temperature predictions by magenta circles and magenta lines. These are the original forecasts as delivered by PIWPS.

If you wish to manipulate these forecasts for one reason or another, click the mouse, as the "Help" line suggests. The following menu appears:

Show last SNOW action
Show last TEMP action
Adjust SNOW fcst
Adjust TEMP fcst
Plow
Exit to first menu

The first two choices pertain to the latest previous manipulations of snow or temperature forecasts that should be recalled from memory for further manipulation. These manipulation results stay in memory, even if the computer has been turned off in the meantime or, for that matter, even if a new set of data has been loaded. If no previous results are available for the location you have chosen, a "beep" will sound, and nothing else will happen. Click the mouse to bring the last menu back again.

If there were previous manipulations of forecasts in memory, but you don't want them you should proceed directly with any of the other menu items. This course of action will simply overwrite old manipulation files.

Suppose, you want to change the SNOW forecast as delivered by PIWPS. Click on that menu item. The menu disappears, and the "Help" line instructs you to click the mouse again. This time a choice of reasons appears why you might want to adjust the snow forecast:

Timing	The timing of the snowstorm is wrong;
Import from Other Area	The present location may have no snow predicted, but a neighboring location has a more reasonable forecast showing some precipitation. The forecast from that location can be imported as first guess.
Intensity (much)*	The intensity of the snow storm should be changed by quite a bit;
Intensity (moderate)*	
Intensity (little)*	
Fluke	Produces a one-time local adjustment
Return to Menu	

Menu items with asterisk (*) should be clicked on at coordinate positions **after** the originally predicted snowfall began. Noting these exceptions, move the mouse cursor to the coordinate location marking the **time** for which a recently received observation holds, and to the **snow depth** reported. Click the mouse at that cursor location. The new forecast will be displayed on the screen by blue circles and white lines. Clicking the mouse will bring back the menu. If no further adjustments are desired, click "Return to Menu". The first menu appears. Choose "Run", and the station which you have just manipulated (or any other desired station). Clicking "Show last SNOW Action" from the menu recalls the last snow forecast manipulation with green circles and blue lines. You can proceed as described above to manipulate this last forecast again. If you are not satisfied with your old forecast corrections, instead of clicking "Show last SNOW Action" proceed directly to "Adjust SNOW fcst". Any actions taken now will over-write files containing the old ones.

If you clicked "Adjust TEMP fcst", another click will bring up reasons why you might want to modify the original prediction. The choices offered are:

Timing	Moves the predicted temperature curve;
Diurnal Var.(Sfc.)	Extrapolates from 600m to temperature conditions near the ground;
Max.Temp.	Allows you to adjust the predicted maximum temperature;
Min.Temp.	Allows adjustment of predicted minimum temperature;

Fluke Provides a constant temperature shift (e.g. to allow for urban heat island effects);

Return to Menu

When adjusting for poor timing in the forecast of temperature changes, be sure to click the mouse at reasonable choices of values. If the mouse is clicked outside the range of originally predicted temperatures, a "beep" will sound and the "Help" message will tell you that your choice was illegal.

The flexibility granted by this menu should be quite useful. Whereas PIWPS predicts precipitation reaching the ground, temperature forecasts pertain to a level approximately 600 m above terrain. Such temperatures are of meteorological interest, but do not reflect the conditions near the earth's surface. First of all, near 600 m the temperature variations between day and night are relatively small. The temperature of the air near the ground is strongly affected by sunshine which, in turn, is influenced by cloudiness. If you click the "**Diurnal Variation**" option, the menu disappears and after another click you are given the choices:

Clear
Partly Cloudy
High Overcast
Low Overcast.

If precipitation is predicted or observed, it is safe to assume "**Low Overcast**" conditions. Clicking any of these options provides a reasonable guess for air temperatures near the surface under the chosen, prevailing conditions.

To allow for road surface conditions which may differ strongly from air temperatures, especially when skies are clear, temperature forecasts should be adjusted again. Observations from sensors embedded in the road pavement, and experience will have to guide the user. It might be expedient to apply another diurnal variation correction on top of the one executed before, or to adjust maximum and minimum temperatures separately. Clicking on one of the latter choices produces menus with a temperature scale

+5
+4
+3
+2
+1
etc.

The appropriate choice is translated into an adjustment of the predicted (and perhaps already modified) temperature curve.

When you "Run" the Roadweather Pro program again, bring up the "Last TEMP Action". It will be displayed by magenta circles connected by red lines.

The "**Plow**" menu choice still needs to be described. After clicking it, move the mouse cursor to a location on the screen which closely describes the time at which the plows passed the location under consideration. Click the mouse at the appropriate cursor location. The snow accumulation expected after plowing will be exhibited by green circles and green lines. You should use this option only if road surface conditions are your sole concern. In your next choice "**Show last SNOW action**" the road state after plowing will be exhibited.

Appendix B

Figures

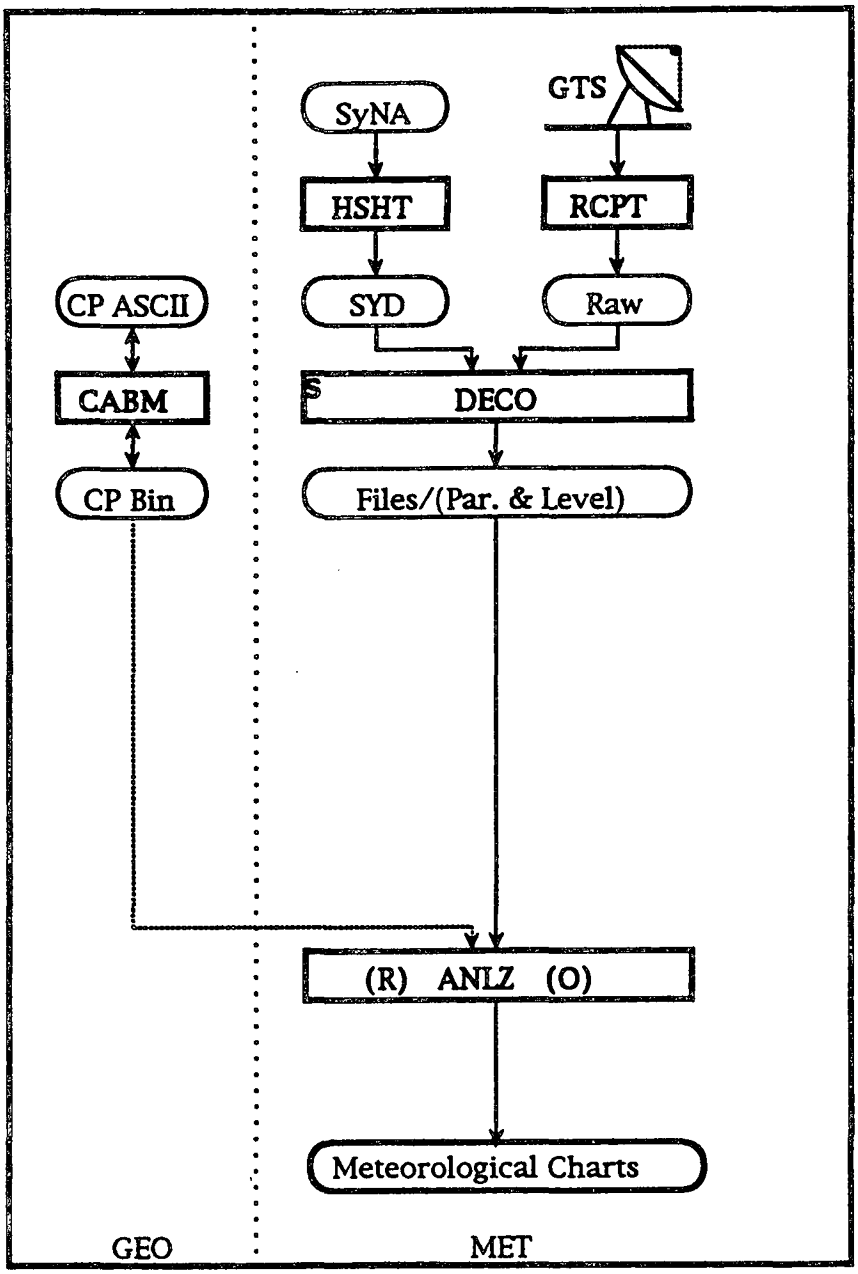

Figure 3.1: Flow diagram of the Basic Meteorological System. For detailed explanations see text.

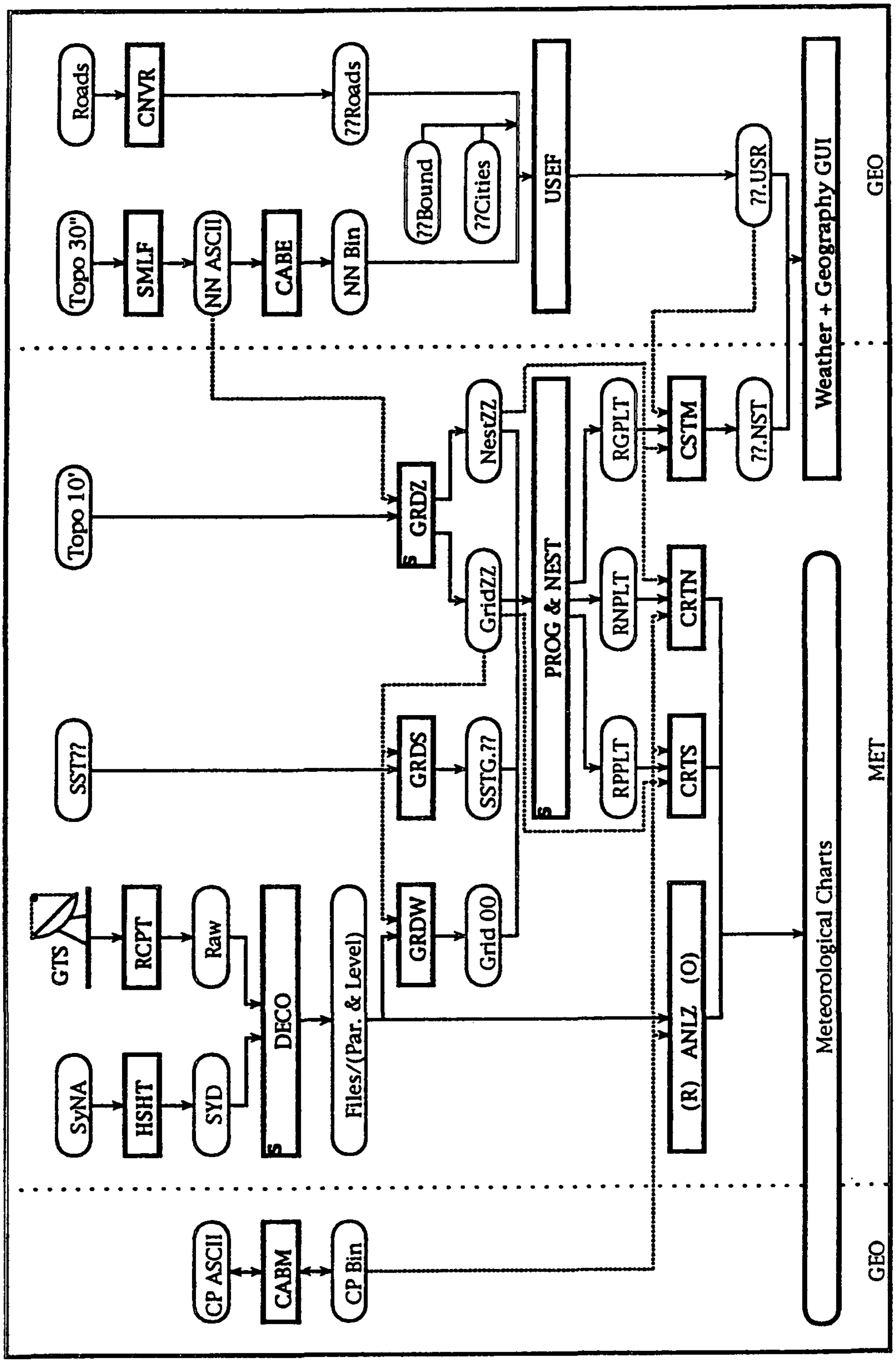

Figure 3.2: Flow diagram describing the full weather and geographic data systems.

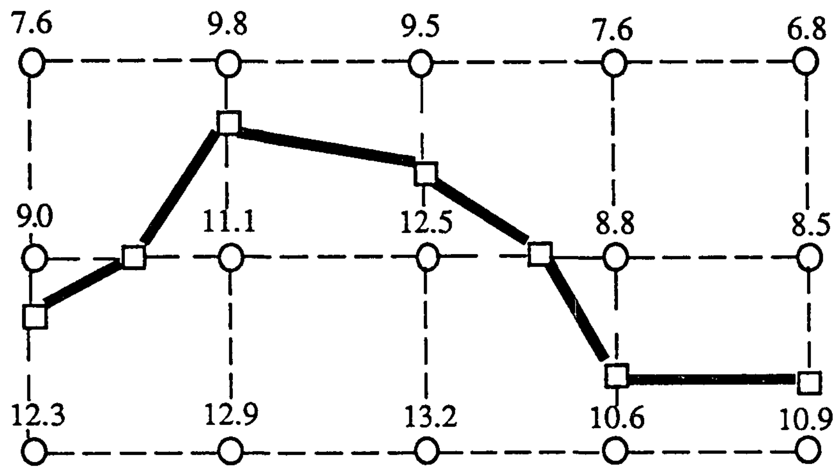

Figure 3.3: Schematic example of irregularly spaced data points interpolated from regularly spaced, gridded data. The interpolated points carry the value "10" and are connected by a spline function to smooth the jagged appearance of the line.

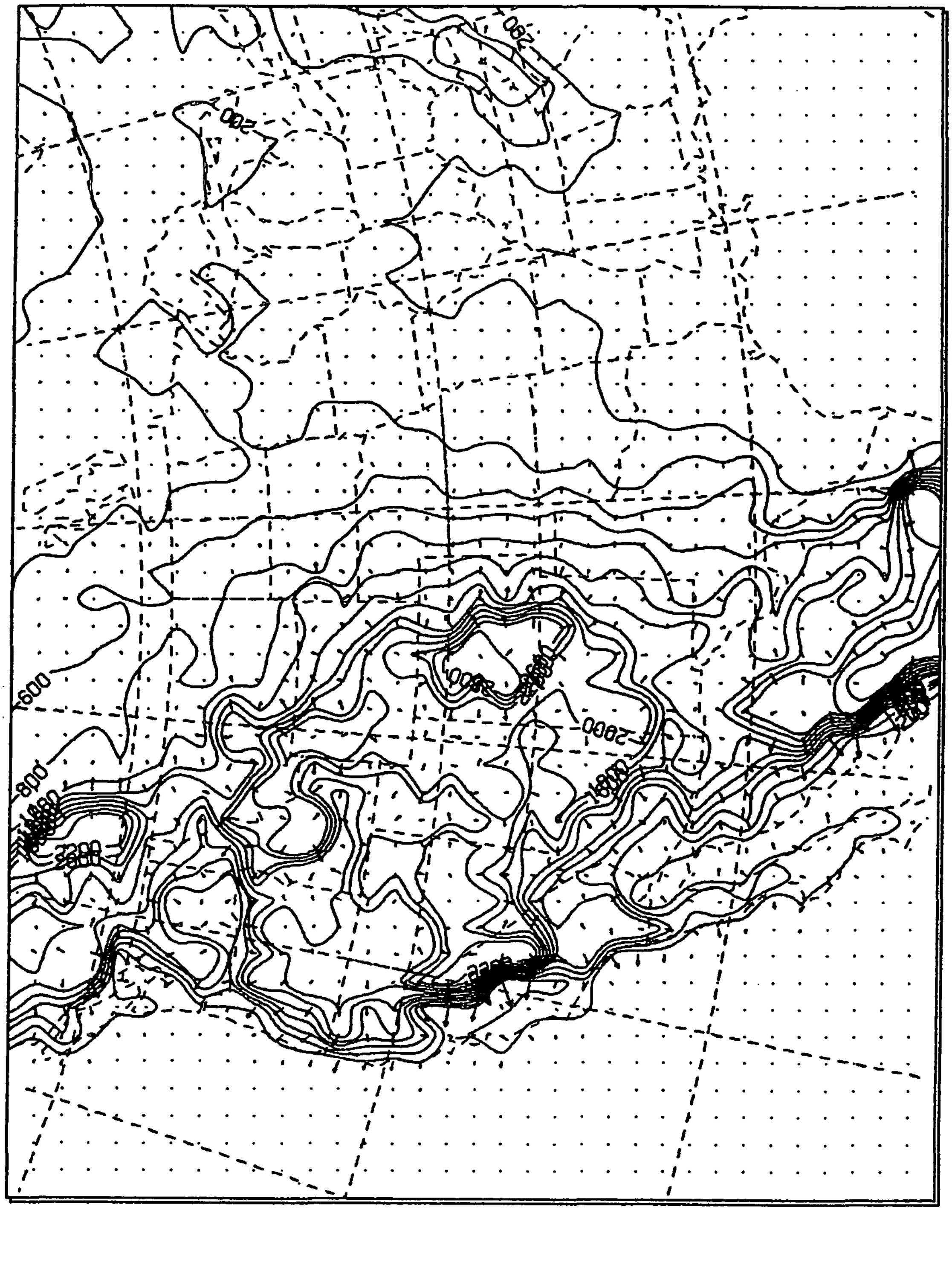

Figure 3.4 Domain over which the PIWPS model is run in its present configuration. Dots indicate grid points of the model. Terrain contours, as the model "sees" them, are drawn for every 200 m.

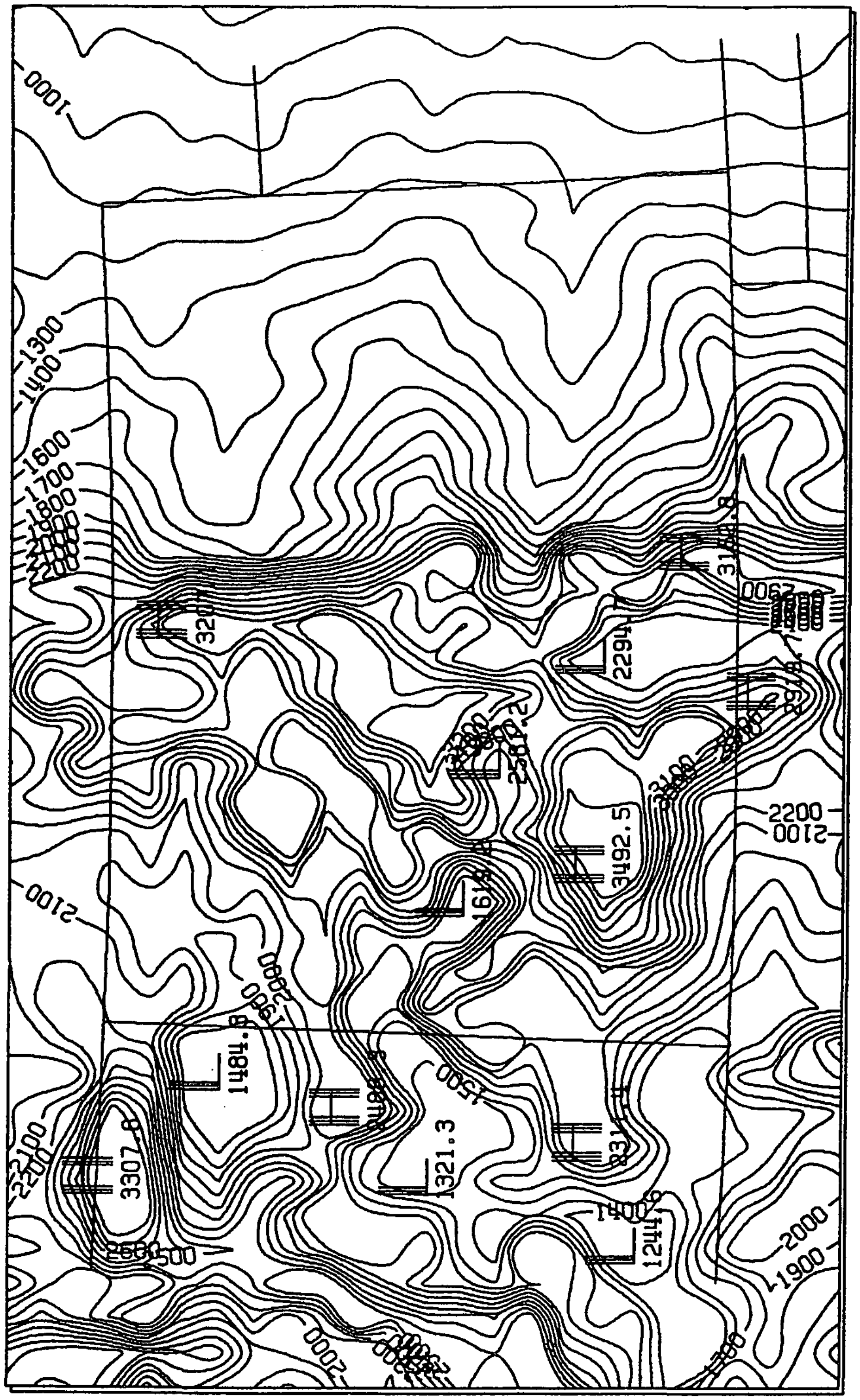

Figure 3.5 Domain of the nested grid model, presently configured for the State of Colorado. Terrain elevations used by the model are drawn at 100 m intervals.

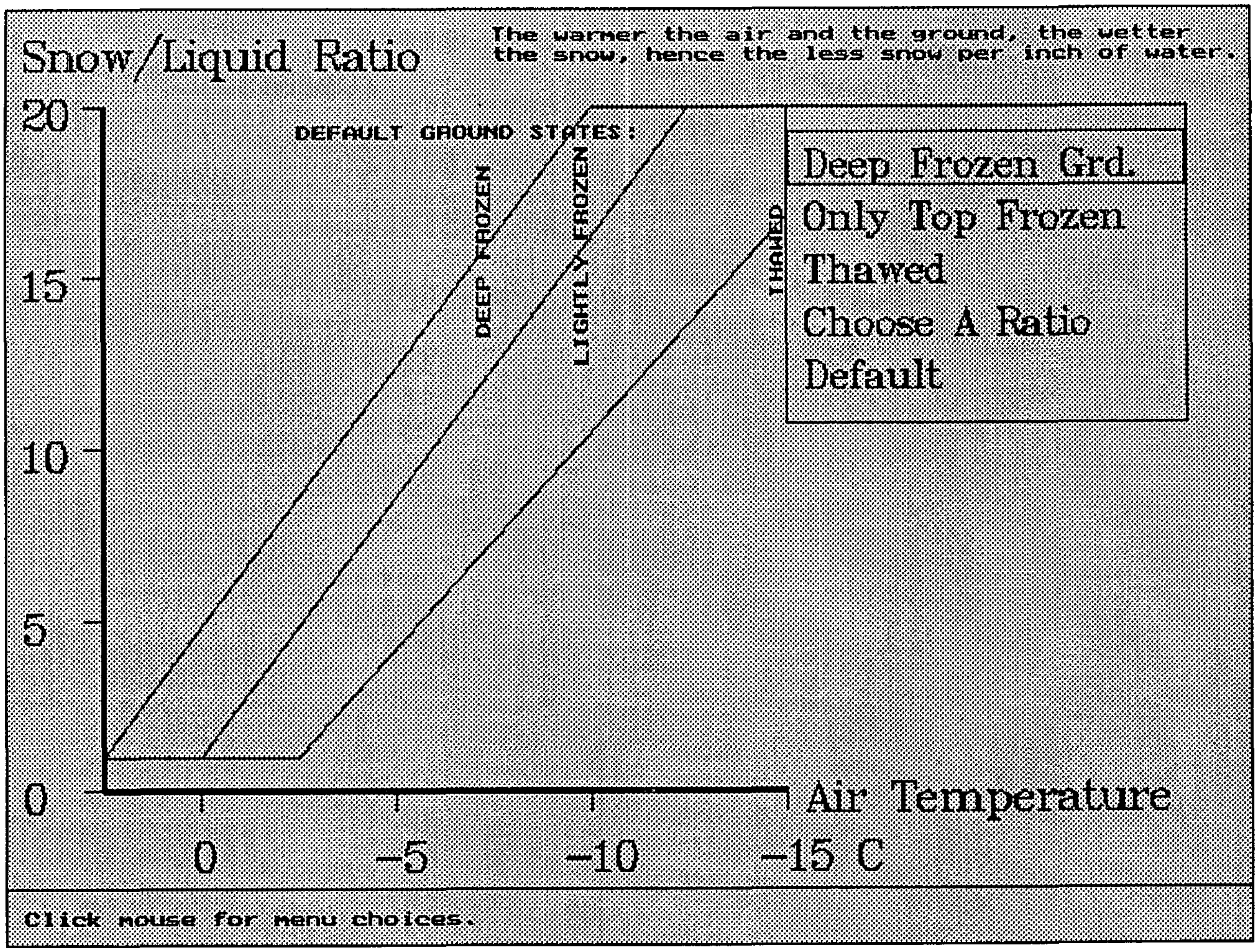

Figure 3.6: Conversion of liquid water-equivalent to snow, depending on user's choice of ground state or of a fix* conversion ratio. Background diagram indicates embedded conversion algorithms.

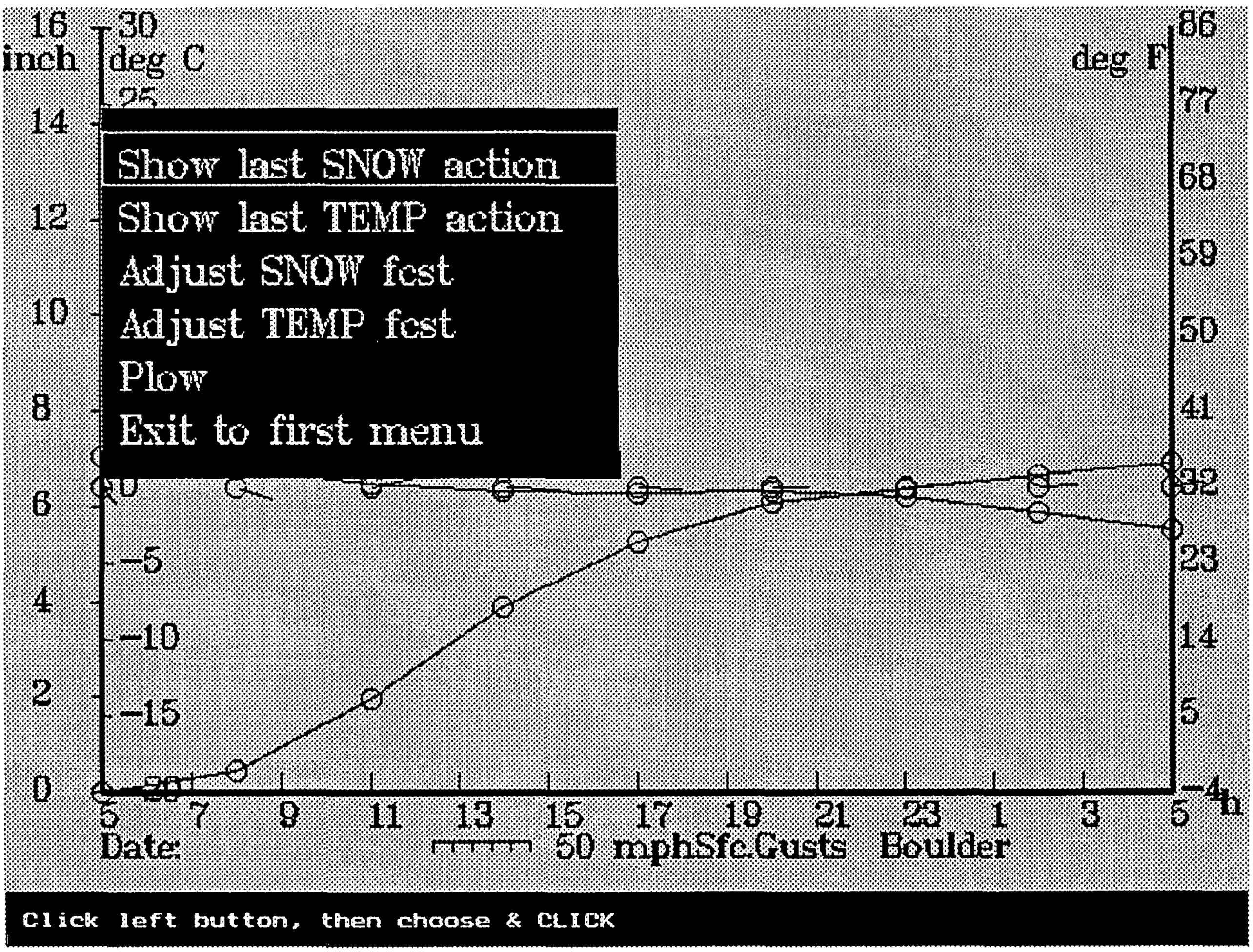

Figure 3.7: Forecast for snow (blue line), temperatures at 600 m above terrain (red line) and winds ("arrows" with scale indicated near bottom), valid for Boulder, 5 a.m. MST, March 8, 1992, till 5 a.m. March 9. Choose "Adjust SNOW fcst" from menu to arrive at Fig. 3.8.

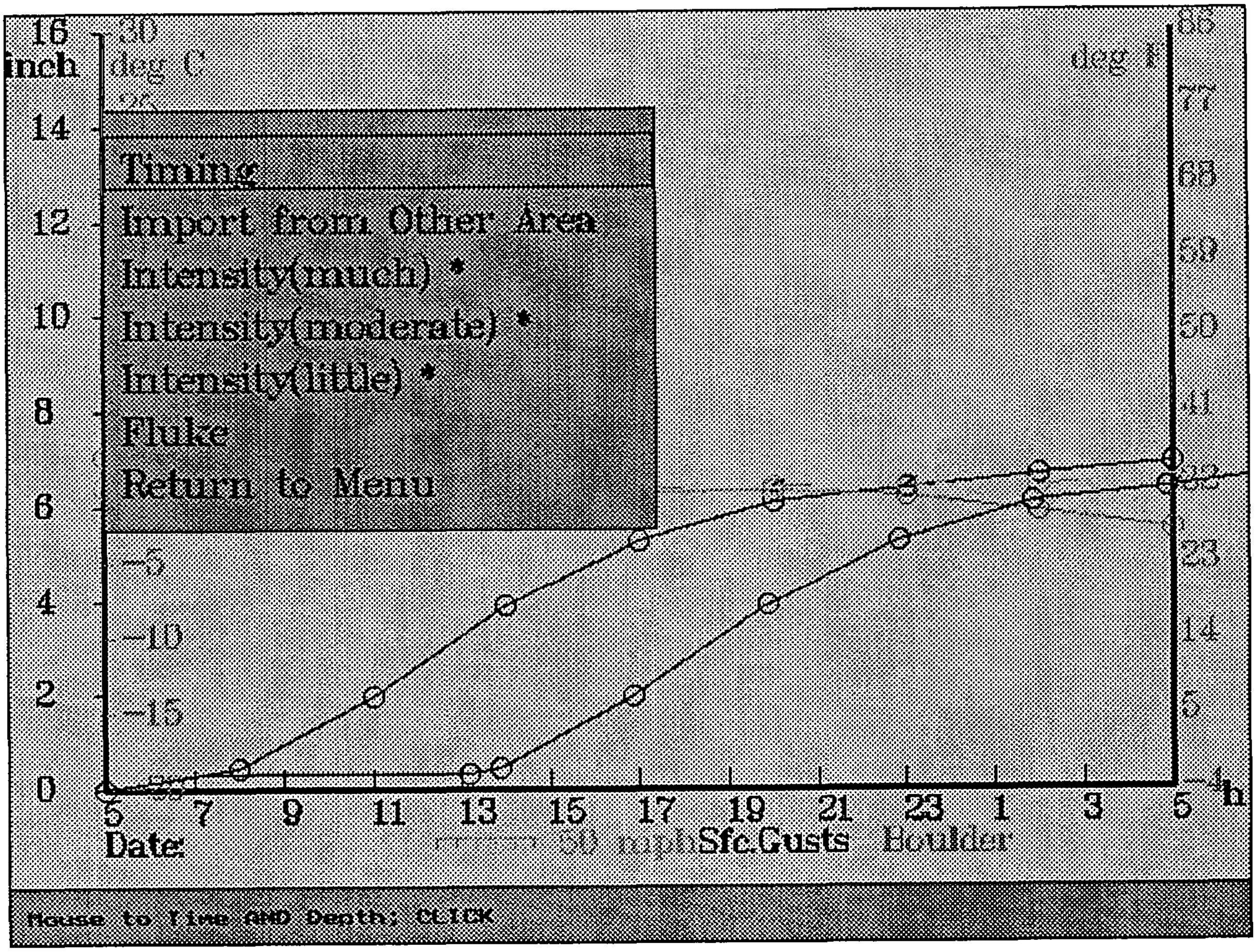

Figure 3.8: "Timing" was chosen from menu, and cursor was clicked near 15 h and 0.25 inches. New forecast (brown line) delays the blizzard.

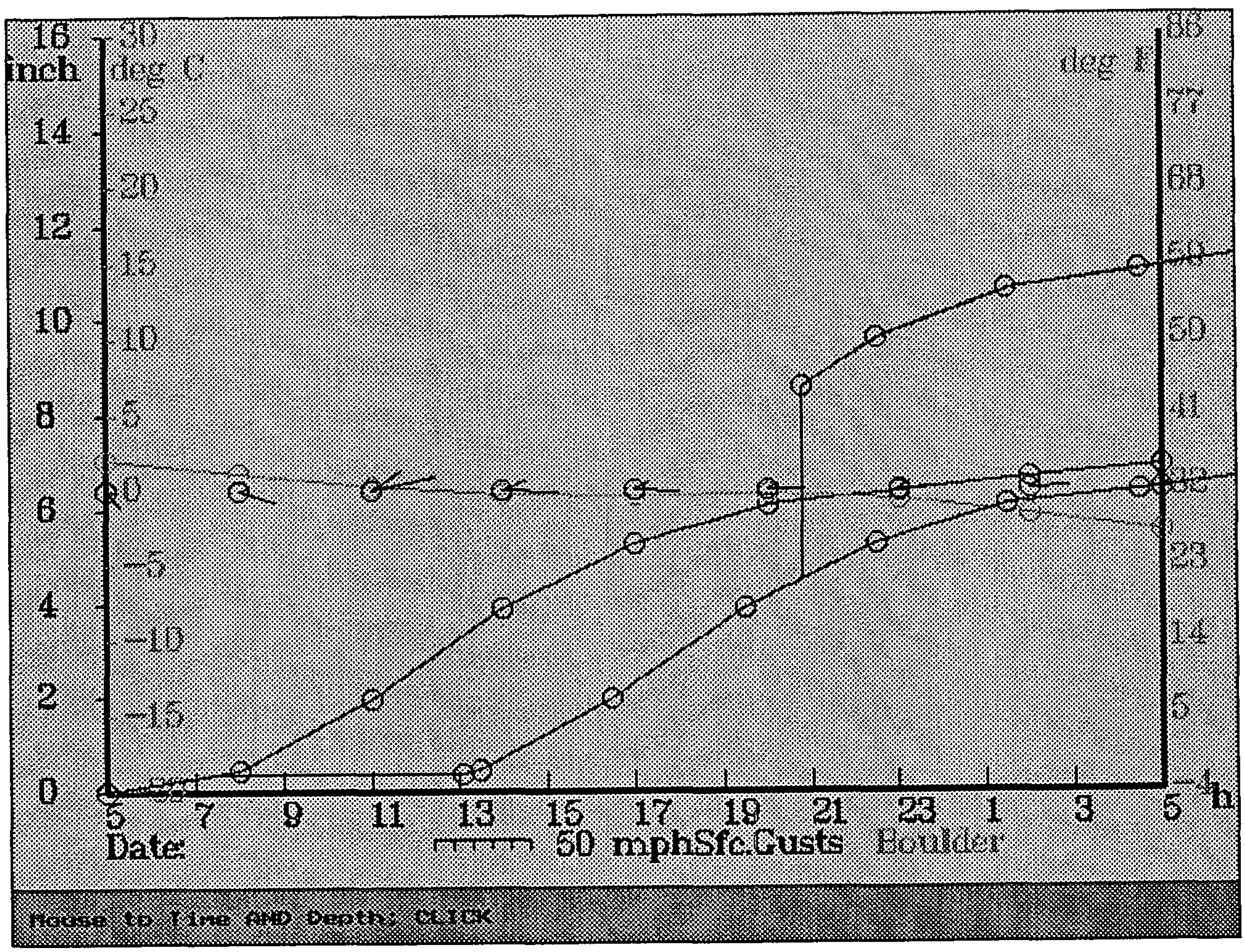

Figure 3.9: By choosing "Intensity (much)" from the menu in Fig. 3.8, and clicking the cursor in reference to snow observation at 21 h of >8" a new forecast (white line) is obtained.

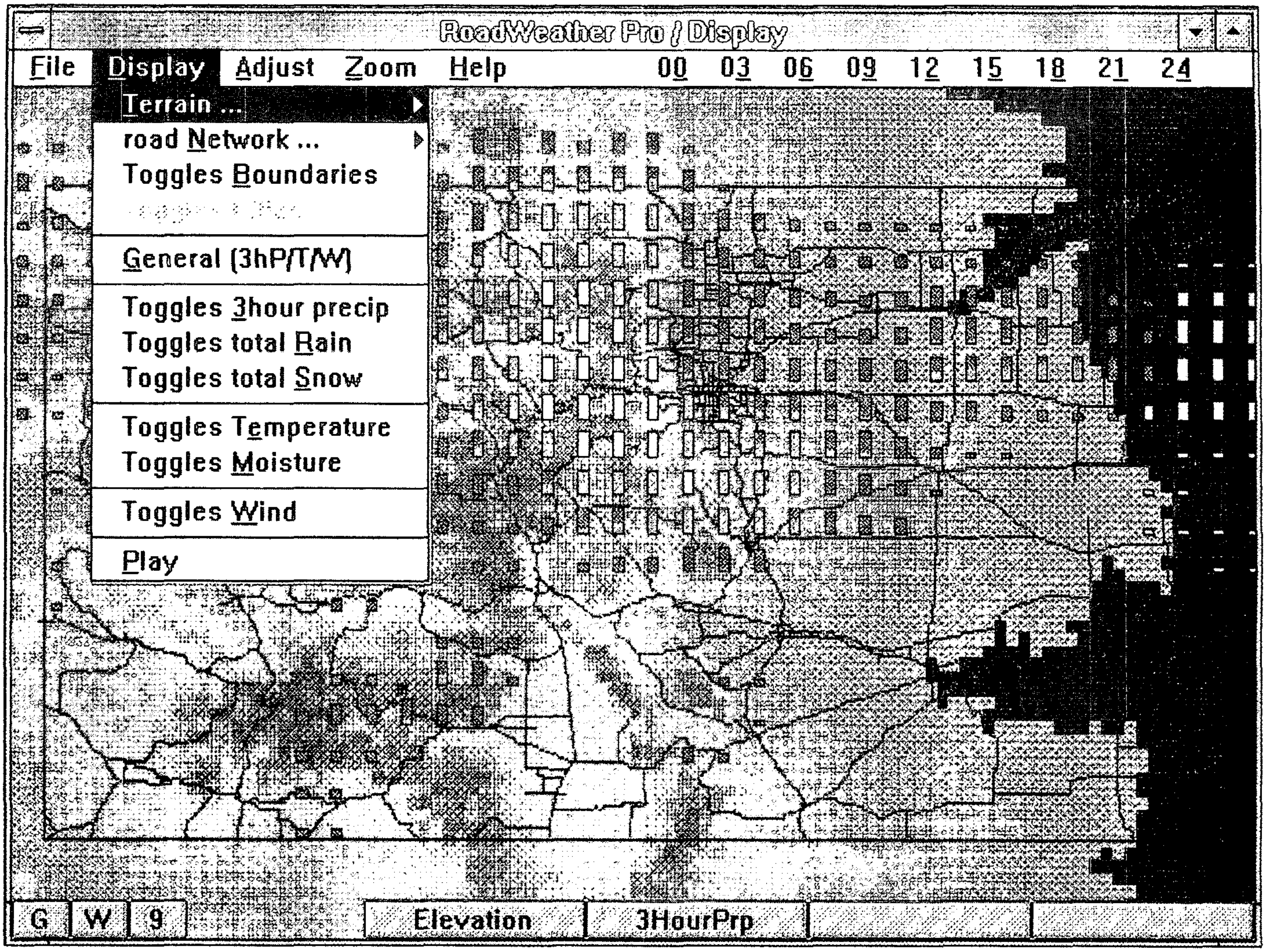

Figure 3.10: Clicking the pull-down menu choice "Toggles 3hour precip" brings up icon boxes which fill up with different colors for predicted rain or snow. Each successive color step indicates increments of 0.2 inches for rain, and 2 inches for snow. The underlying terrain and road network map of Colorado demonstrates the flexibility of the geographic database: Only terrain between 4,500 ft and 16,000 ft has been drawn, leaving eastern Colorado black, thereby showing the Platte and Arkansas River valleys. The "buttons" along the lower edge of the screen have the same function as the pull-down menus. They also indicate what is currently displayed. The "Play" option provides a time-lapsed display of the forecast times, which can also be clicked on in the menu bar.

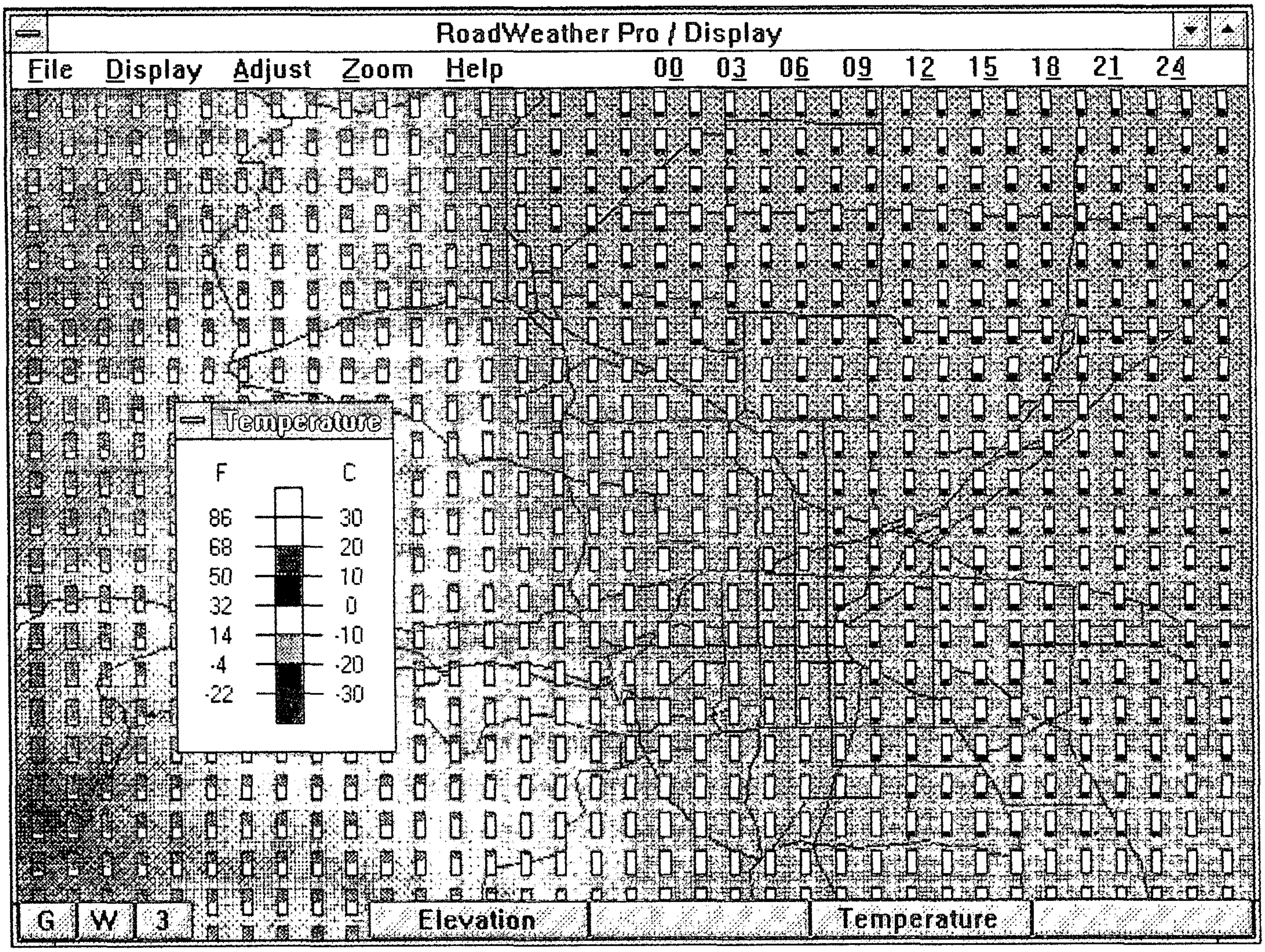

Fig. 3.11: Display of icons symbolizing 3-hour temperature forecast. First appearance of red in these icons shows temperatures to be above freezing. Clicking on the "Temperature" button displays a small window with the color code. This window can be moved on the screen. The background shows the topography and road network for the Boulder/Denver area.

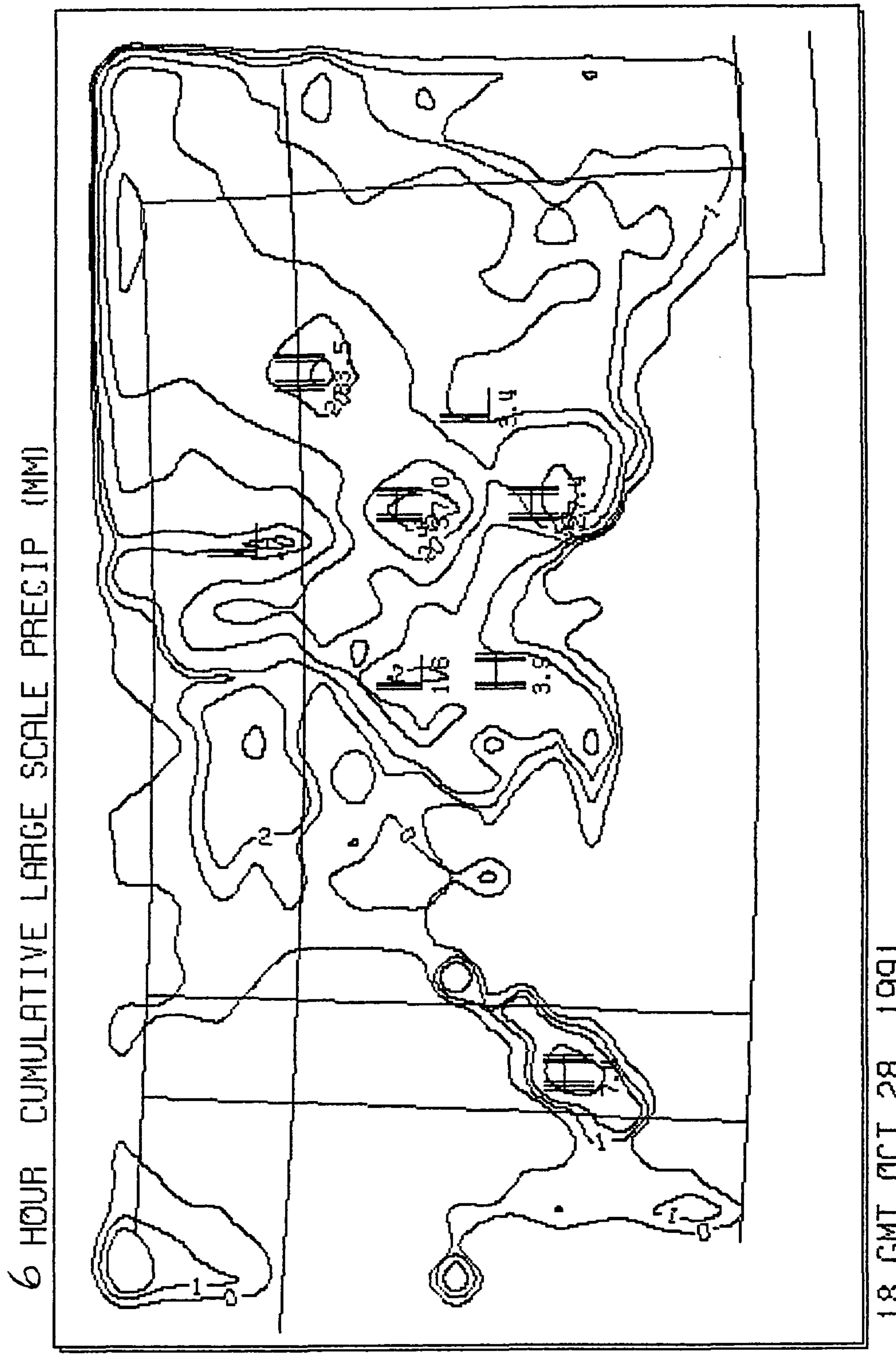

Figure 4.1: Forecast output of large-scale precipitation in mm of liquid-water equivalent from 5 a.m. to 11 a.m. MST (= 1800 GMT), October 28, 1991.

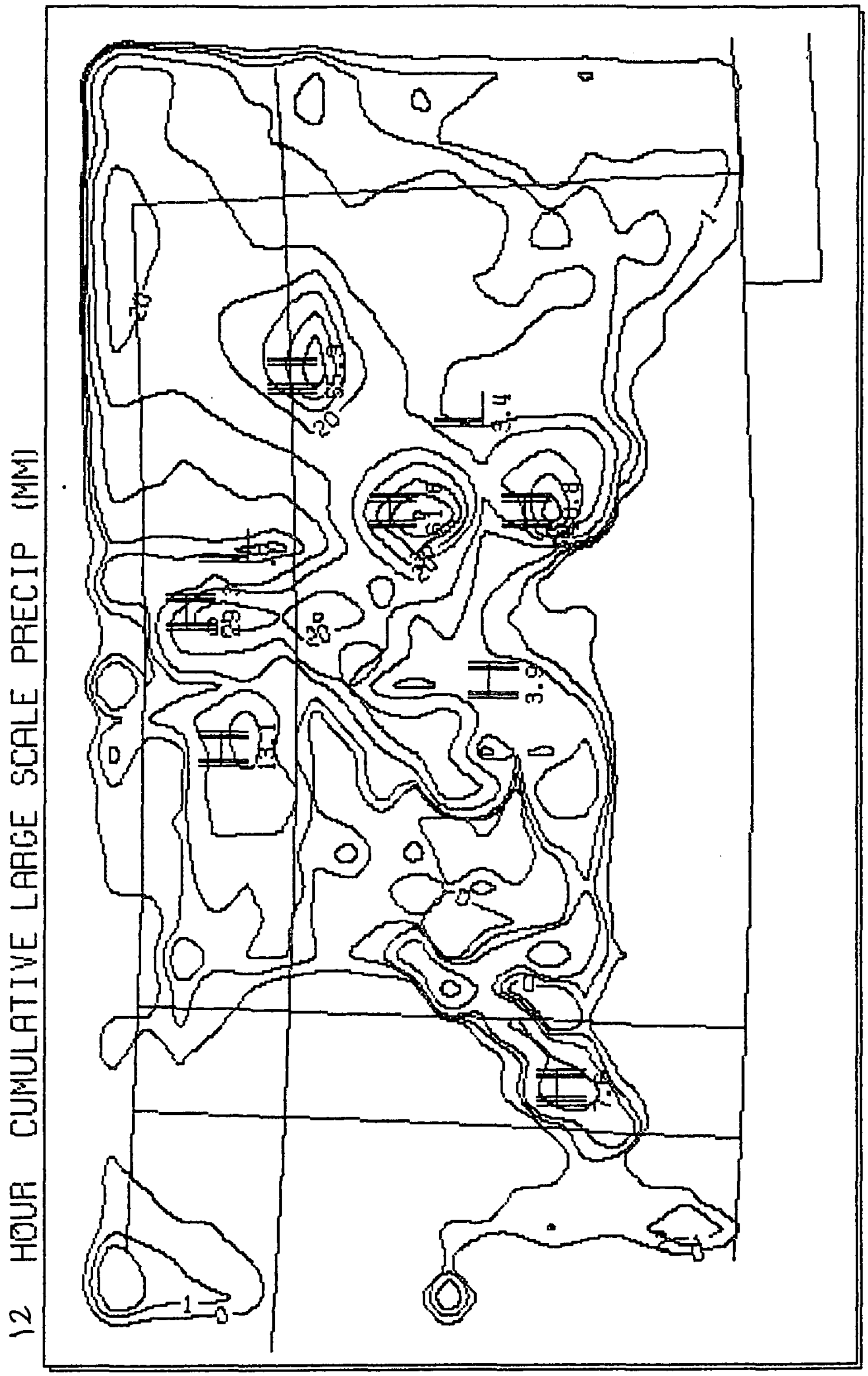

Figure 4.2: Forecast of precipitation accumulation between 5 a.m. and 5 p.m. MST, October 28, 1991.

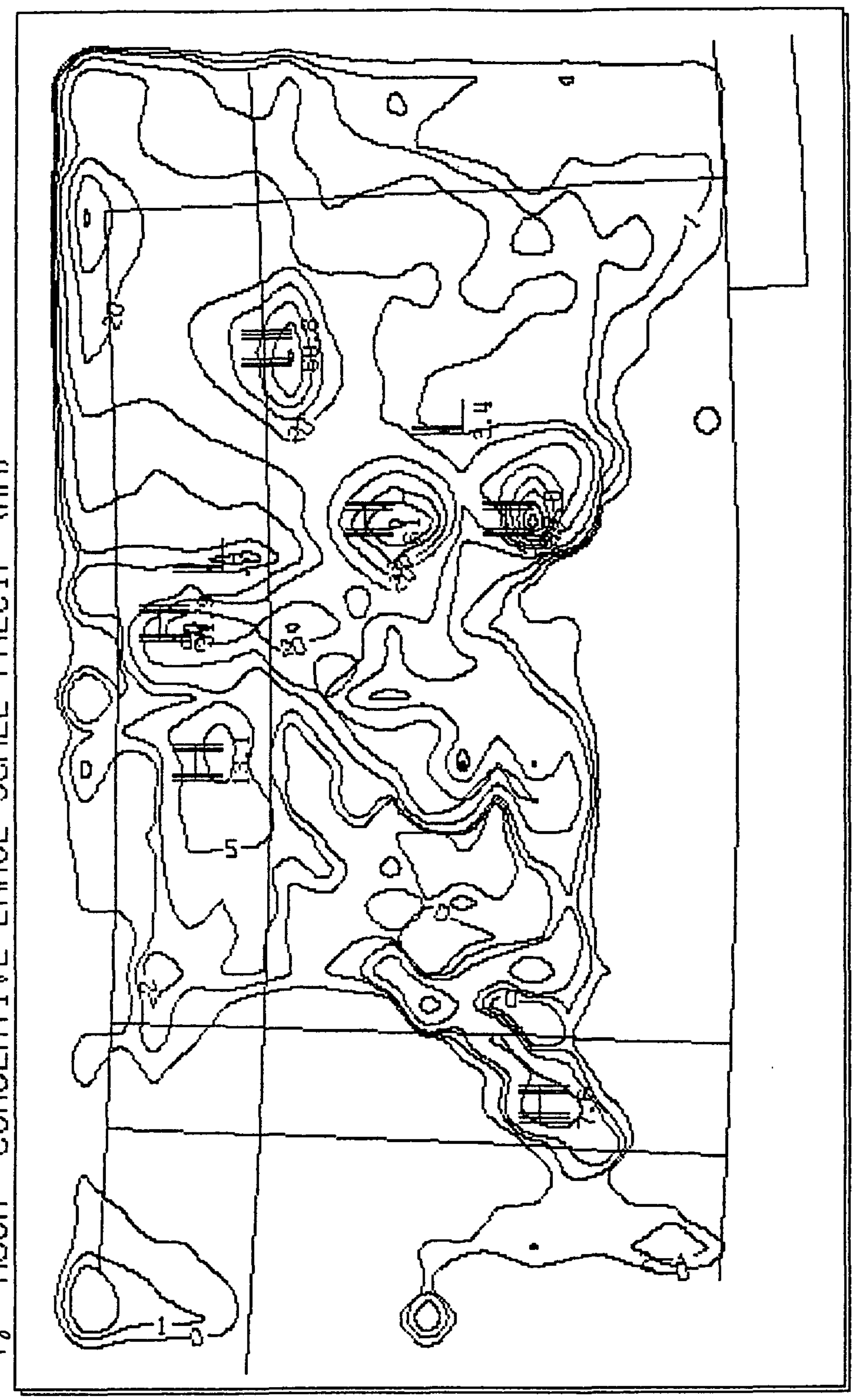

Figure 4.3: Forecast accumulation of precipitation during the 18 hours between 5 a.m. and 11 p.m., October 28, 1991.

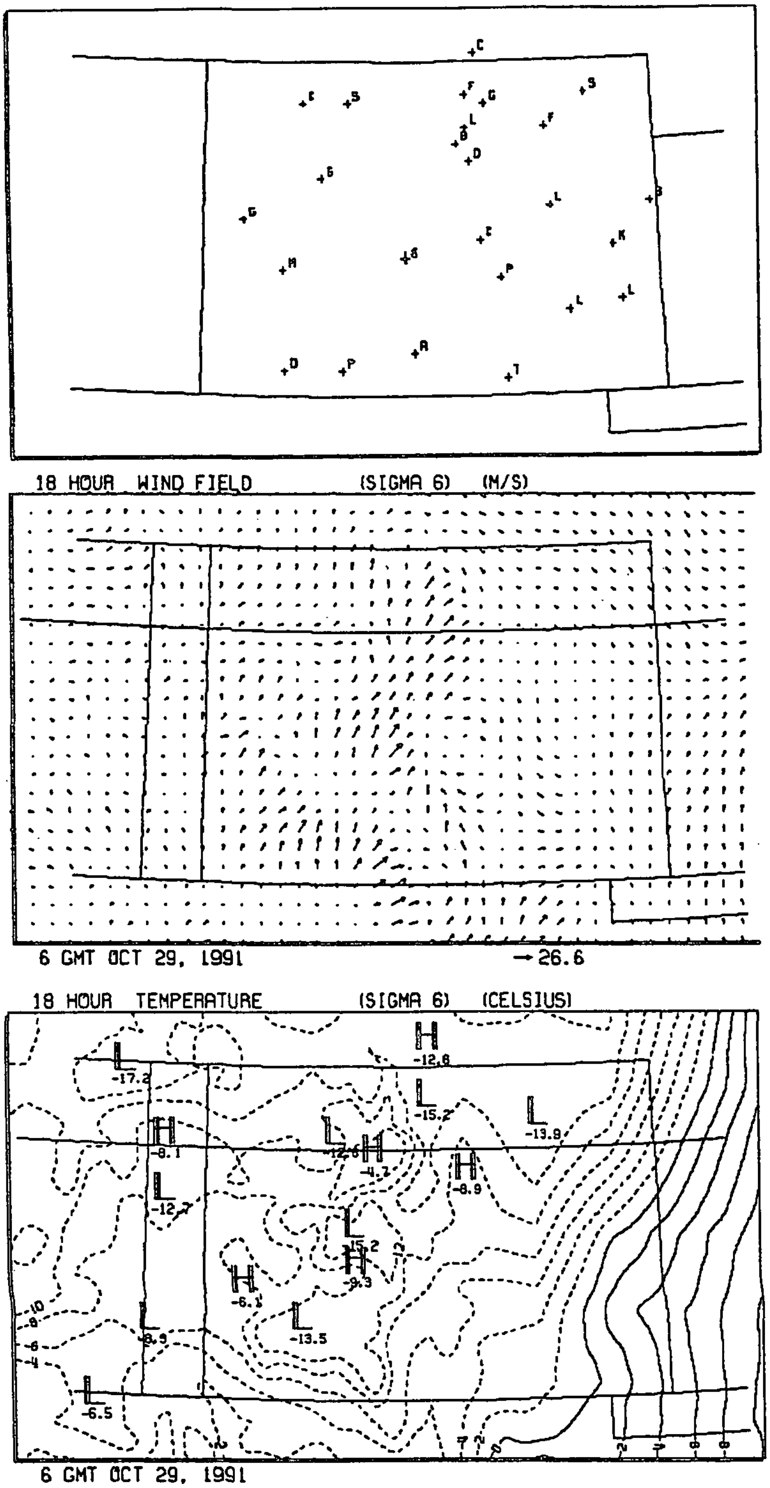

Figure 4.4: Top: City locations by initial letters. Middle: Winds forecast for 11 p.m. MST, October 28, 1991, at 600 m above terrain; top speed (m/sec) indicated by length of arrow and value at lower right of diagram. Bottom: Temperatures forecast for same time at 600 m above terrain in deg centigrade, drawn for every 2 deg; solid lines 0 and positive, dashed lines negative values (below freezing).

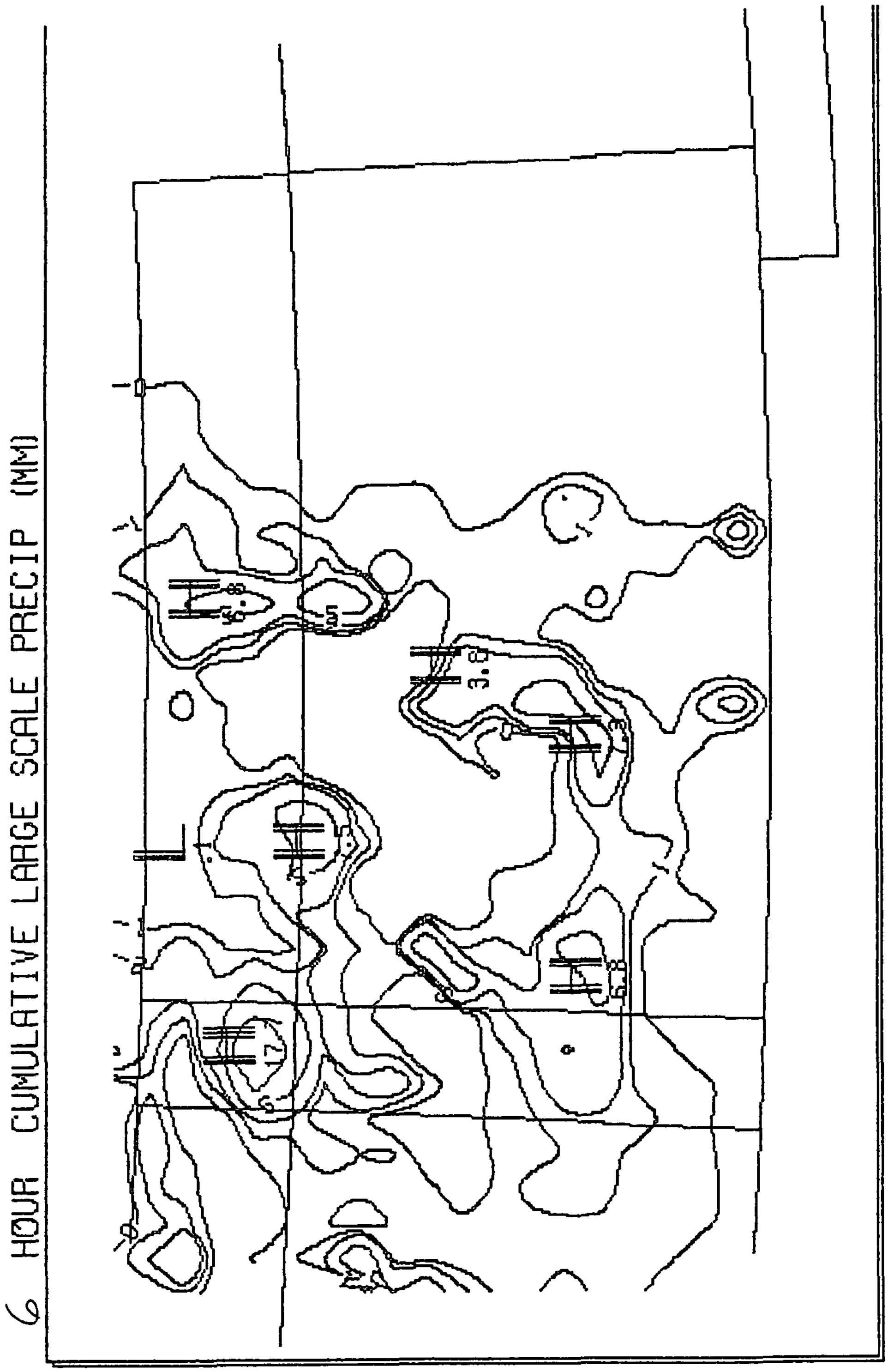

Figure 4.5: Forecast of precipitation (mm liquid-equivalent) between 6 p.m. and 11 p.m. MST, October 29, 1991.

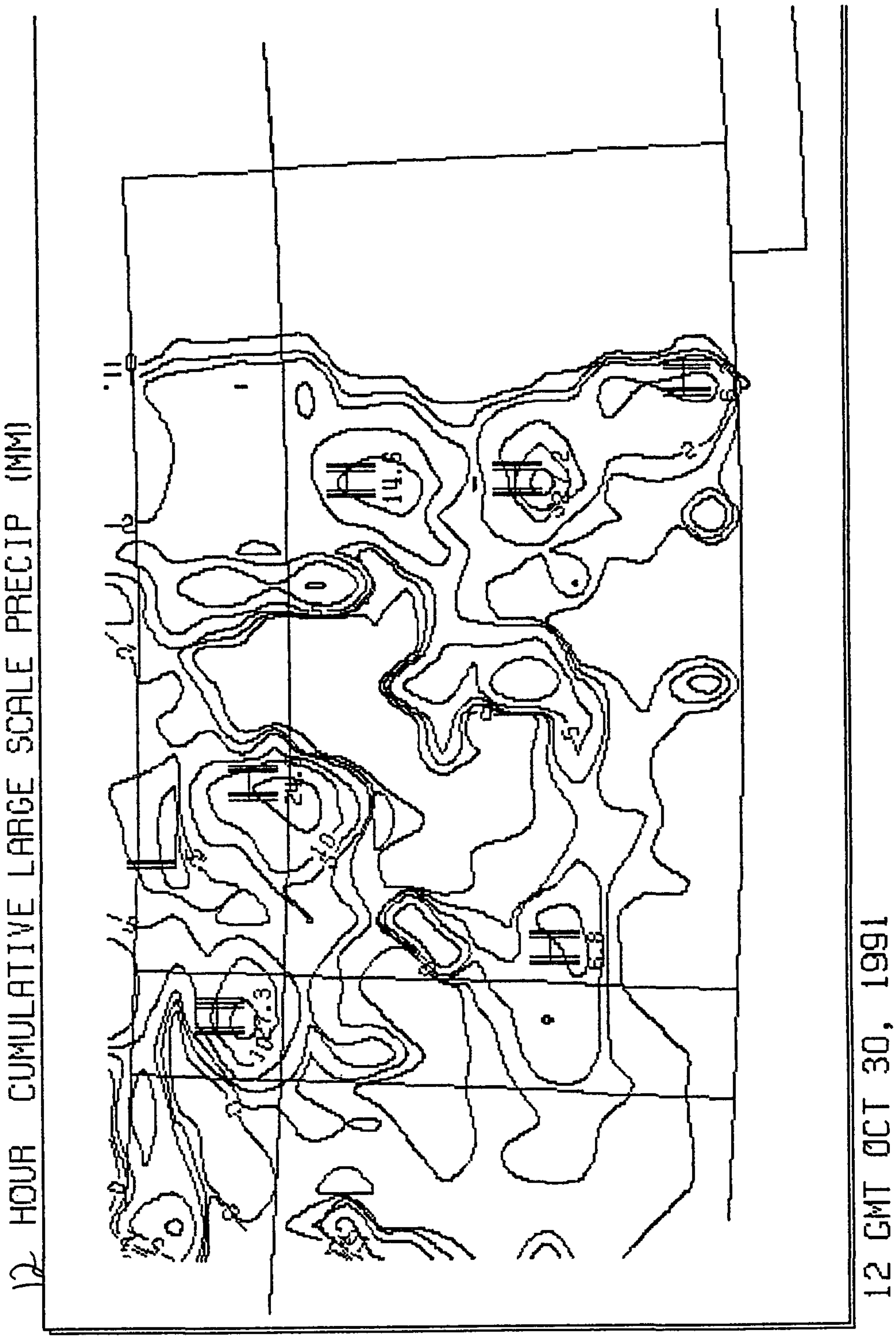

Figure 4.6: Forecast of precipitation (mm liquid-equivalent) between 6 p.m. MST, October 29, 1991, and 6 a.m. MST, October 30.

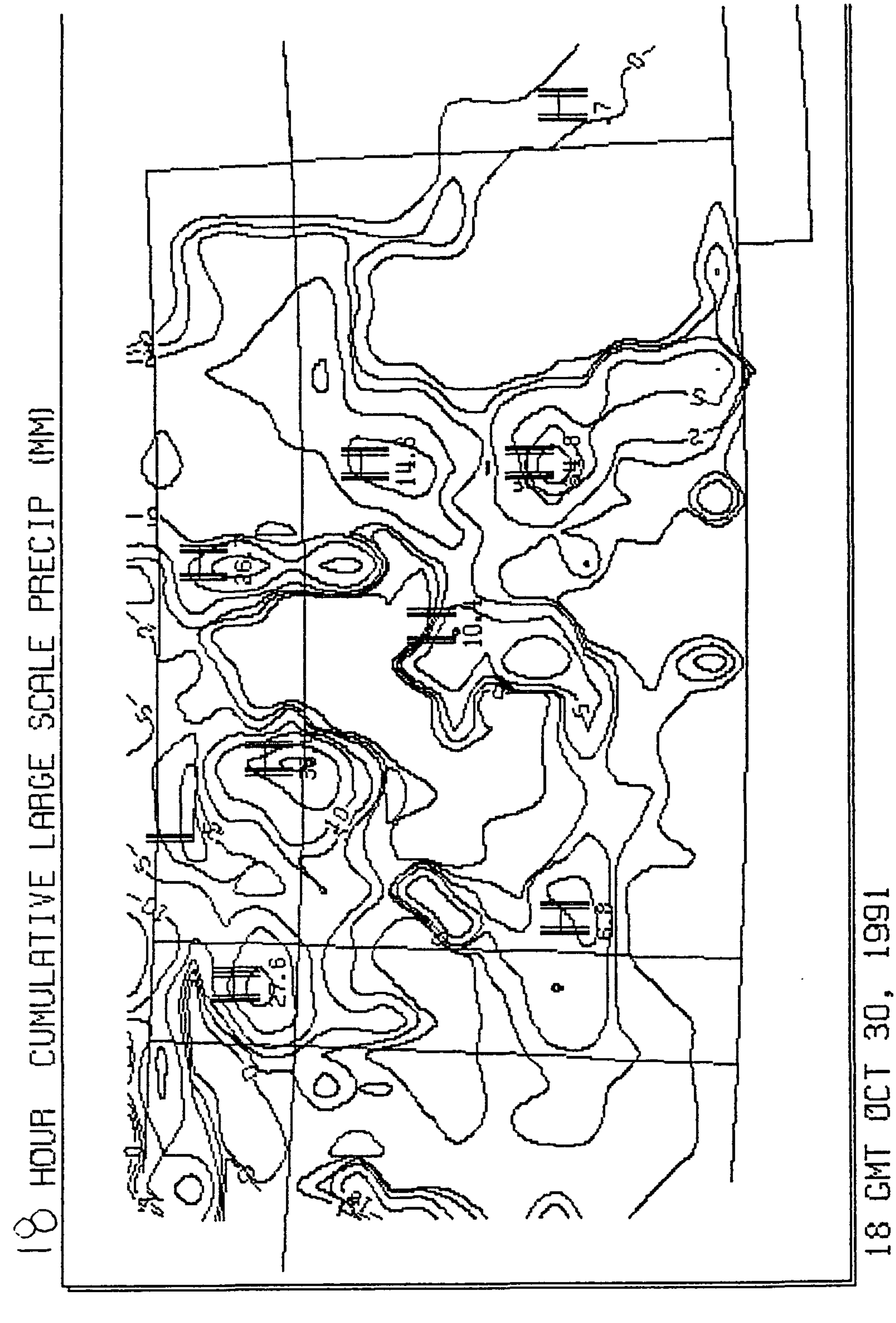

Figure 4.7: Forecast of precipitation (mm liquid-equivalent) between 6 p.m. MST, October 29, 1991, and 11 a.m. MST, October 30.

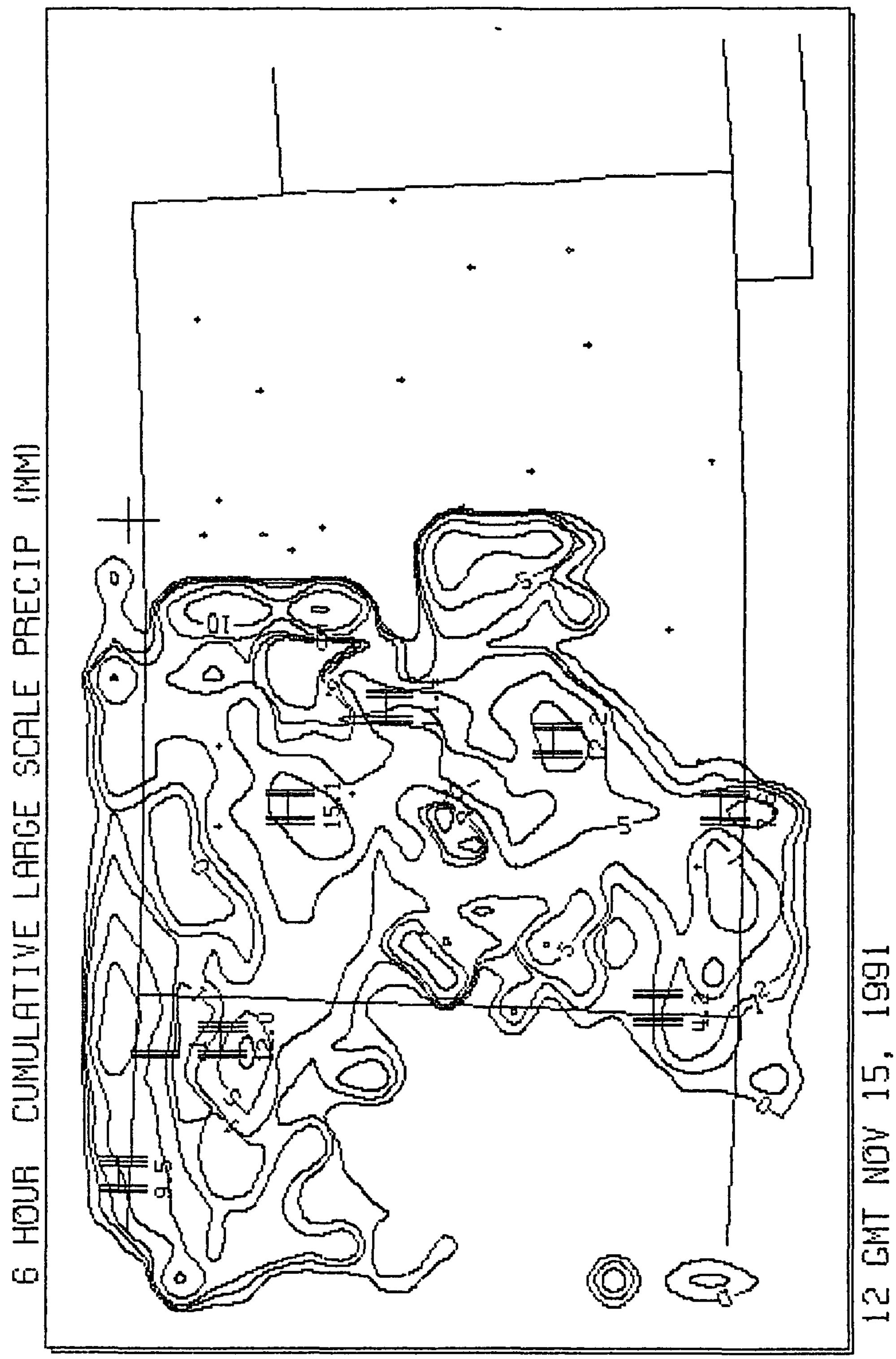

Figure 4.8: Prediction made from 5.a.m. MST data on Nov.14, 1991, for precipitation (mm liquid equivalent) to fall during the 6-hour period between 11 p.m. on the 14th and 5 a.m. MST on the 15th of November.

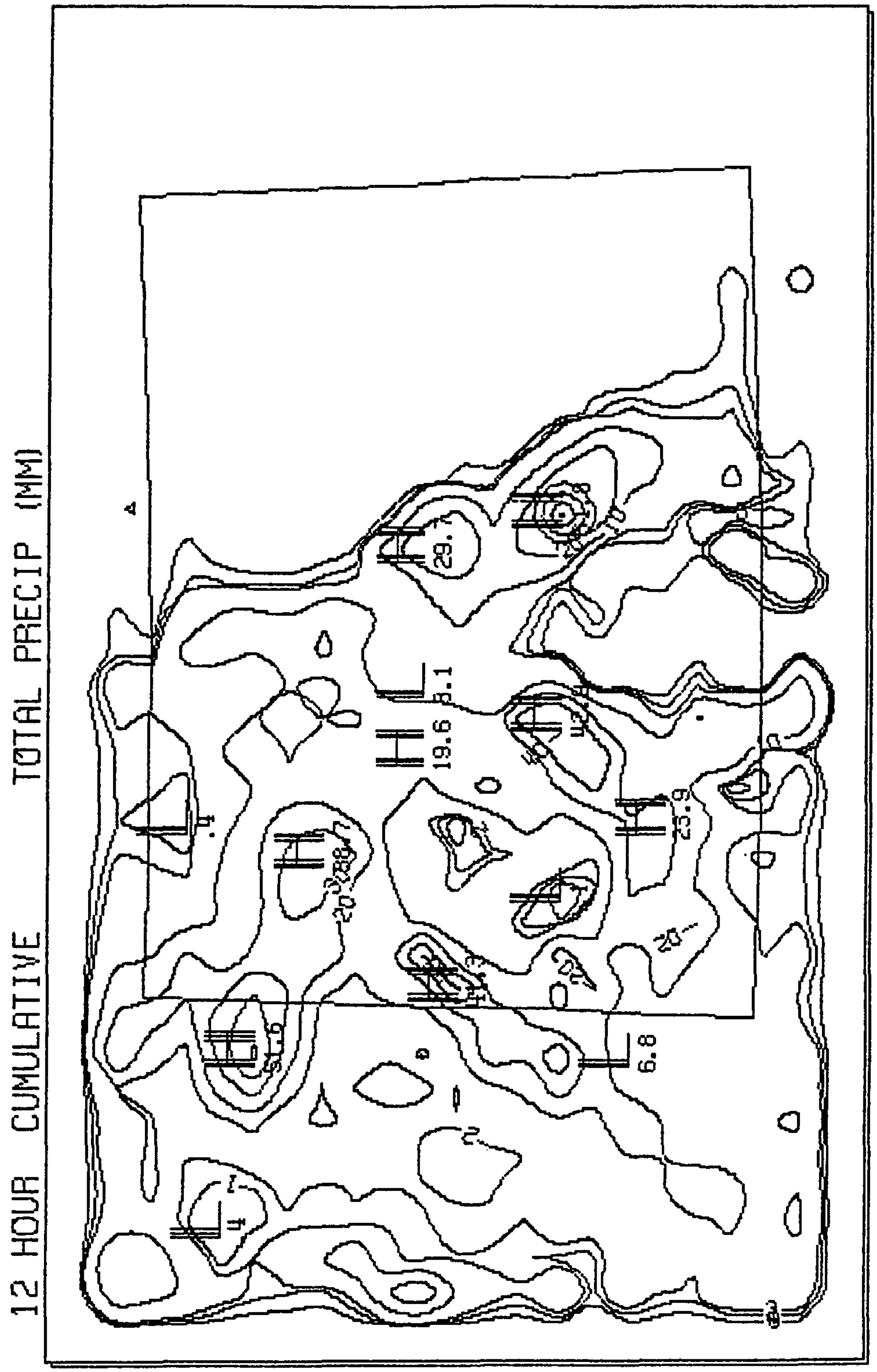

Figure 4.9: Prediction made from 5.p.m. MST data on Nov.14, 1991, for precipitation (mm liquid equivalent) to fall during the 12-hour period between 5 p.m. on the 14th on the 14th and 5 a.m. MST on the 15th of November.

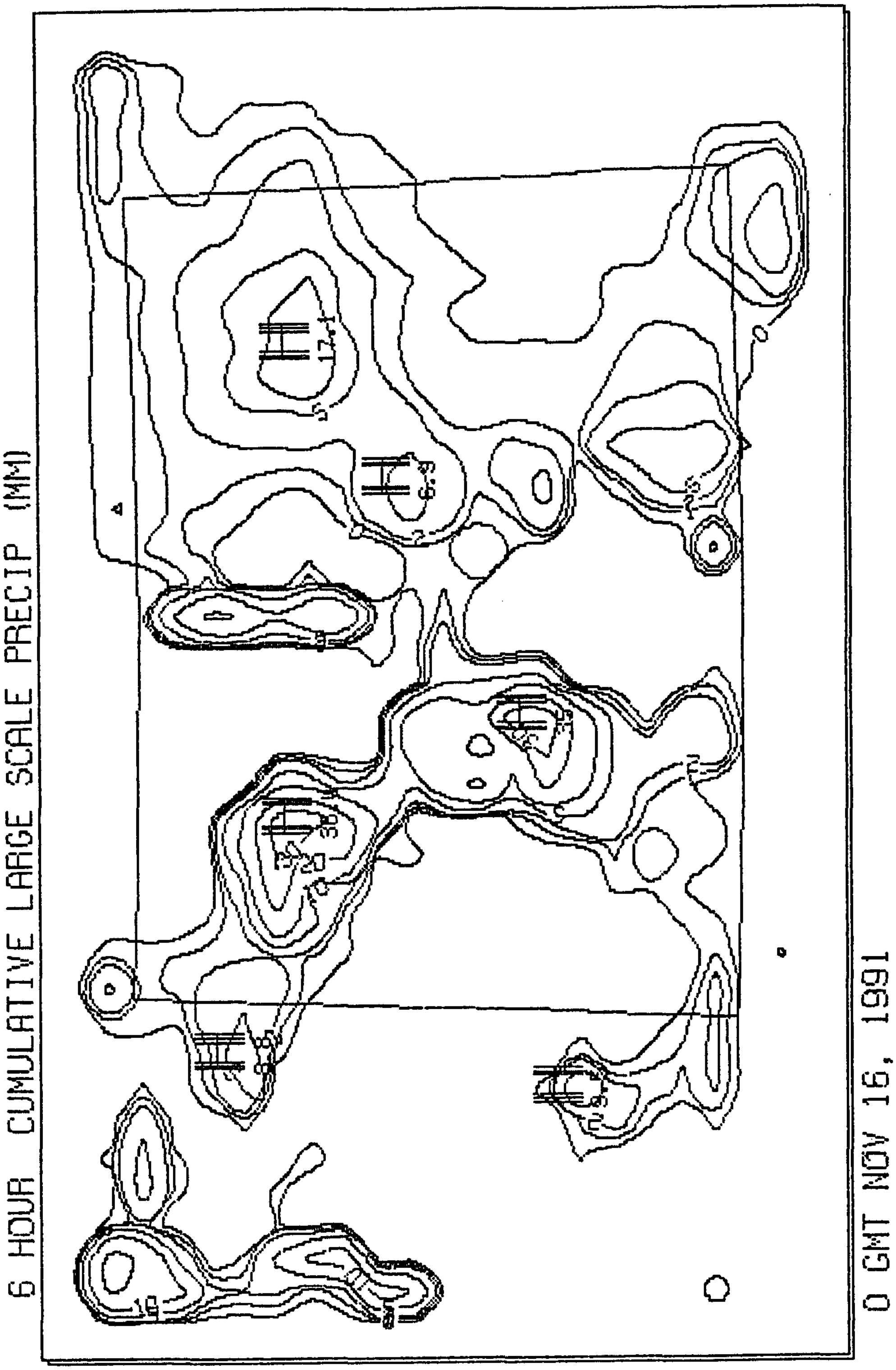

Figure 4.10: Prediction made from 5.p.m. MST data on Nov.14, 1991, for precipitation (mm liquid equivalent) to fall during the 6-hour period between 11 a.m. and 5 p.m. MST on the 15th of November.

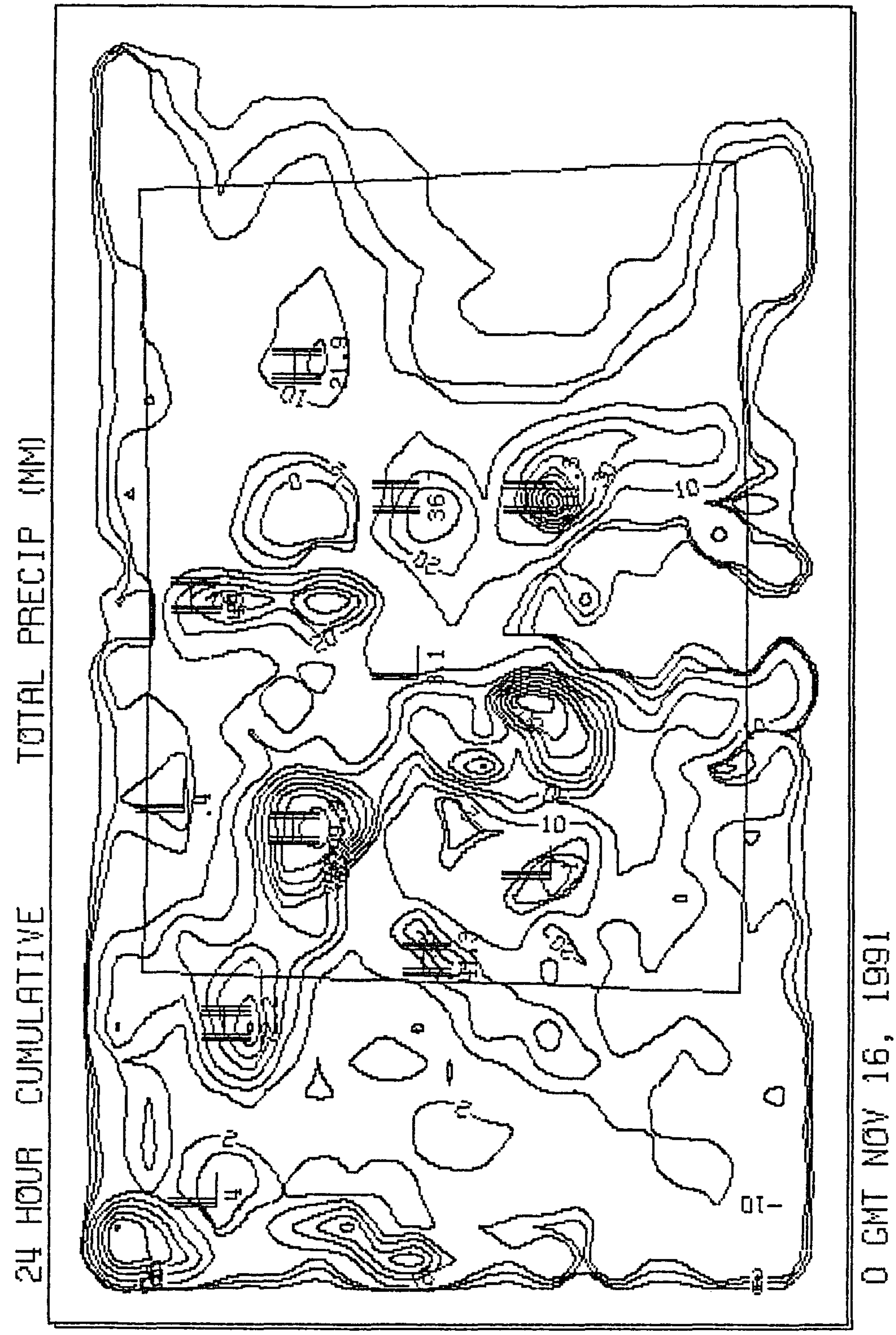

Figure 4.11: 24-hour precipitation forecast for the period ending at 5 p.m. MST on November 15, 1991.

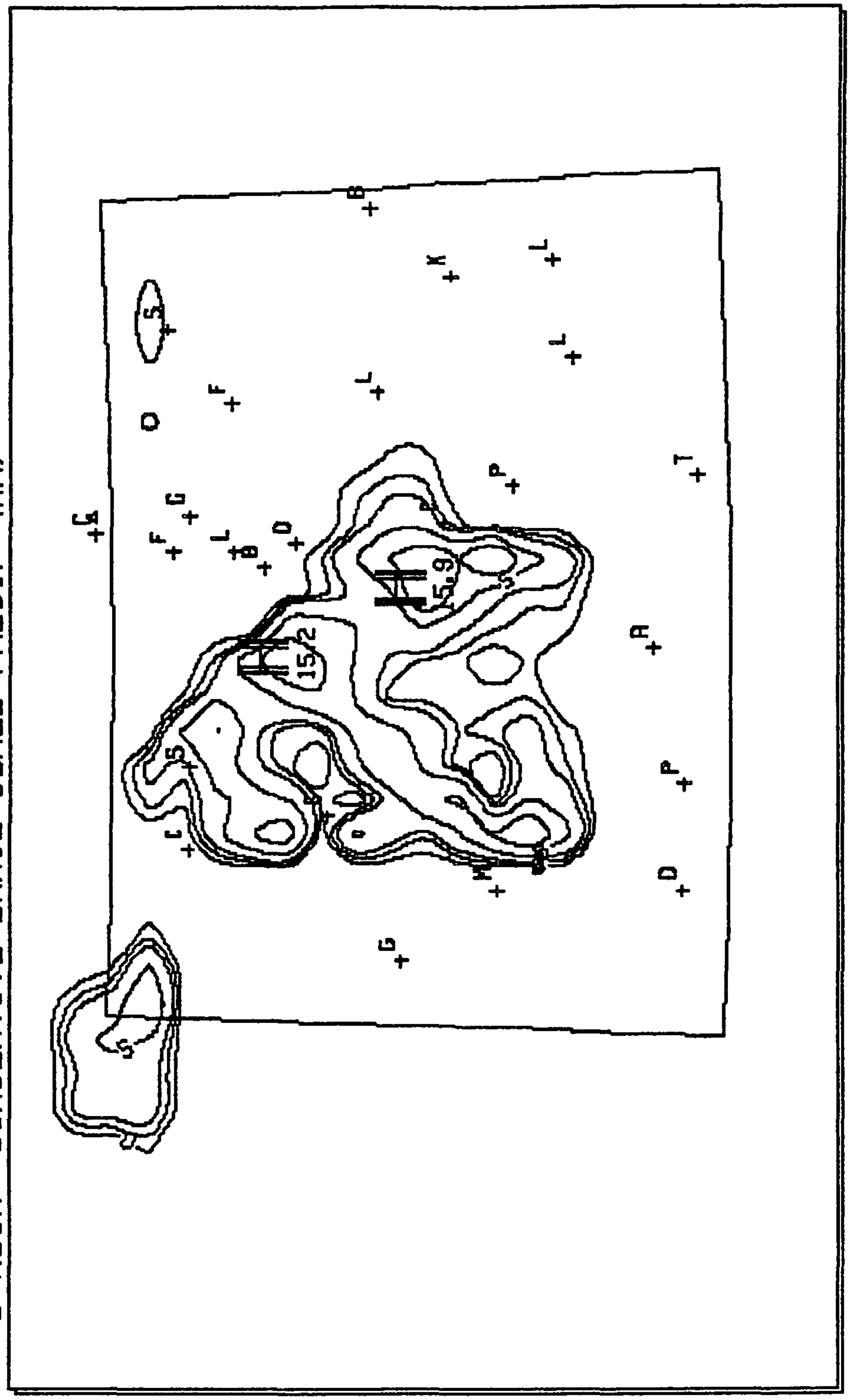

Figure 4.12: Forecast starting with data from 5 a.m. MST on November 27,1991, for the 6-hour period ending at 5 p.m. MST on November 28 (00 GMT November 29).

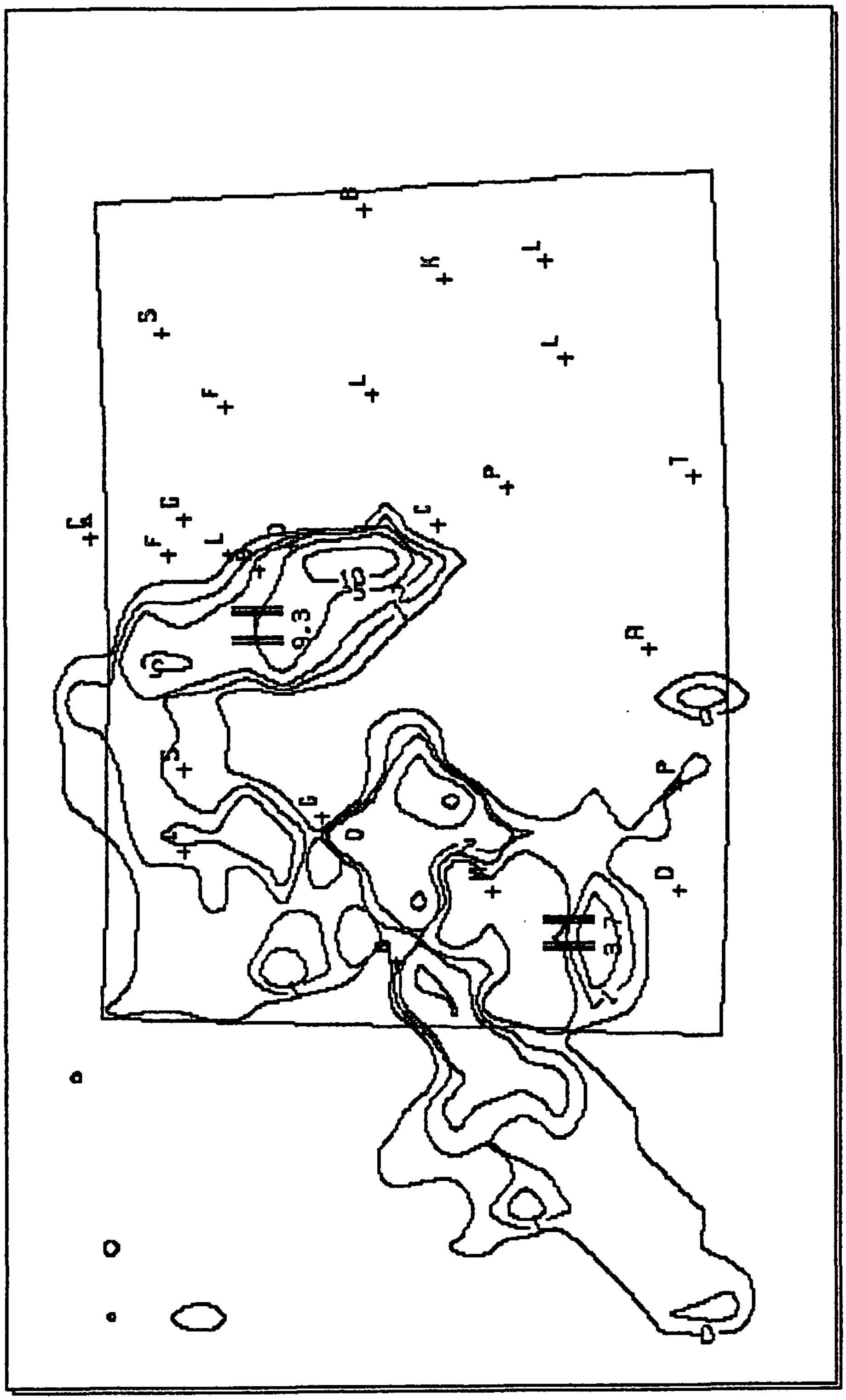

Figure 4.13: Forecast for 6-hour period ending at 11 a.m. MST, Novemner 29, 1991.

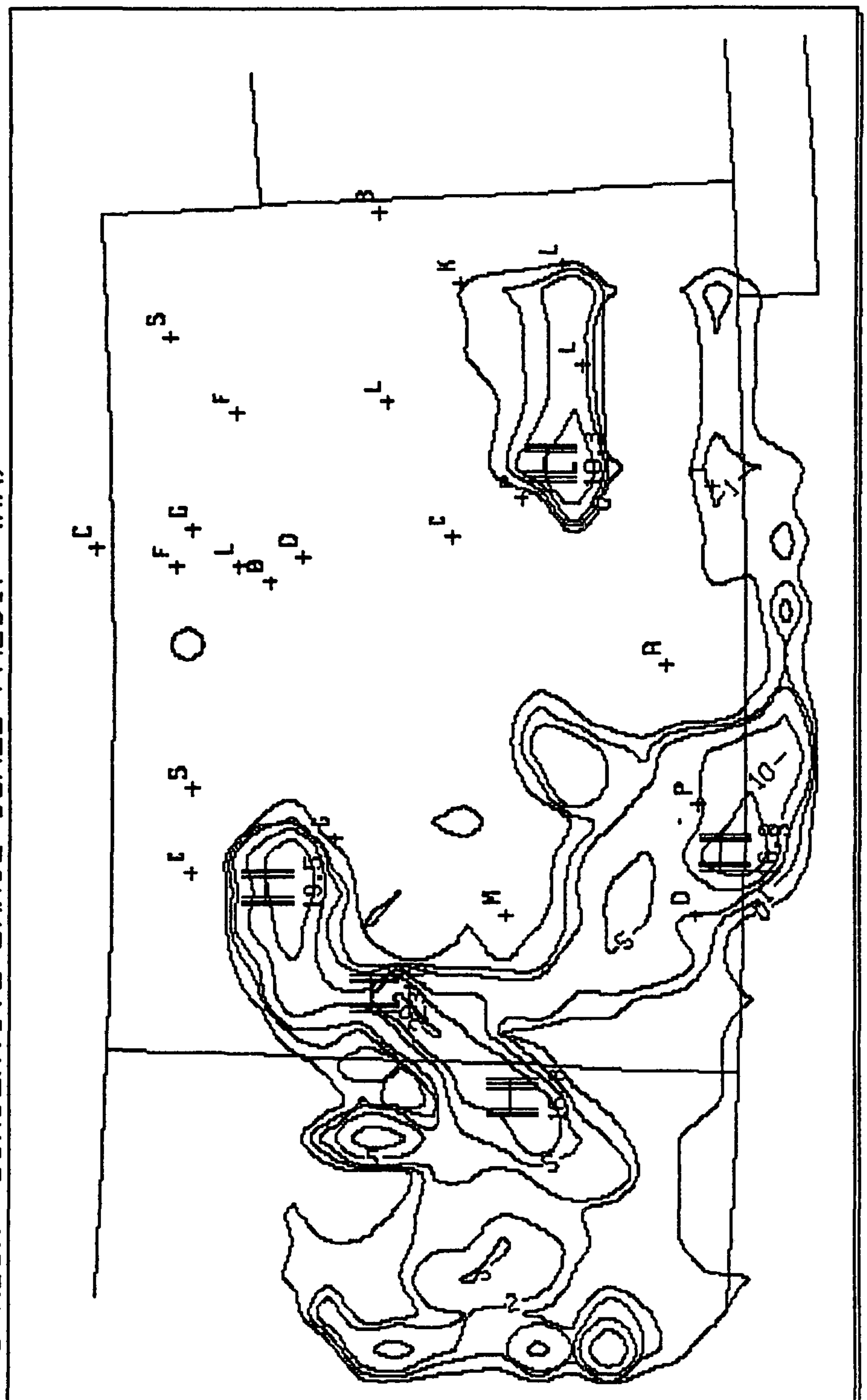

Figure 4.14: Precipitation forecast starting with data from 5 a.m. MST on December 11, 1991, for the 6-hour period ending at 5 p.m. MST on that day.

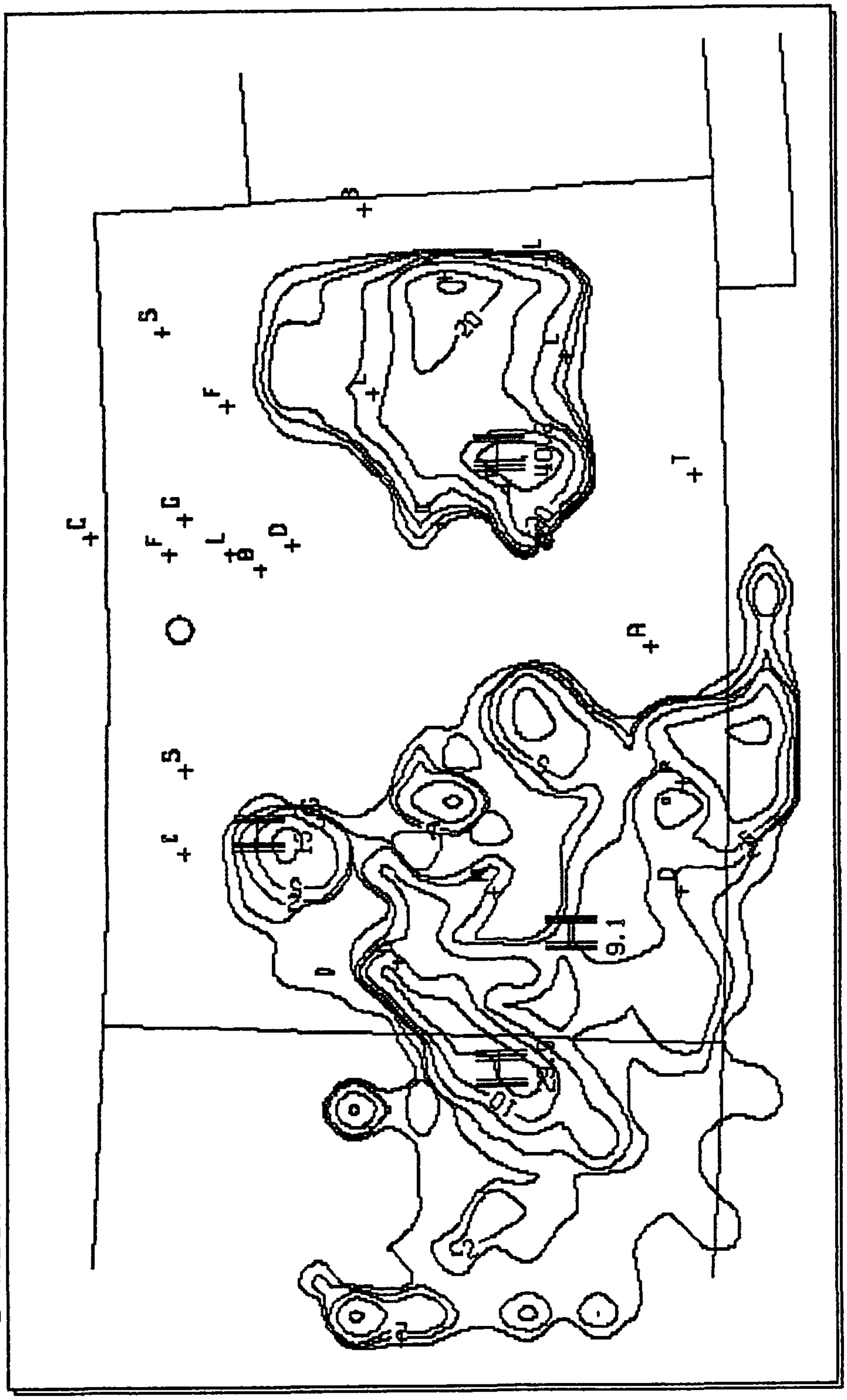

Figure 4.15: Precipitation forecast starting with data from 5 a.m. MST on December 11, 1991, for the 6-hour period ending at 11 p.m. MST on that day.

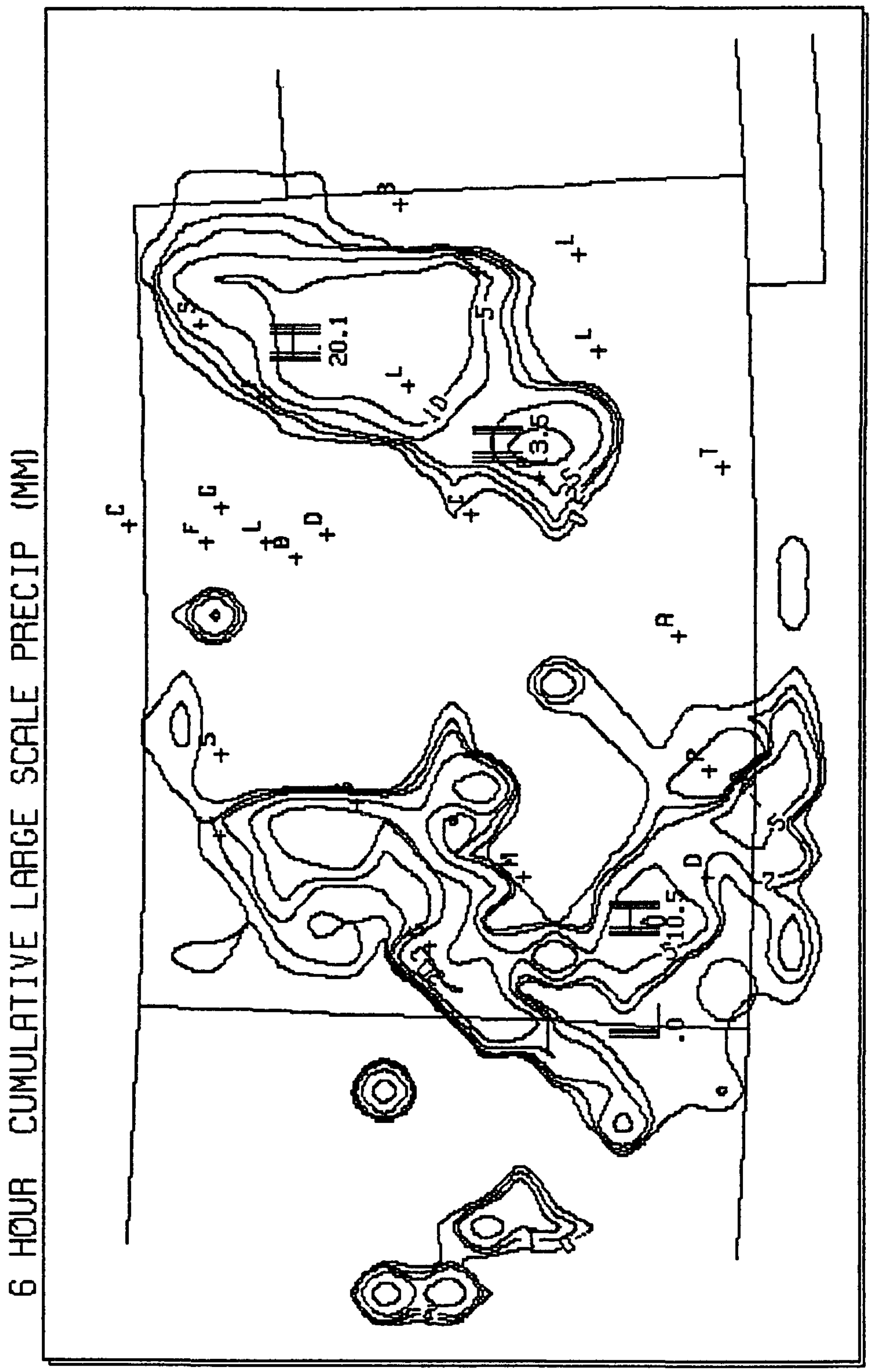

Figure 4.16: Precipitation forecast starting with data from 5 a.m. MST on December 11, 1991, for the 6-hour period ending at 5 a.m. MST on December 12.

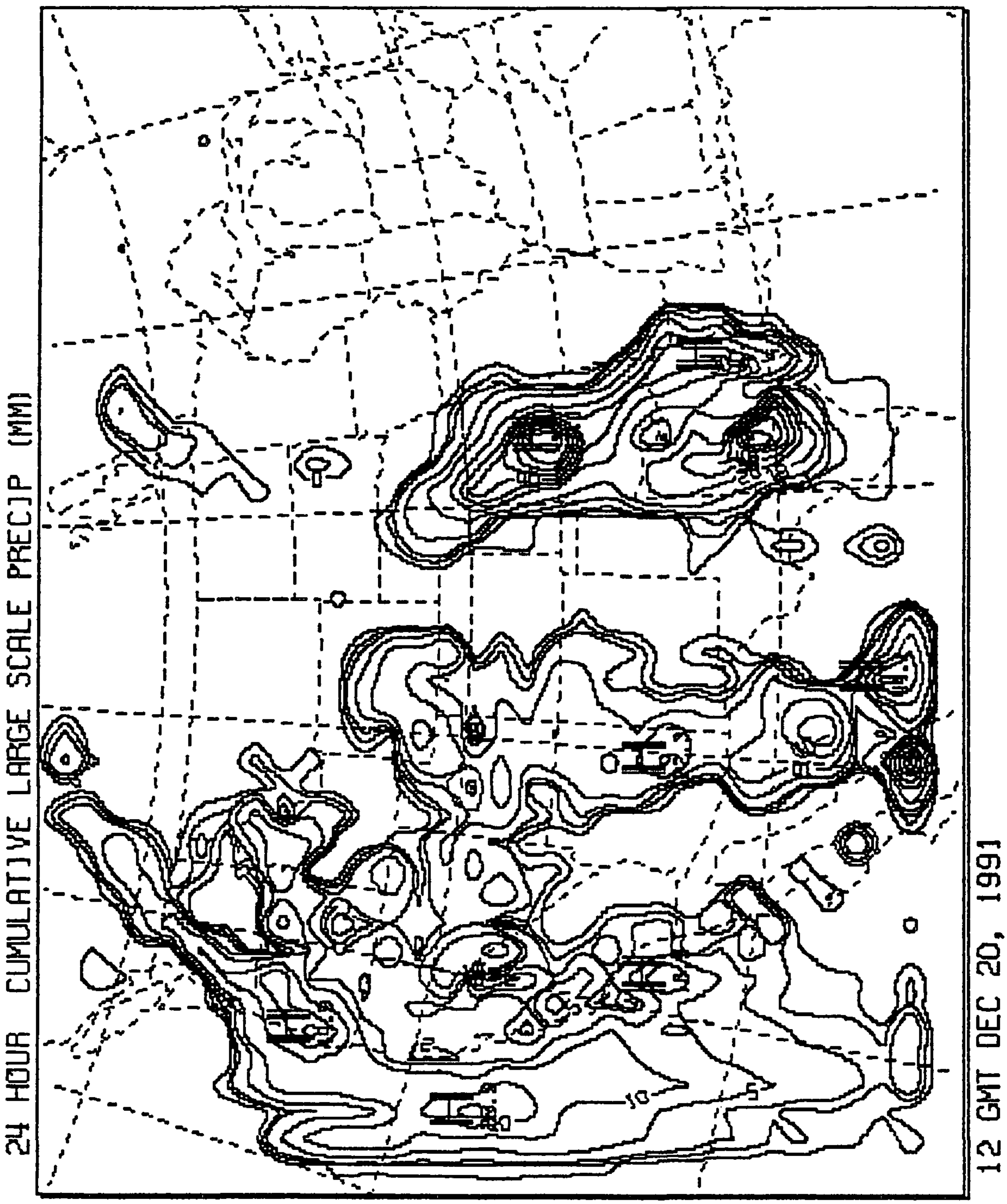

Figure 4.17: 24-hour large-scale precipitation (mm) forecast by the WELS limited-area forecasting model for the period ending 5 a.m. MST, December 20, 1991. Note the extremely heavy precipitation over Texas, Oklahoma and Kansas.

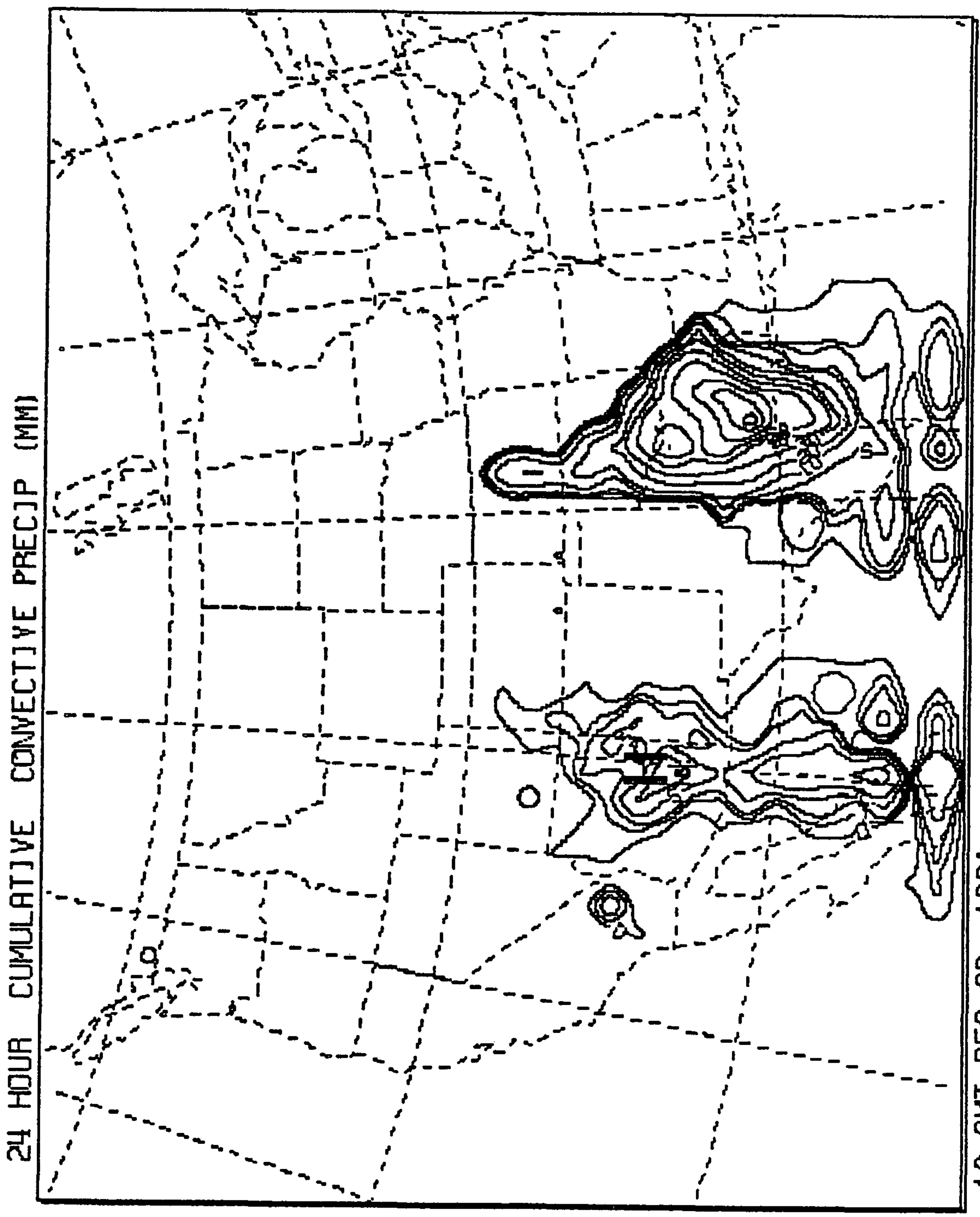

Figure 4.18: 24-hour convective precipitation (mm) forecast by the WELS model for same time period as in Fig. 4.17. The amounts shown in this figure have to be added to those in Fig. 4.17 to yield total 24-hour precipitation.

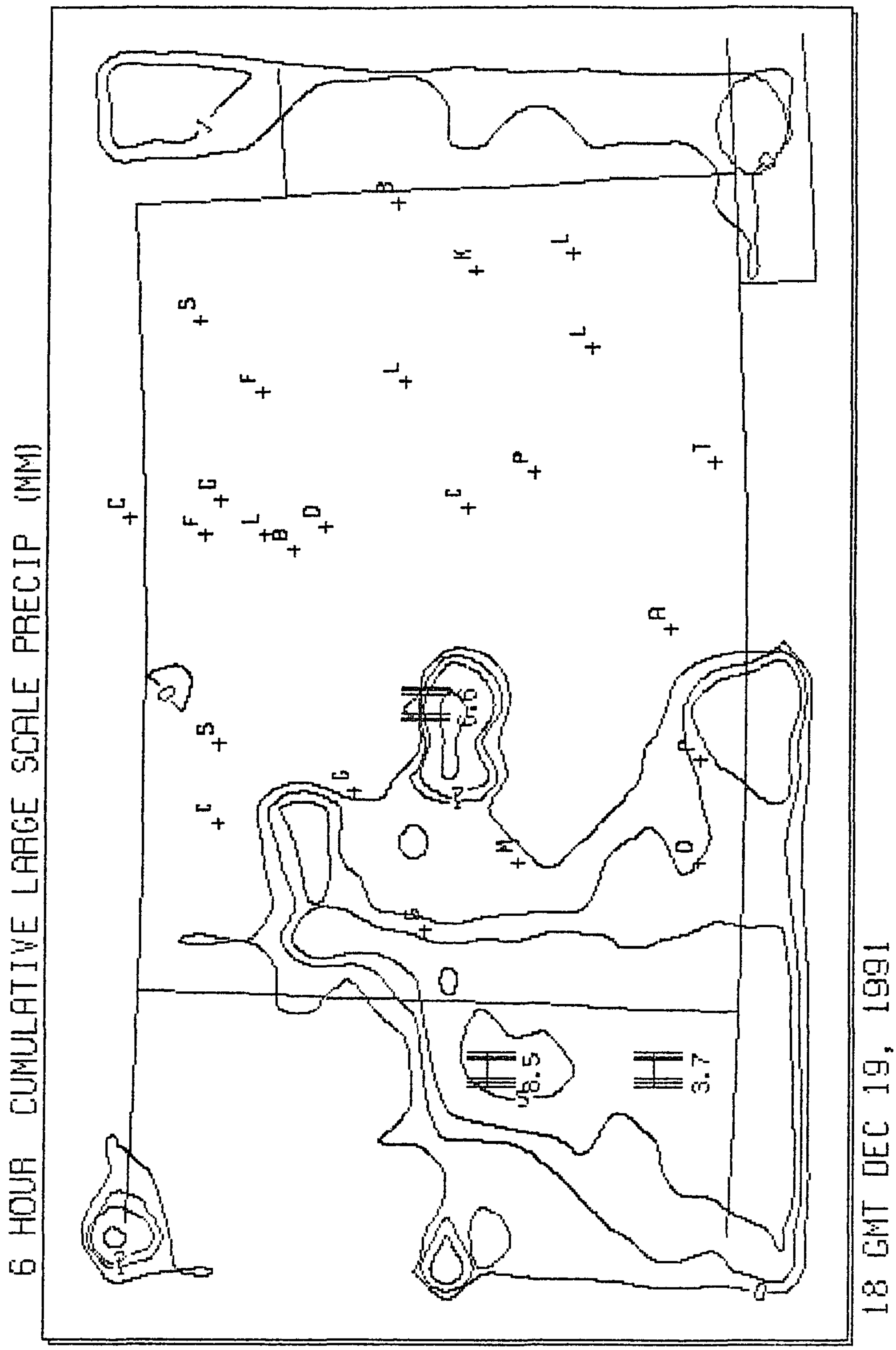

Figure 4.19: Precipitation forecast (mm, liquid-water equivalent) using data from 5 a.m. MST, December 19, for the 6-hour period until 11 a.m. of the same day.

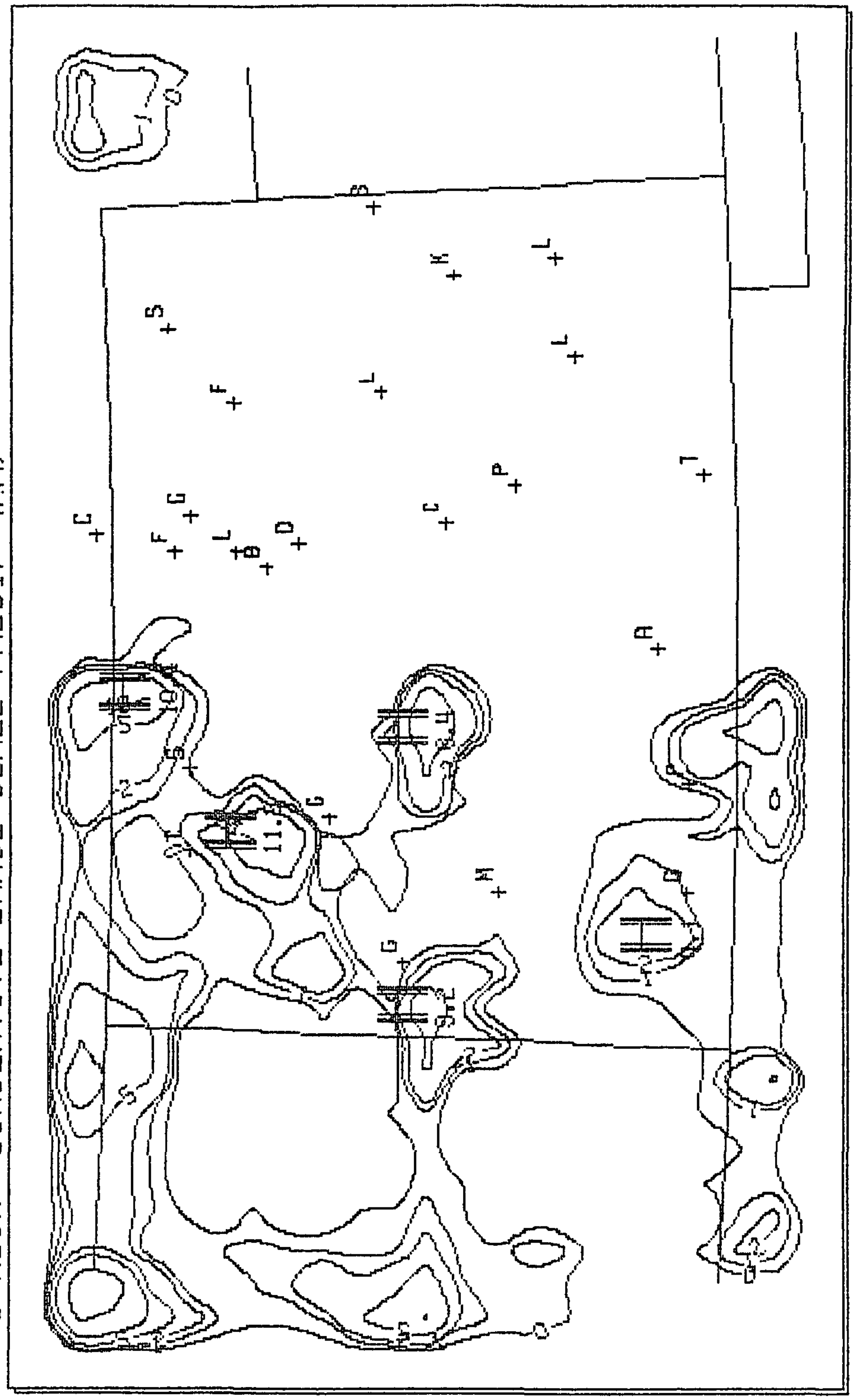

Figure 4.20: Precipitation forecast (mm, liquid-water equivalent) using data from 5 a.m. MST, December 19, for the 6-hour period ending at 5 p.m. MST of the same day.

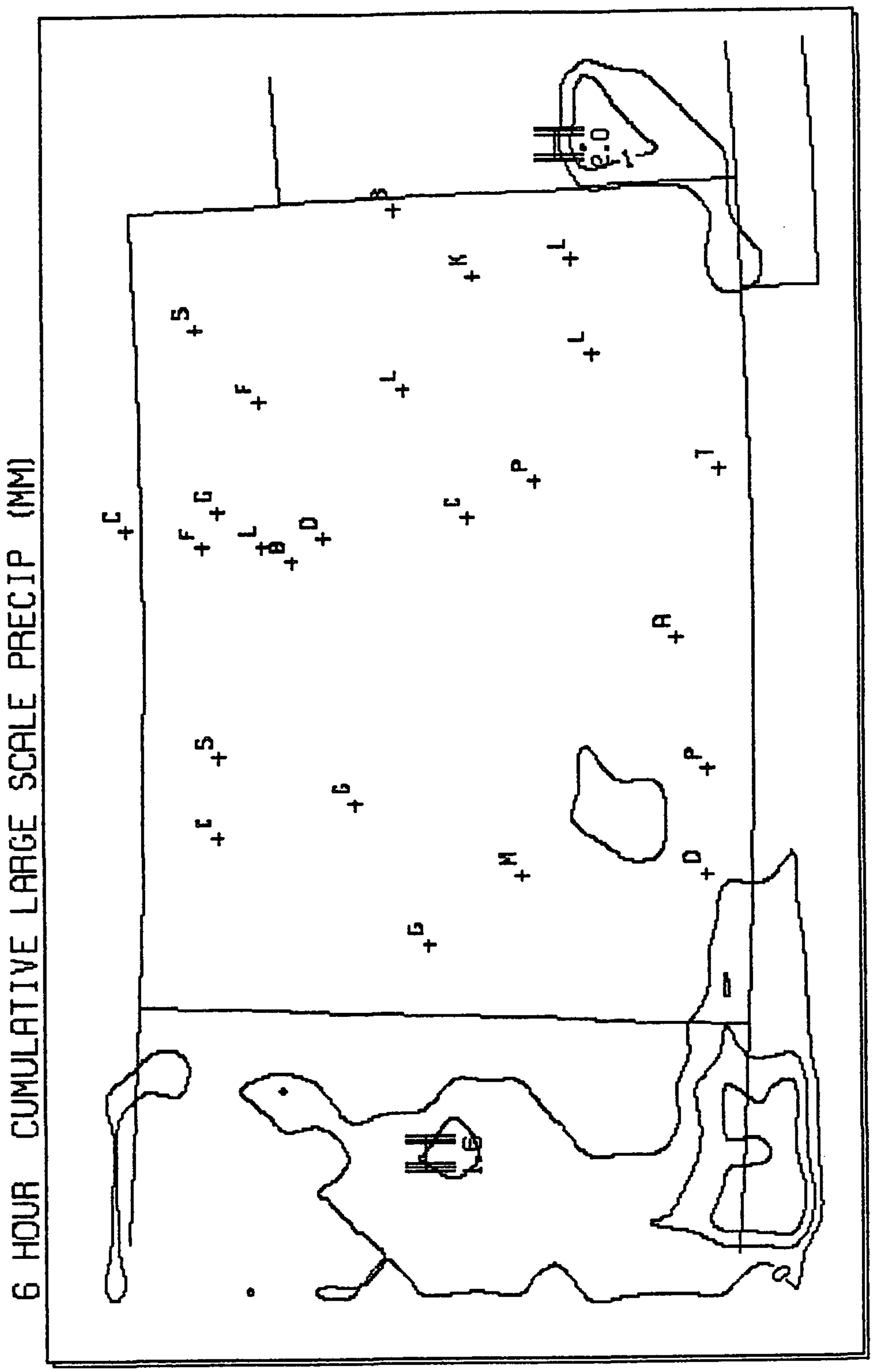

Figure 4.21: Precipitation forecast (mm, liquid-water equivalent) using data from 5 a.m. MST, December 19, for the 6-hour period ending at 11 p.m. MST of the same day.

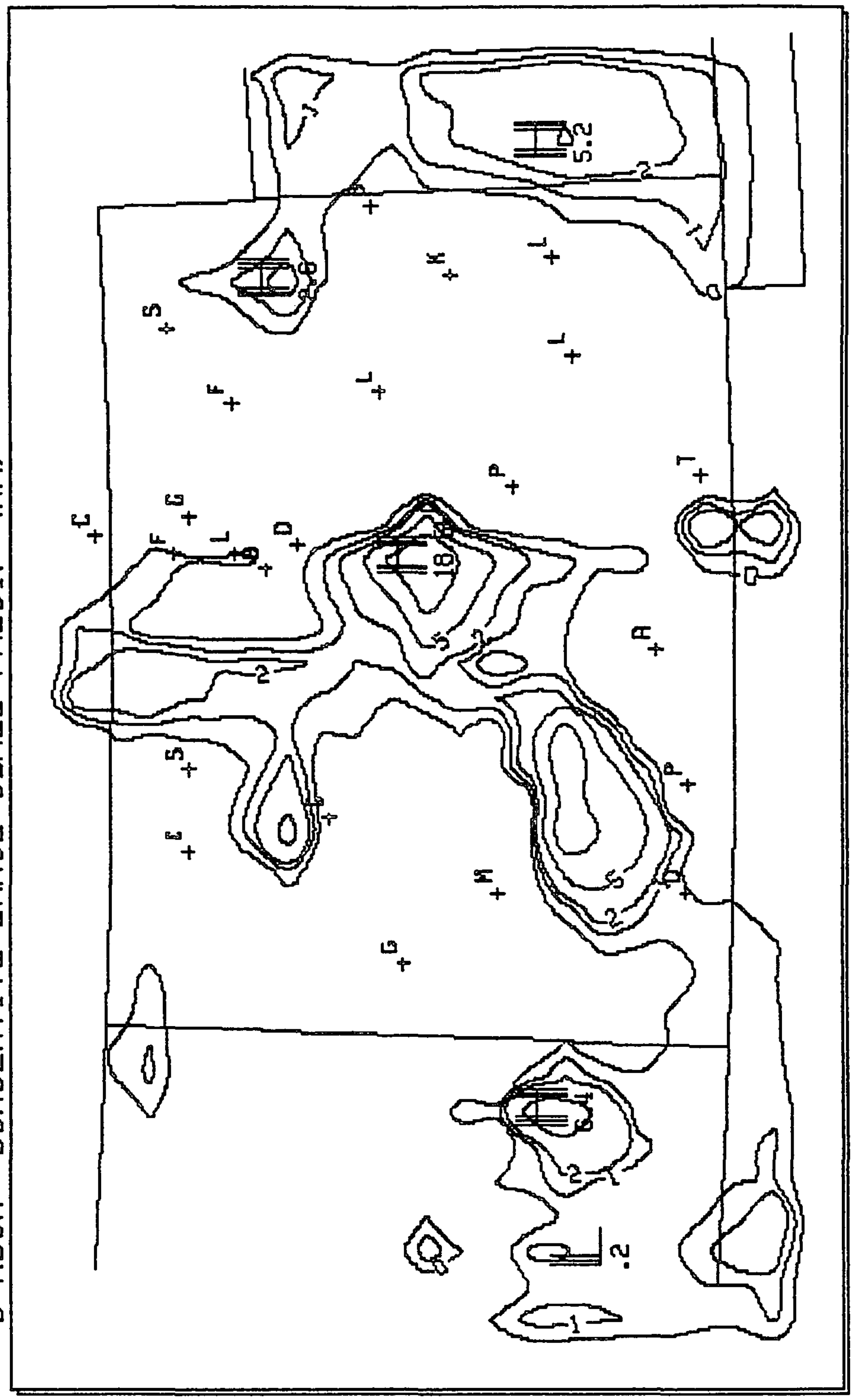

Figure 4.22: Precipitation forecast (mm, liquid-water equivalent) using data from 5 a.m. MST, December 19, for the 6-hour period ending at 5 a.m. MST on December 20.

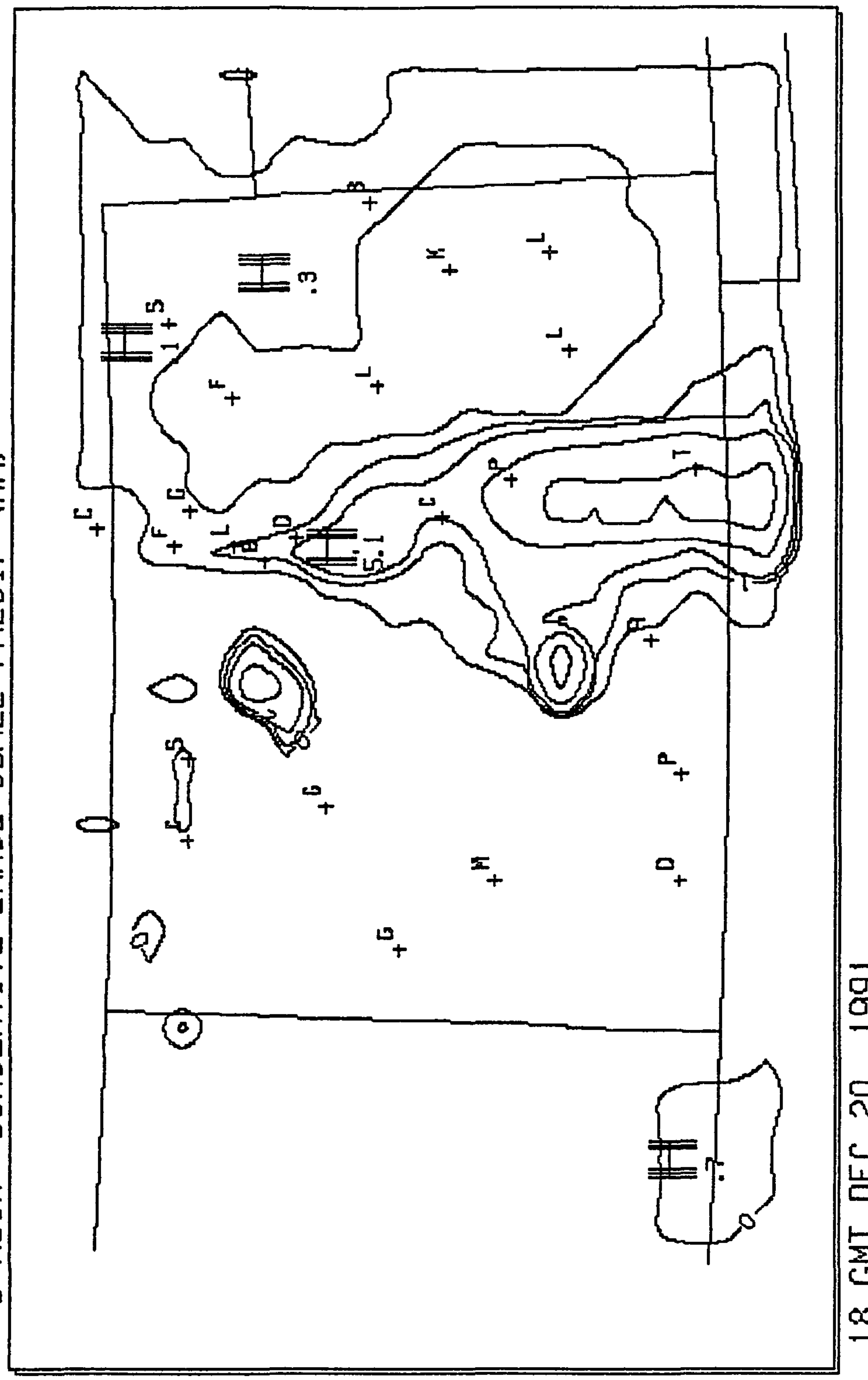

Figure 4.23: Precipitation forecast (mm, liquid-water equivalent) using data from 5 a.m. MST, December 20, for the 6-hour period ending at 11 a.m. MST on the same day.

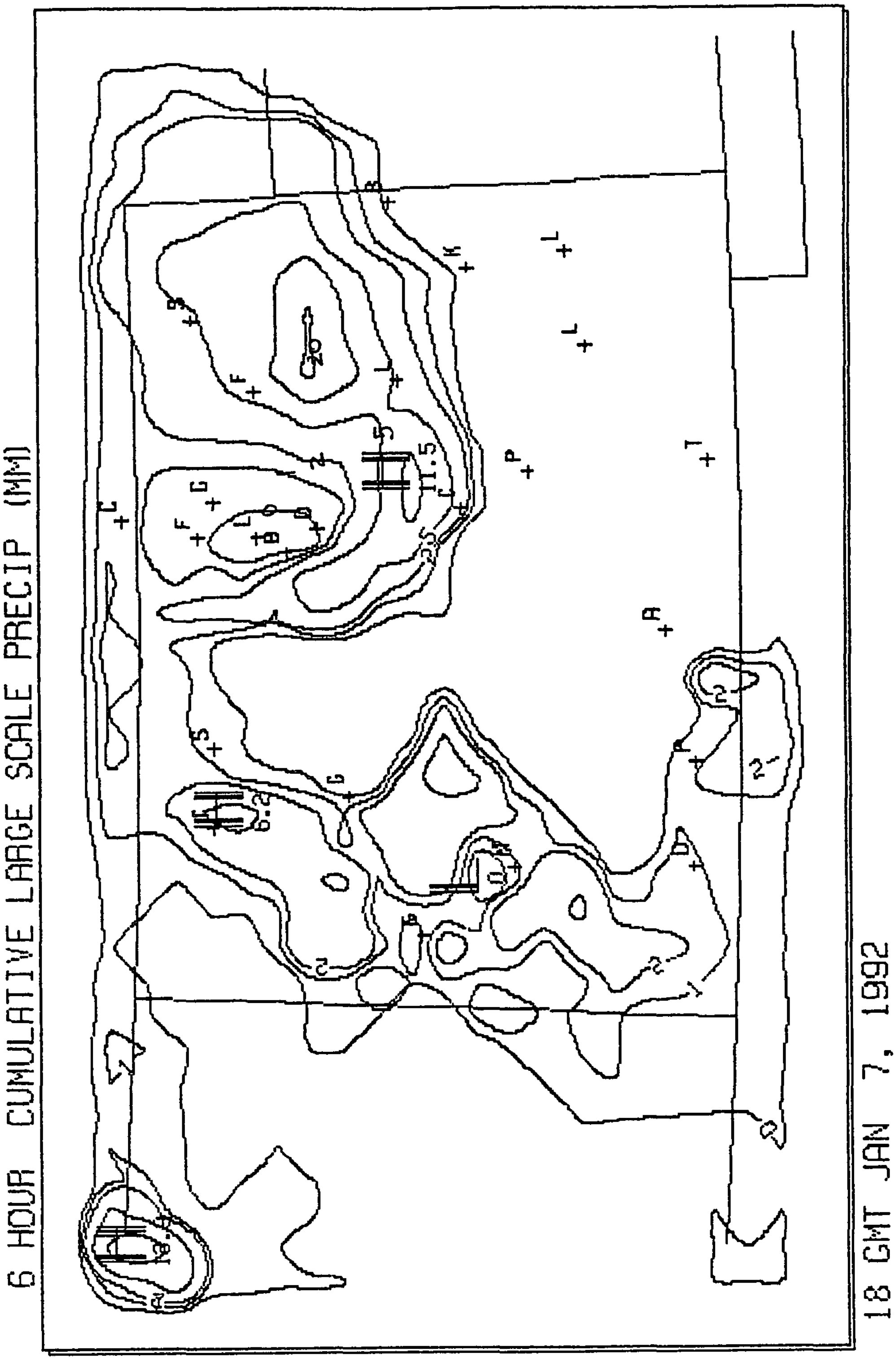

Figure 4.24: Precipitation forecast (mm, liquid equivalent), starting at 5 a.m. MST, January 7, 1992, for the 6-hour period ending at 11 a.m. MST on the same day.

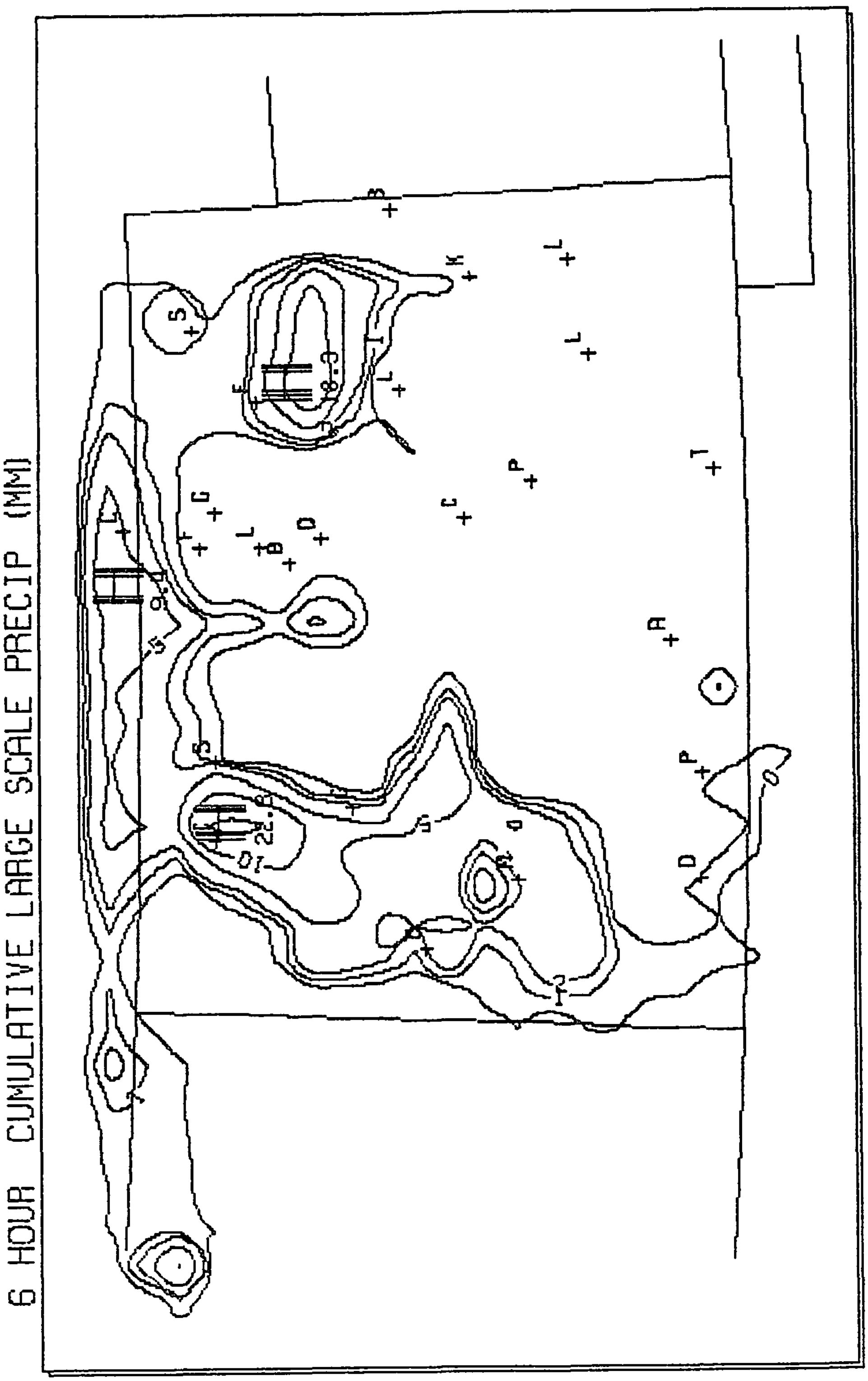

Figure 4.25: Precipitation forecast (mm, liquid equivalent), starting at 5 a.m. MST, January 7, 1992, for the 6-hour period ending at 5 p.m. MST on the same day.

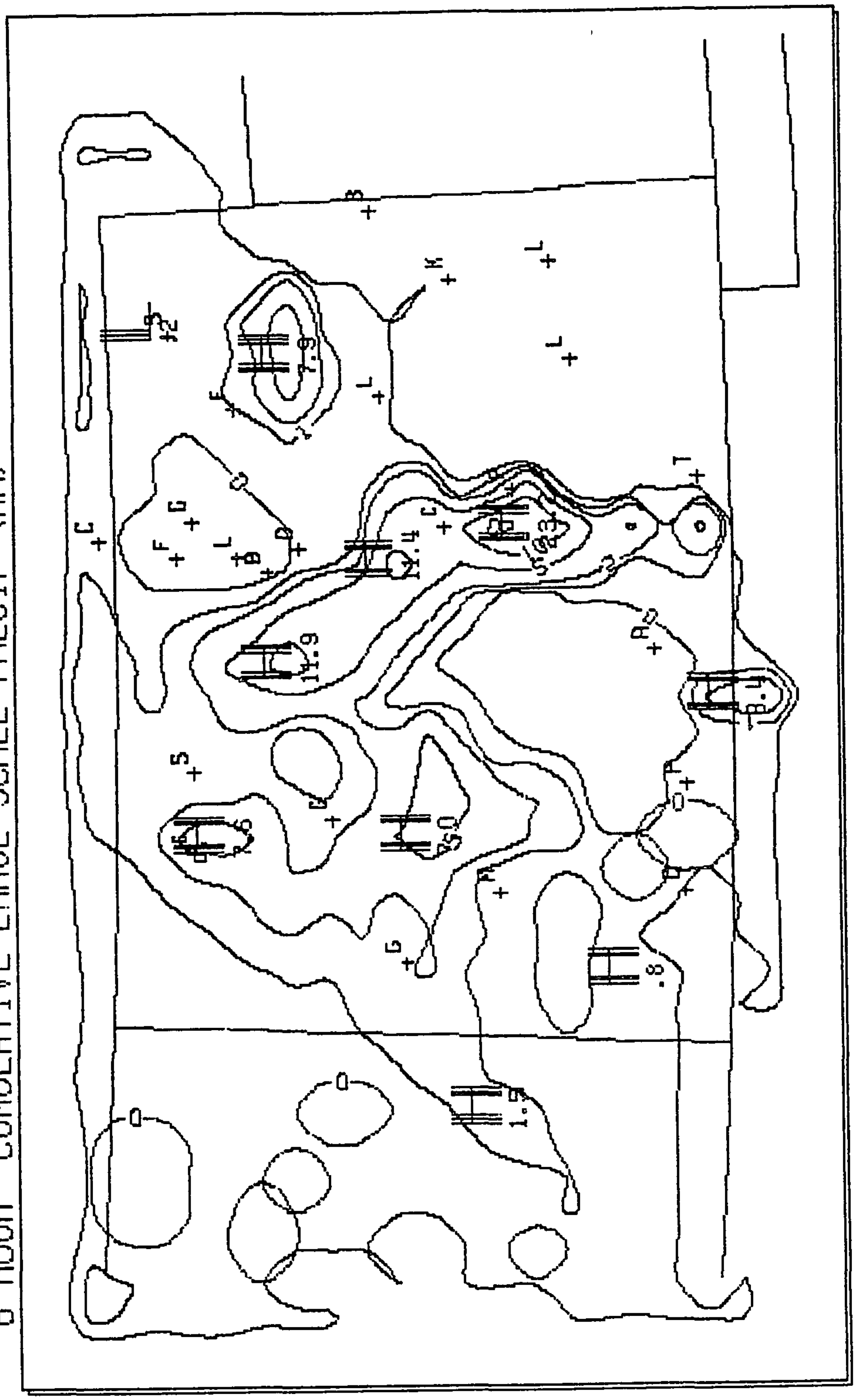

Figure 4.26: Precipitation forecast (mm, liquid equivalent), starting at 5 p.m. MST, January 7, 1992, for the 6-hour period ending at 11 p.m. MST on the same day.

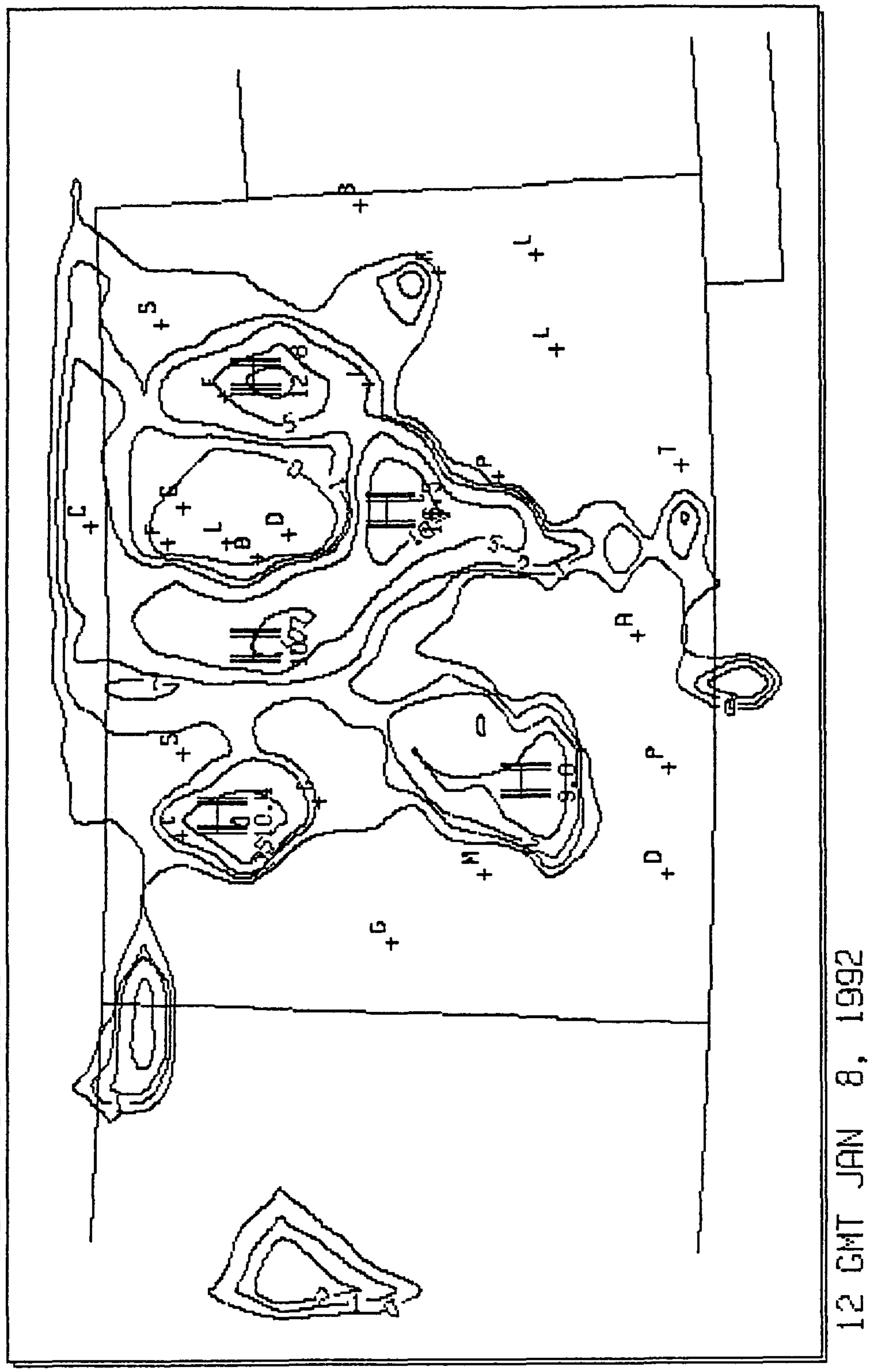

Figure 4.27: Precipitation forecast (mm, liquid equivalent), starting at 5 p.m. MST, January 7, 1992, for the 6-hour period ending at 5 a.m. MST on January 8.

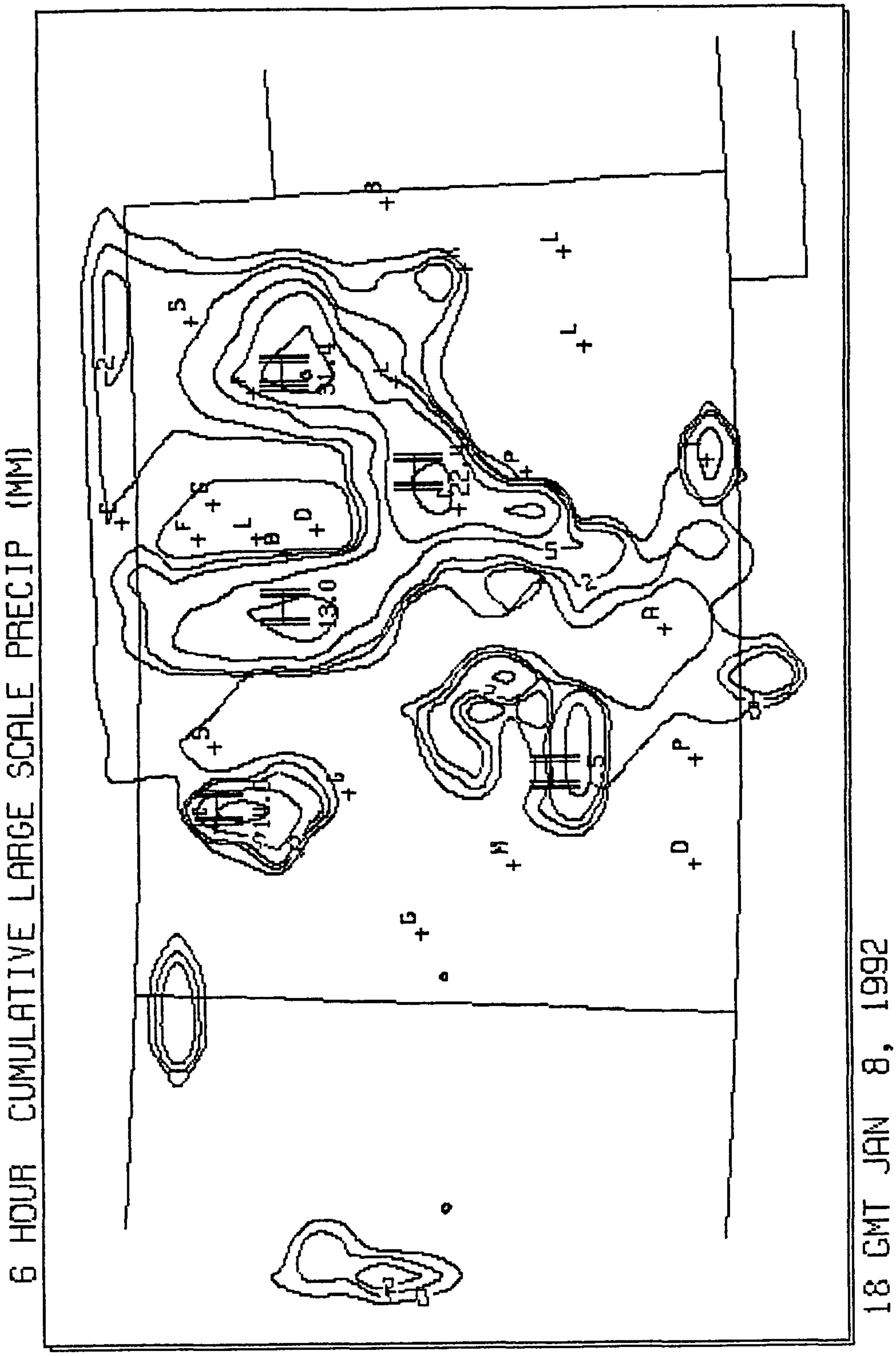

Figure 4.28: Precipitation forecast (mm, liquid equivalent), starting at 5 p.m. MST, January 7, 1992, for the 6-hour period ending at 11 a.m. MST on January 8.

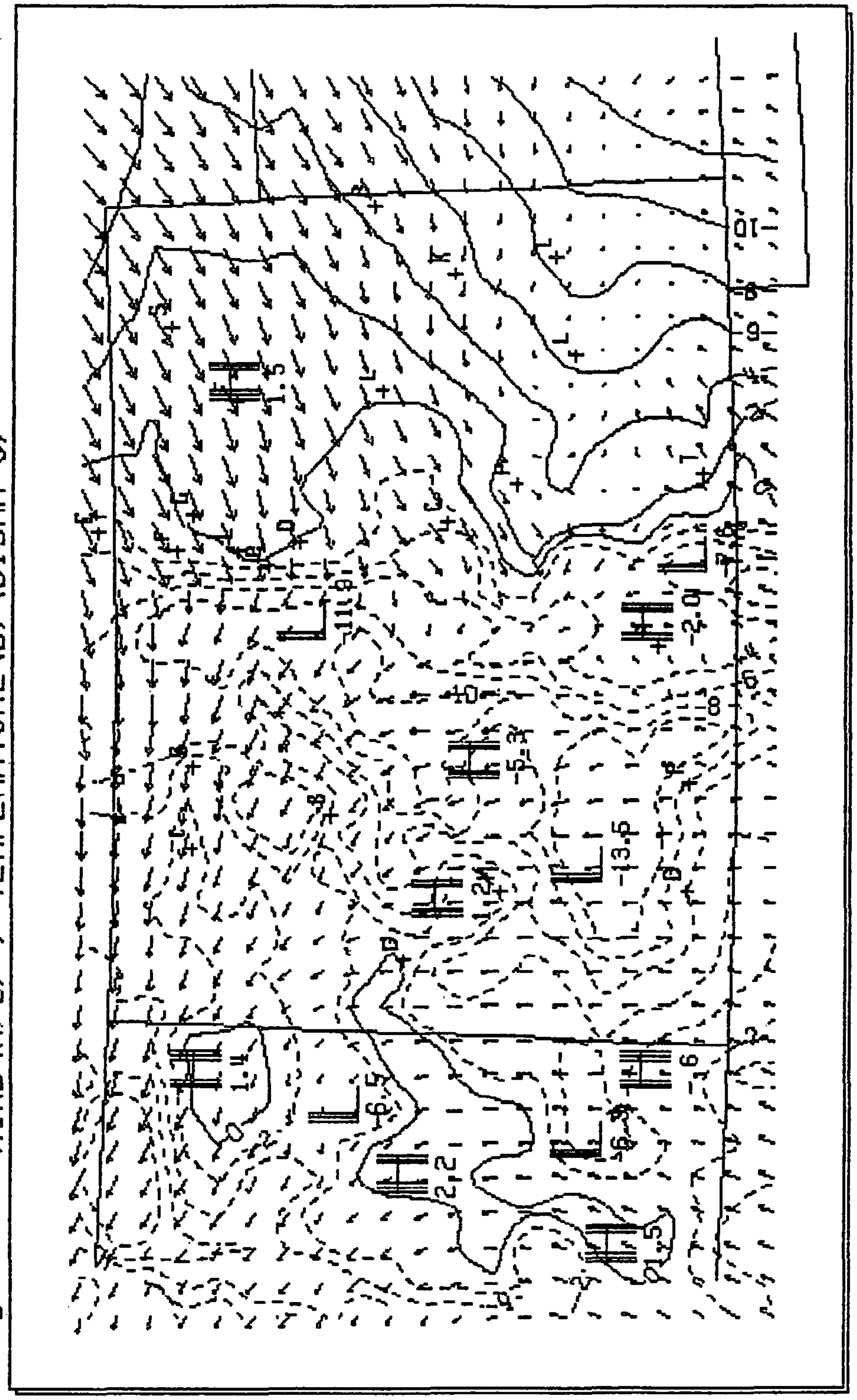

Figure 4.29: Forecast starting at 5 a.m. MST, March 8, 1992, for 11 a.m. MST on same day, of temperatures (deg centigrade drawn at 2-deg intervals, 600 m above terrain) and winds (m/sec, 600 m above terrain). Solid lines are temperatures 0 deg or higher, dashed lines are temperatures below freezing. Scale for longest wind arrows is given in lower right of diagram.

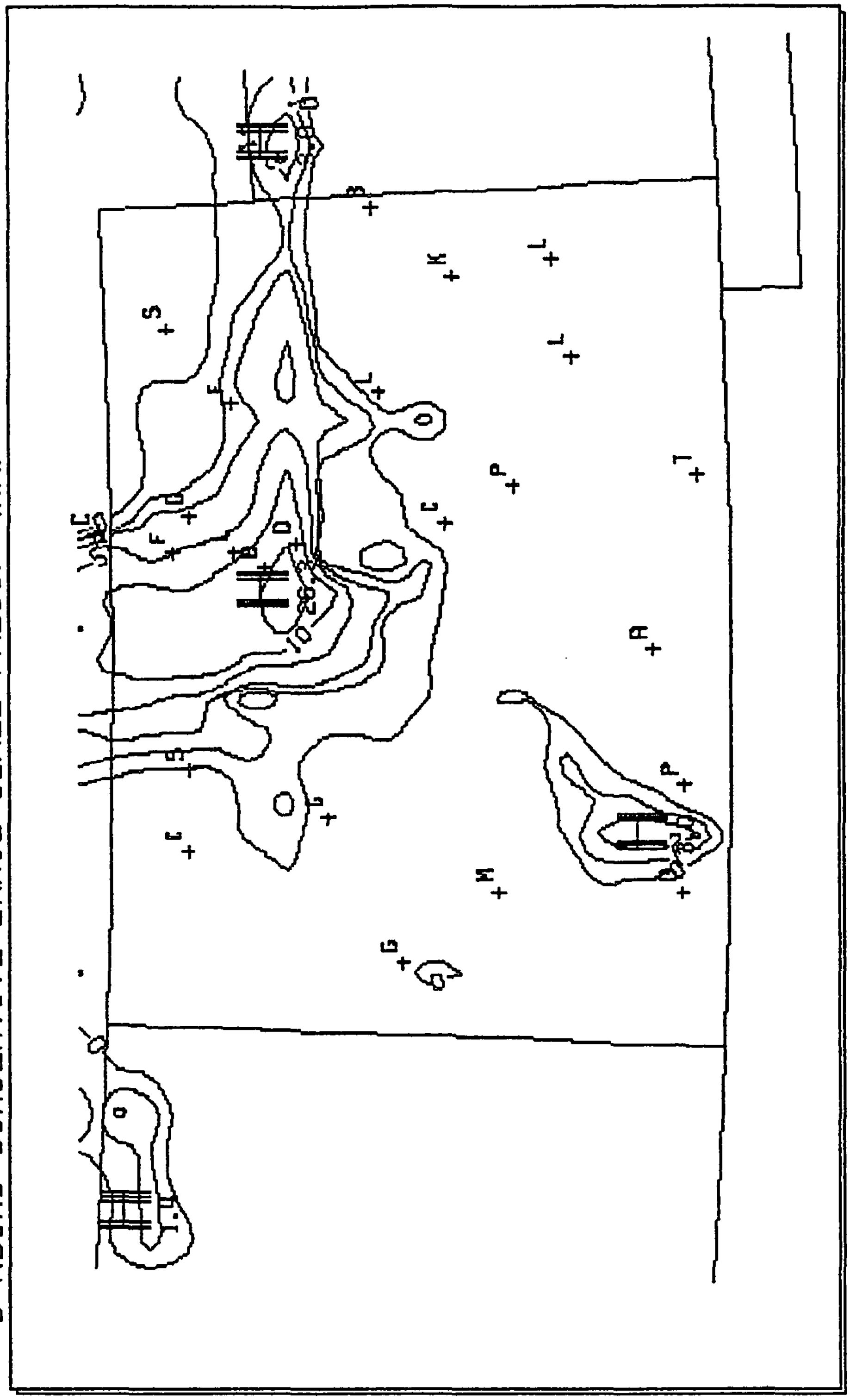

Figure 4.30: Forecast of large-scale precipitation (mm of liquid-equivalent), starting at 5 a.m. MST, March 8, 1992, for 6-hour period ending at 11 a.m. of same day.

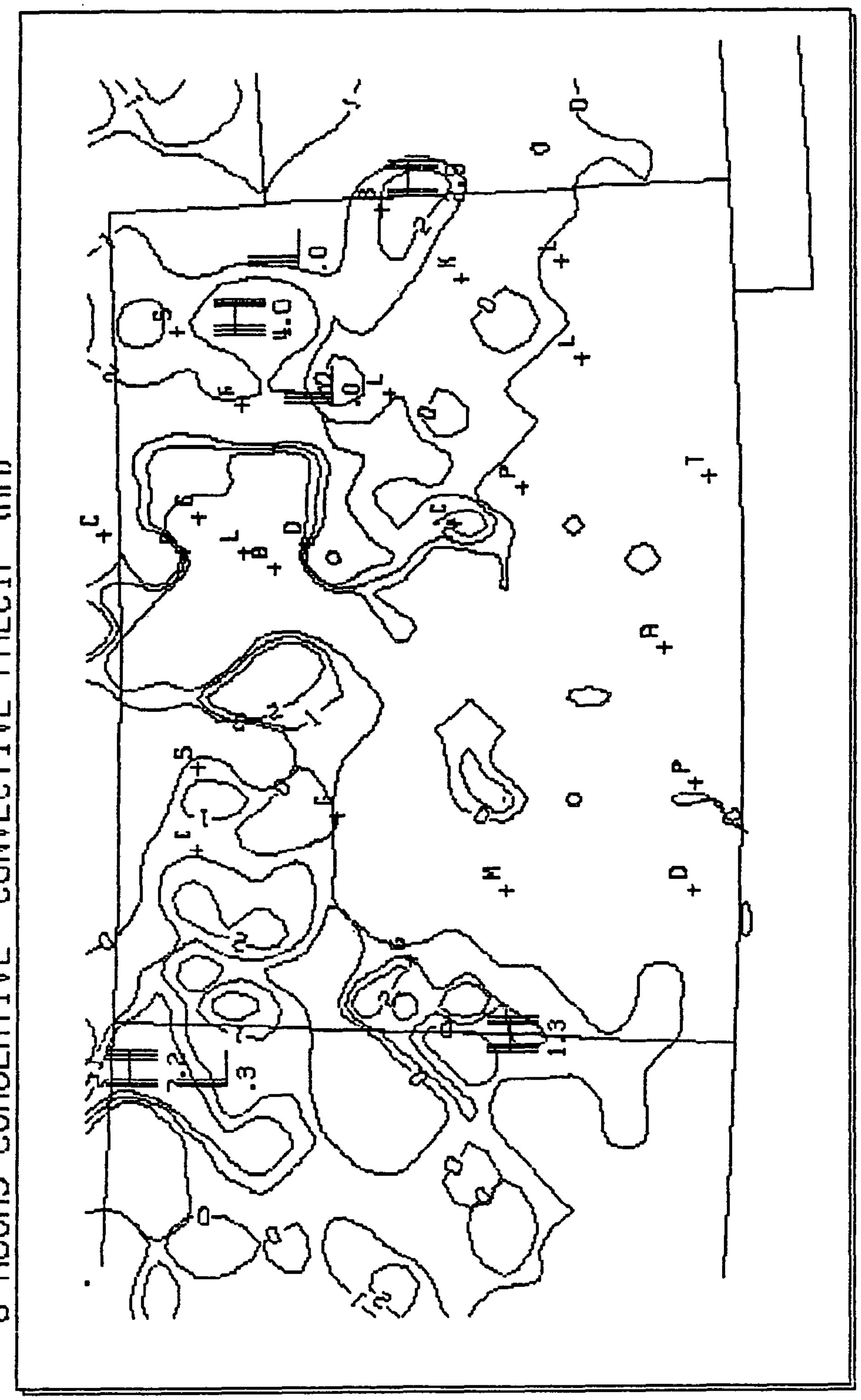

Figure 4.31: Forecast for convective (small-scale) precipitation (mm of liquid-equivalent) for same time period as in Fig. 4.30.

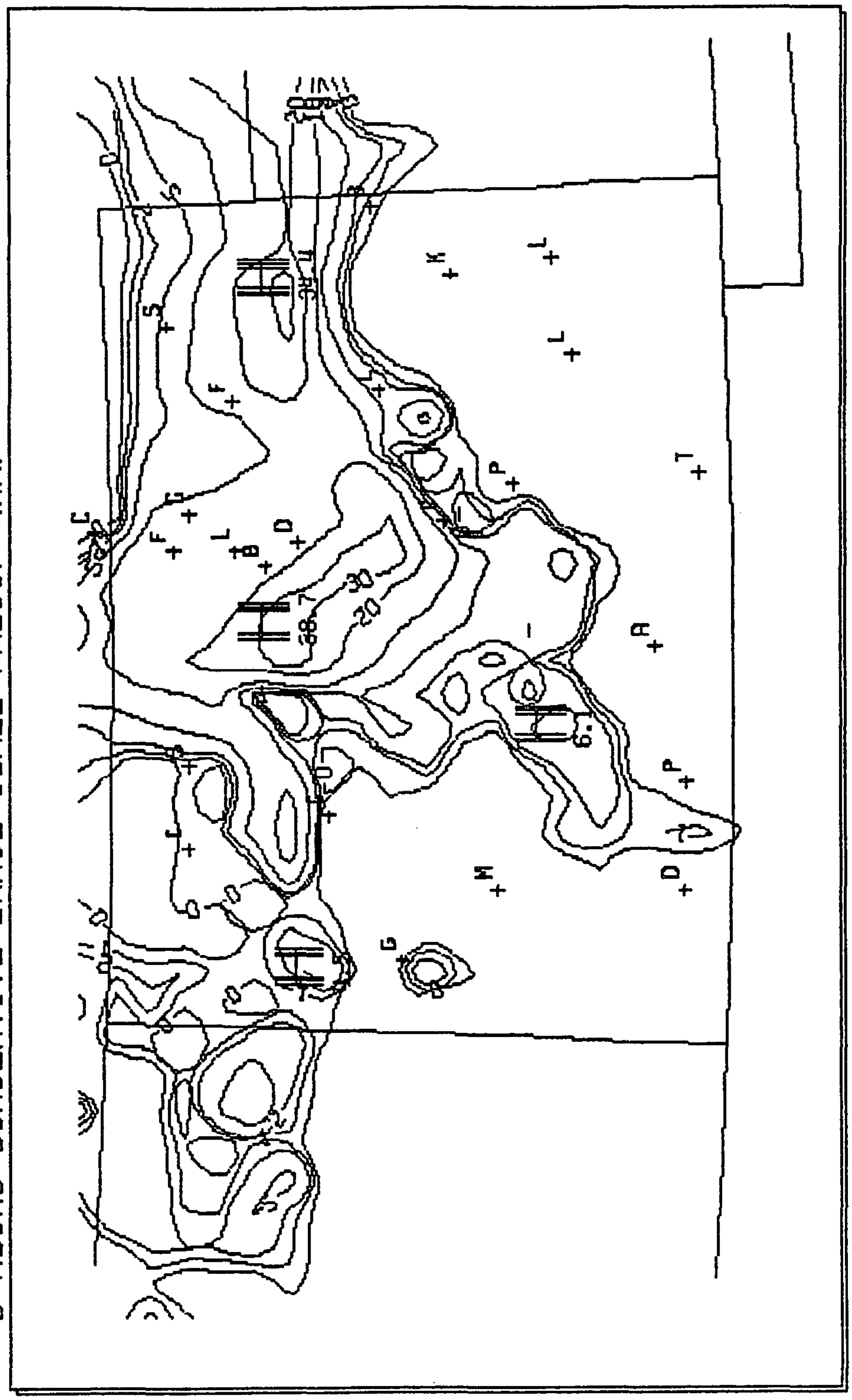

Figure 4.32: Precipitation forecast (mm liquid-equivalent) starting at 5 a.m., March 8, 1992, for 6-hour period ending 5 p.m. MST, March 8, 1992.

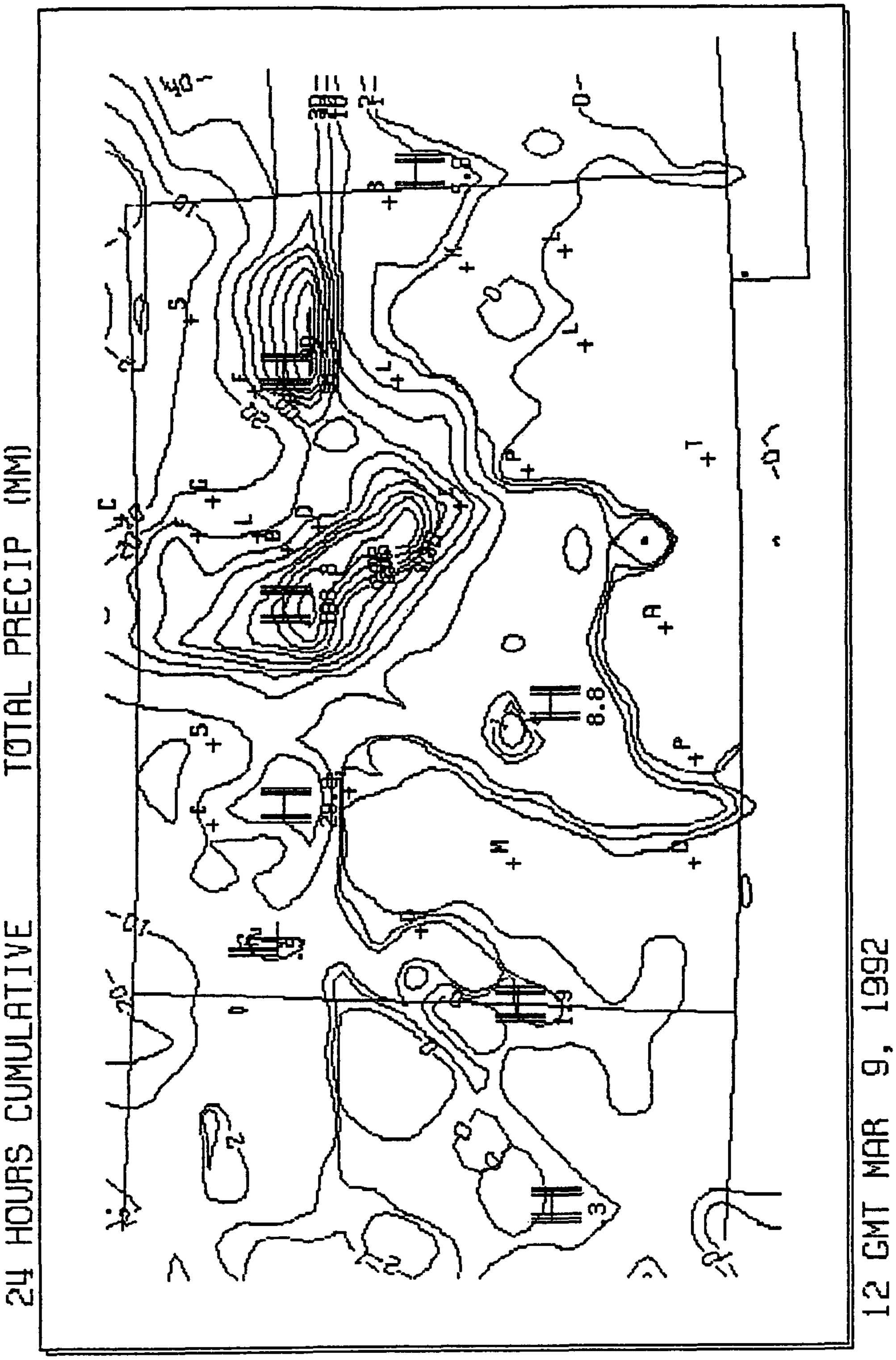

Figure 4.33: Precipitation forecast (mm liquid-equivalent) for the 24-hour period ending 5 a.m., March 9, 1992.

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