Detailed Weather Prediction System for Snow and Ice Control

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A computerized weather prediction system for snowstorms and blizzards was designed and tested extensively during the 1991–1992 winter in Colorado, and installed operationally in January 1993. The system contains several technological innovations. It uses the raw radiosonde and surface observations disseminated via satellite communication links by the National Weather Service. From these data a numerical prediction model generates forecasts at 3-min intervals over a 24-hr period, covering an area the size of the United States, but zooming in over a statewide area (e.g., Colorado) with much greater prediction details. The system runs on a 486 PC and relies on a detailed geographic data base with topographic elevations available in 1- × 1-km horizontal resolution. This data base is used to (a) compute the effects of terrain on weather development and (b) generate graphic displays of terrain and weather. A road network data base is also available for display. Terrain and predicted weather can be shown in several resolution steps, specified by the user, throughout the state, maintenance district, or county. The user can compare predicted weather (precipitation, temperature, winds, humidity) with actual data from sensors or human observers as they become available. If major discrepancies develop, the user can change forecasts locally or regionally by simple point-and-click operations on the computer screen, calling on embedded expert systems.

Highway maintenance operations currently rely on forecasts issued either by the media—which they presumably obtained from the National Weather Service (NWS)—or by vendors that redistribute NWS forecast products. Although the quality of these forecasts has improved steadily over the past few years, it still leaves much to be desired when tough decisions must be made on the basis of the weather. What does one do with a forecast for "30 percent chance for snow between one and five inches along the foothills tonight"? The "30 percent" means that in past history numerical weather forecasts looking similar over the area of concern ("the foothills") produced the predicted results ("one to five inches of snow") in approximately 30 percent of the cases. Meteorologists call this the model output statistics of a numerical prediction model (*1*).

A highway maintenance engineer needs different information, which is not easy to obtain under the current system:

- Is it going to snow or not?
- Where exactly is it going to snow? (The "foothills" in Colorado stretch from the Wyoming to the New Mexico borders and are hardly a precise indicator for individual snow patrols.)
- When is it going to start, and when is it going to end? ("Tonight" leaves too wide a margin for idle "cruising" time.)
- Is it going to come as snow, freezing rain, or rain? (Do we call out the plows, the sanding trucks?)
- If it comes as snow, will it first melt on the pavement, then freeze?
- How much snow can we expect? (1 in. might melt by itself; with 5 in. the plows will be out all night.)
- Will there be enough wind to cause snowdrifts that require plowing even after it stops snowing?
- What if observations show that the forecast is going off track? Can it be corrected to provide again useful information?

These are tough questions to which the media forecasts can hardly provide answers. Therefore, maintenance personnel usually assume the worst case. In Colorado the saying goes, "If it starts snowing, the second snowflake should hit the back of your truck." This may sound good, but it costs an awful lot of money. What if there are only two snowflakes in the whole "predicted" storm? The Colorado Department of Transportation budgets nearly $20 million each winter for snow and ice control. North America puts up in excess of $2 billion each winter for the same purpose. Estimates by the Matrix Corporation, Seattle, indicate that 10 percent or more of these amounts could be saved if we were smarter about weather.

STRIVING TOWARD AN IMPROVED SYSTEM

Timing Problem

Forecast output from the NWS comes in the form of weather maps for the whole United States, usually at 12-hr intervals, to be interpreted by professional or news media meteorologists. Having only two snapshots a day under highly variable weather conditions does not provide enough time resolution to allow precise forecasts. NWS does provide numerical forecasts at time steps of a few minutes, but the communication system is inadequate to handle information transfer with greater frequency than available now.

The WELS system does not require weather maps sent out by NWS. Instead it takes the raw observational data from North American stations distributed by NWS each morning and evening [at 00 and 12 Greenwich mean time, or 5 p.m. and 5 a.m. mountain standard time (MST)], then generates its own numerical forecasts with 3-min time steps. Saving and displaying forecasts at such short time intervals would be

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overkill. Displays at 3-hr intervals usually give enough time resolution to permit detailed tactical planning. The raw data needed to feed the prediction model are in hand 3 hr after the observations have been taken. To run a forecast on a 486/33 MHz machine takes less than 1 hr. Thus, detailed 24-hr forecasts are available with the WELS system as three-hourly time-lapse picture sequences by 9 p.m. and 9 a.m. MST. We call this approach distributed weather prediction, because the forecast computations are not run in a single national center but can be run here or there, wherever needed. So that there are no blind spots between 5:00 and 9:00 MST, one generates 24-hr forecasts overlapping every 12 hr.

Timing Accuracy

One can hardly ever expect a completely accurate weather forecast. Precisely timing an event, such as the arrival of a front or a blizzard, is especially difficult. Weather stations from which the numerical prediction models receive their data are, on the average, 400 km apart, even in the dense network of the United States. Under such circumstances, predicting the arrival time of a snowstorm is impossible, unless one can upgrade forecasts by using observations to correct any discrepancies between prediction and reality. Thus, one could fine-tune the arrival and departure times of weather events to make predictions highly accurate. To offer such a capability, the prediction system must be interactive, that is, the user will have to be able to

- Compare forecast weather with observed developments,
- Decide if there are enough discrepancies to warrant upgrading the forecast, and
- Interact with the forecast by implementing changes affecting the rest of the forecast period.

Of course, such interactivity makes sense only if forecast adjustments can be made quickly and easily. It would not be an acceptable procedure to require re-running the numerical prediction model and waiting for an hour for results that may or may not give the desired answers. The WELS system provides all necessary interactivity through a graphical user interface (GUI), which is a colorful display of weather conditions on the computer screen that can be manipulated and adjusted by simple mouse point-and-click actions. These actions are directed by an embedded expert system that plays the role of a professional meteorologist advising the user.

Precipitation Type

Is it going to snow or not? Several factors play a role in answering this question and related ones enumerated in the earlier list. One first must decide whether there will be precipitation. The WELS system provides numerical model output in terms of liquid water-equivalent precipitation over grid points spaced approximately 24 km apart, either as 3-hr incremental amounts or as three-hourly amounts summed since the start of the forecast period. Plotting these precipitation values on top of terrain and road networks provides an easy first answer as to when and where one should expect precipitation. If reality departs from these predictions, the user can point and click with a mouse to correct timing as well as location of expected precipitation.

Rain, freezing rain, or snow? This decision depends largely on air and ground temperatures. The latter don't change very quickly and depend on the past weather history for the location of concern. At this stage of development, the WELS system does not keep track automatically of such multiday histories. An expert system asks the user for one out of several choices (e.g., deeply frozen, lightly frozen, or thawed ground). Pavement sensors can be consulted for more accurate input.

Air temperatures 600 m above terrain are predicted by the WELS system. If they hover above freezing one should expect rain or sleet. If the ground is frozen, light rain (more so than heavy rain) should give rise to ice warnings. Even fog or drizzle may cause icing conditions. The WELS model does provide estimates of humidity near the ground with predicted values of the differences between dewpoint and actual temperatures. As these differences approach zero, fog and condensation on roadways are likely.

With air temperatures below freezing, one should expect snow, but how much? The colder it gets, the fluffier the snow. Under cold and calm conditions on can expect a maximum of 20 cm of snow from 1 cm of water. Such ideal conditions are rarely ever met, however. Compaction by wind and snowdrift formation cause wide variations, often preventing meaningful estimates. Warm road surfaces will reduce snow accumulation, at least during the early stages of a storm. A 10:1 ratio has been found adequate under many conditions in Colorado. The WELS system lets the user choose snow/liquid-water ratios depending on air temperatures and ground states. These suggested choices can be overridden by the user's own preference of a constant ratio between 1 and 20. And, of course, under the interactive provisions of the system, users may change their minds should an initial choice turn out to be inadequate.

Precipitation Amount

"One to five inches" in a typical media forecast contains a lot of leeway. It is still better, however, than having to plow through 5 in. of "partly cloudy." We realize that such wide error margins—most likely designed to avoid litigation—can be quite costly. Overpredictions mean idle crews eating into precious resources; underpredictions mean delays in service, often costly to the public in terms of accidents, traffic pileups, and ill tempers.

The WELS system places great emphasis on the prediction of precipitation amounts in terms of when and where they can be expected. Again, the user can adjust these predictions as time rolls by if discrepancies with observations begin to emerge.

With more reliance on such forecasts the user can make tactical decisions before, rather than after, emergencies arise:

- From a threat evaluation for each snow patrol (and not just for the whole "foothills" region) it can be determined if available resources are adequate to cope with the predicted storm.

- From a districtwide evaluation of threats it can be determined if resources can safely be pulled from one patrol to aid another, or if priority rankings and road closures should be brought into effect.
- Road hazard advisories could be issued to the public before they occur—assuming that the public listens.

In tests during the winter season of 1991–1992, and in current operational deployment at several locations in Colorado, including the Avalanche Information Center, the WELS model performed very well in predicting wind conditions over the mountains and plains of Colorado, thus providing a good handle on where and when to expect blizzard conditions. Because the WELS system interacts with a geographic information system, locations known for hazardous snowdrift formations could be identified in the computer display, if such a data base were made available.

Tactical Planning

The WELS system offers the capability of on-line, real-time weather prediction with details of timing, intensity, and location of snow events as influenced by large-scale weather conditions and local topography. Furthermore, forecasts can be corrected locally and regionally as observational evidence accumulates. With such capabilities in hand, state highway departments must learn to be much more demanding in the access to, and use of, weather information. No longer must they be satisfied with "one to five inches in the foothills tonight"!

To make full use of detailed and customized weather predictions, their information contents need to be integrated into all levels of decision processes.

First of all, some soul searching will be needed as to the level of service that needs to be provided. Colorado currently adheres to a dry-pavement policy, meaning that during and after a snowstorm roadways will be restored to "dry" surface conditions as quickly as possible. This policy is comforting to tourists and carries minimal risk of litigation, but it is very expensive to the taxpayer. What is an acceptable compromise that still provides more-than-adequate service to the public but measures more judiciously the risks and threats of inclement weather against financial burdens? By better identifying the times and mileposts under threat, confining service to these targets, and minimizing risks of neglect by keeping a watchful eye on observations and upgraded forecasts, significant savings in annual road maintenance costs could be realized.

But these are only the beginnings of weather input applications. Weather forecasts, as those provided by the WELS system, can be combined with data bases on "cold spots" (i.e., locations of frequent road ice formations under certain weather conditions), preferred snowdrift corridors, avalanche hazards, and so forth. Only a few such locations need to be equipped with sensors whose data can provide verification of forecasts or cause for their correction. The forecast details provided by the WELS system can then be used to gauge the impact of predicted weather on other potential hazard points identified in the data base within a relatively wide area, without having to plaster the whole state with instruments. Such hazard points can be identified on the computer screen whenever predicted conditions or corroborating observations give cause for caution.

Detailed threat predictions for individual maintenance sections, and even individual snow patrol areas within such sections, invite the use of computerized data bases on personnel and equipment availability in a direct access mode. The rate of snowfall predicted by the WELS system for certain times and over certain patrol areas can provide a reasonable estimate of the frequency of plowing and sanding operations needed to maintain road trafficability and safety. These estimates can be checked against rosters of available personnel and equipment. Under prolonged storm conditions the scheduling of maintenance operations can be complicated by work safety rules that restrict the lengths of duty shifts and impose "off time" conditions. Equipment may not be available when needed, due to repair work and unanticipated breakdowns. Highway engineers have learned over the years how to cope with these pitfalls. Nevertheless, weather information integrated with computerized data bases can provide significant help in exploring a variety of scenarios on the computer screen before committing to one that might be far from the best. Thus, "whose patrol, how many plows should be sent when and where and for how long" should rely on information of considerably more substance than a look out the window.

CASE STUDY: MARCH 8, 1992

Weather forecasts provided by the media tend to be more cute than they are accurate: a sun disk hiding behind clouds, raindrops scattered here and there, snow crystals covering half a state, and maximum and minimum temperatures each with a 10-degree margin of error. Forecasts released by the NWS and accessible to users in a repackaged format through value-adding vendors usually are more instructive but leave a wide range of possibilities in their interpretation. They are issued in the form of "stories," because average nonmeteorologists cannot be trusted with interpreting pressure contour and vorticity advection charts. As an example, the forecast distributed by WeatherBrief at 5:30 a.m. MST on Sunday, March 8, 1992 (before the "Big Blizzard of '92" hit eastern Colorado that evening) read:

> Colorado state forecast: heavy snow warning today and tonight San Juan and central mountains. Snow advisories northern mountains ... southwest and northeast through tonight. Periods of snow today mountains and west. Accumulations of 6 to 12 in. San Juan and central mountains south of Aspen today, 3 to 6 in. 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 late. Partly cloudy west. Highs today 40s west, upper 20s and 30s mountains, 40s and 50s east. Lows tonight 20s and 30s with 10s mountains. Highs Monday upper 20s to mid 40s mountains and west. Colder east with highs 30s to mid 40s.

An update issued at 5:05 p.m. on March 8 reads:

> Conditions across Colorado will deteriorate tonight and many winter storm warnings and advisories are in effect through early Monday. Snow will fall over much of the state. Low temperatures

will be in the 20s and 30s with 10s in the high country. On Monday showers will continue over the state and are expected to decrease in the early afternoon in the east. High temperatures will be cooler ... only reaching the upper 20s to mid 40s.

Another update followed at 6:30 p.m.:

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.

The first forecast, issued at 5:30 a.m., aside from being wrong, provided too much latitude. The WELS forecast, using data collected at 5 a.m. MST on March 8, delivered the meteorological charts shown in the following figures. (These diagrams are actual screen reproductions, albeit without color, of the WELS GUI. Weather is presented as icons whose size and color indicate the severity of an event.) Already by 11 a.m. strong winds of about 20 m/sec were predicted to prevail over northeastern Colorado while temperatures there remained above freezing (Figure 1) and the first widespread precipitation (rain in the lower elevations, snow in the high country) started to appear (Figure 2). Especially south of Denver convective cloud buildup was expected. We, too, made a small mistake: although threatening clouds were obscuring the mountains already by mid-morning, precipitation in Boulder did not start until shortly after 2 p.m. with a strong thunderstorm. (By clicking the right mouse button on the map location of Boulder, detailed forecasts as shown in Figure 3 can be obtained in an instant.) We jumped the gun by a couple of hours with our forecast. The 3-hr period between 2 p.m. and 5 p.m. MST called for heavy snow in the mountains west of Boulder (Figure 4) and also southwest of Fort Morgan. The total 24-hr precipitation expected by 5 a.m. on March 9 (Figure 5) reveals the scope of the disaster. Hardest hit were the Front Range area west and south of Boulder and Denver and the region between Fort Morgan and Limon in northeastern Colorado. According to Colorado Department of Transportation personnel in Greeley (Maintenance Section 1 responsible for this area), several snowplows got stuck in the blizzard out there.

There is no doubt that the "southern" storm predicted by NWS did not materialize: Alamosa in the San Luis Valley of southcentral Colorado went from a 6-in. snow cover on the day before the alleged storm to a 4-in. cover after the storm. Trinidad, next to the San Juan Mountains, reported only a trace of precipitation. Table 1 provides more comparisons with observation reports issued by WeatherBrief in terms of inches of liquid-water equivalent (or inches of snow in parentheses).

During the 1991–1992 winter, WELS tested its prediction system on 25 Colorado snowstorms, some of them lasting for several days. During the 1992–1993 season, the operational system encountered one of the snowiest winters on record, as reflected in avalanche accidents. Because of its detailed attention to terrain effects, the WELS system provided significantly better guidance in terms of timing, location, and intensity of predicted events than that provided by the media or NWS, even without user-generated adjustments.

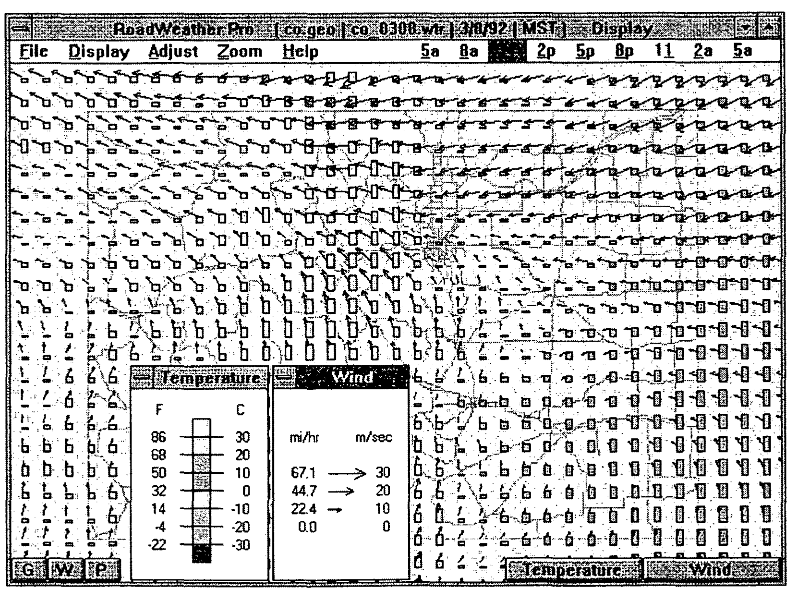

FIGURE 1 Temperatures and winds at 600 m above terrain predicted for 11 a.m. MST on March 8, 1992, from observations at 5 a.m.MST. Over eastern Colorado these rectangles would be red, indicating temperatures above freezing. A fully extended dark rectangle indicates + 10°C. Lighter shades of red, first appearing at bottom of such rectangles (see southeast corner of Colorado) signify still warmer temperatauares. Over the mountains light blue (gray) rectangles indicate temperatures below freezing. A full-height rectangle means −10°C.

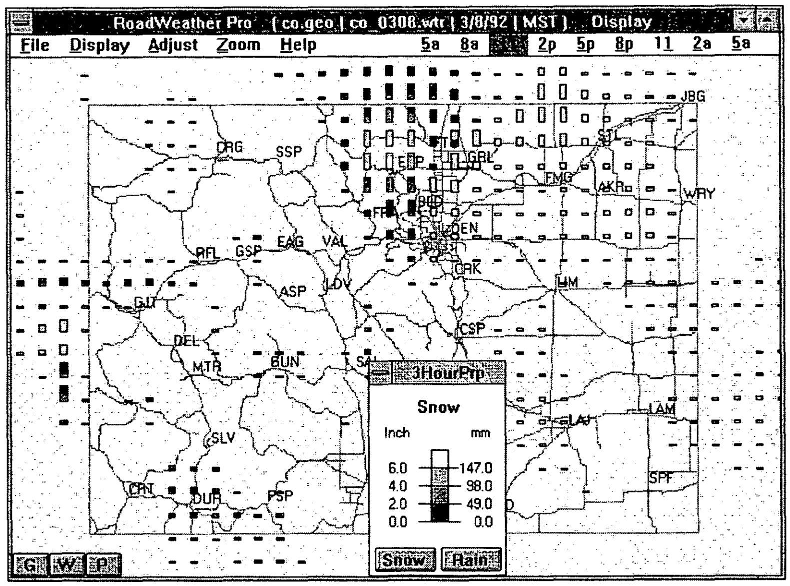

FIGURE 2 Precipitation predicted for 3 hr ending at 11 a.m. MST, March 8, 1992. Over the mountains snow is predicted, as indicated by size and shade of rectangles. Heavier snowfall is symbolized by lighter shades. Over the plains, rain is predicted and shown by rectangles in shades of green. (Scale display in scale window can be switched from "Snow" to "Rain" by clicking on appropriate button.)

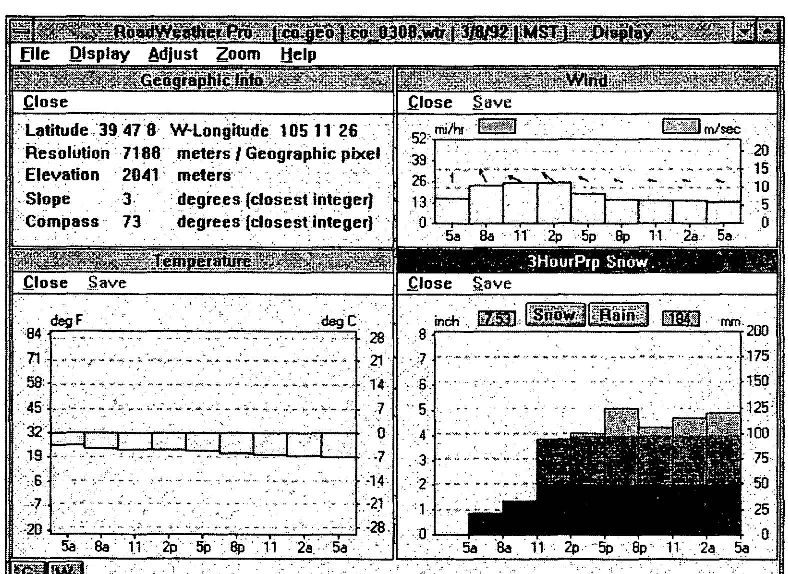

FIGURE 3 Clicking right mouse button on location of Boulder, Colorado, in previous map reveals 24-hr forecasts of temperature, wind, and precipitation for Boulder. Upper left window shows location of point and characteristics of geographic pixel on which mouse was clicked.

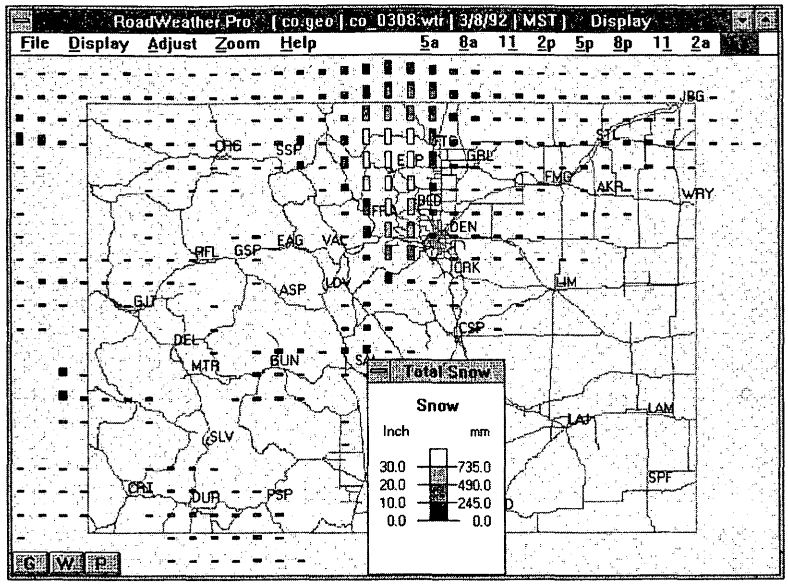

FIGURE 4 Total snowfall predicted for 24-hr period ending at 5 a.m. MST, March 9, 1992. Amounts are indicated by size and shade of rectangles.

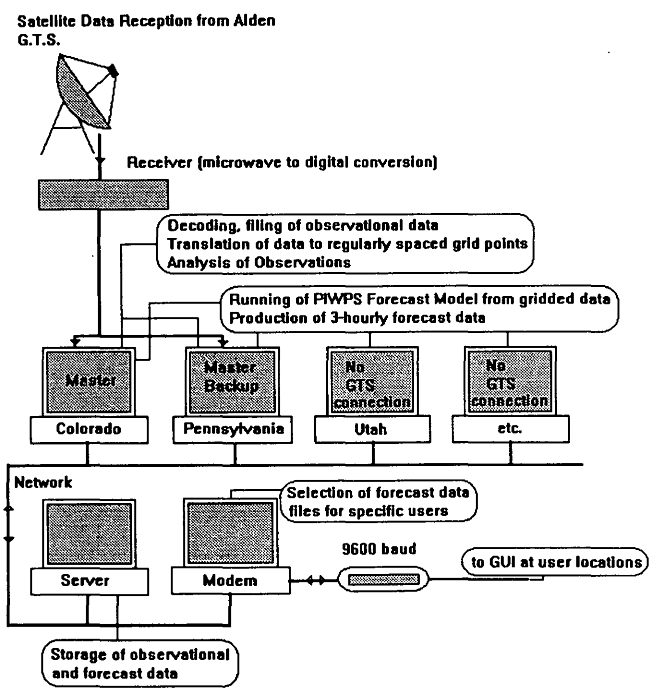

FIGURE 5 System configuration at WELS Weather Central.

GRAPHICAL USER INTERFACE

The weather examples given in Figures 1 to 4 came straight off the laser printer hooked to the WELS computer. The computer screen output of these maps is much clearer, showing precipitation systems of increasing intensity in different colors. WELS took full advantage of Microsoft Windows 3.1 graphics capabilities in a relatively inexpensive PC environment. The WELS system design includes a GUI that serves the following purposes:

- It provides quick access, by simple mouse point-and-click choices from a menu or from "buttons," to geographic information data bases used to display terrain elevation, slope, or azimuth angles with user-specified horizontal resolution. Since underlying terrain has a strong effect on the behavior of snowstorms, we deemed it important to show terrain details in the manner they deserve, and not just as state boundaries. (In the previously shown examples, terrain details have been omitted to avoid clutter in a black-and-white rendition.)
- A detailed road network data base and city locations can be overlaid on the terrain and exhibited on the computer screen.
- Different degrees of horizontal resolution can be attached to different data bases stored on hard disk for quick display purposes. Thus, a map of Colorado provides an overview of statewide terrain, roads, and weather. A map of Maintenance Section 1 brings to the computer screen a more detailed display of terrain and weather in the northeastern sector of Colorado. A data base for the Boulder-Denver region shows even higher resolution with about 1-km horizontal data point spacing.
- A "rubber-band" zoom capability is part of this GUI. When placed on any of the displays just mentioned, it will magnify the area within the zoom box to fill the whole computer screen. This option is of specific benefit if road networks should be shown in details that may get lost on large-area maps.

To suit the design of this GUI, geographic data bases have been translated into geographic pixel objects. Each of these objects knows its location on the globe and on the computer screen, and carries values of elevation, slope, azimuth angles, and such. (With access to appropriate data bases, we can attach additional values for vegetation, soil cover, soil con-

TABLE 1 Precipitation Observations at Colorado Stations for 24 hr Ending 5 a.m., March 9, 1992.

Station	Observed (in.)	WELS Predicted (in.)
Akron	0.60	2.0
Alamosa	missing	none
Boulder	missing (20)	1.8 (ca. 18)
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, but 10 miles to west
Salida	missing	0.1
Trinidad	Trace	none

dition, etc.). Because of this object-oriented structure, the user can specify on the fly what should be shown (or blotted out) on the screen: for example, "elevations between 4,500 and 12,000 ft." Making such choices allows emphasis on certain elevation bands that might be prone to specific weather conditions (such as the expected freezing level in a mountainous region experiencing precipitation).

The output from the described WELS forecasting model of predicted weather parameters are translated automatically into the same object-oriented geographic pixel format. Instead of showing weather maps, the WELS system now can depict weather in the form of icons superimposed on terrain and road displays. These icons are not as cute as umbrellas or raindrops in a TV forecast show, but they are much more informative. In the present configuration, rain and snow are shown by differently colored rectangles arranged on the computer screen, with the underlying terrain and road details still clearly visible. These rectangles fill up with increasing amounts of rain or snowfall expected during 3-hr intervals. As certain threshold values are exceeded (e.g., 2 in. of snow or 0.2 in. of rain in 3 hr), the rectangle changes color, filling up again until the next threshold is reached. Through this form of display, areas and intensities of rain and snow clearly stand out on the computer screen. Temperature and humidity forecasts are displayed in a similar manner, either together or separately. Winds are shown by the length and directions of arrows, as in Figure 1.

Because the system no longer draws weather maps but calls on graphical icon data loaded into fast computer memory, the displays can be changed instantaneously by clicking on different weather parameters in a display as shown in Figure 3. A simple mouse click in any of the histograms allows the user to change predicted values.

This object-oriented GUI approach to terrain and weather display is a major step in giving the user quantitative information on expected weather developments with detailed resolutions in time and space.

INTERACTIVITY

Weather forecasts cannot be expected to be 100 percent accurate, so we designed a way by which the user can adjust predictions according to local observational evidence. Again, the output from the numerical prediction model is used to depict the forecast history for specific locations on the map. These locations can be selected by simple mouse point-and-click actions. If reports from human observers (e.g., a snowplow operator or a highway patrolman) or from data from roadway sensors indicate that the forecasts of precipitation, wind, or temperature are off significantly, a simple mouse click in any of the histograms shown in Figure 3 will adjust the forecasts. Such adjustments may become necessary because of errors in the timing or the intensity of the predicted phenomenon. Corrections to forecasts are made by simply moving the cursor on the screen to the desired coordinate position and clicking a mouse button. An expert system will figure out what the user's action should do to the rest of the forecast period.

If the user erred in the imposed adjustments, no harm will be done. The original forecasts are still in computer memory and can be recalled to go through different adjustment steps. Thus, the weather forecast can be played as a "what if" game, to test different scenarios and road maintenance strategies. Even on a PC such forecast adjustments take only fractions of a second, because the numerical prediction model need not be run again. (It would take an hour to do so.) Instead, weather "objects" are manipulated through the GUI at lightning speed, making use of object-oriented computational procedures (*2*).

Because observational data can be used to upgrade and correct forecasts, a state highway department would be well advised to gain access to local and regional weather data. Such access should be instantaneous, at any time, and on a statewide basis. Data from pavement sensors and roadside weather stations can be interrogated via a microwave data link. Such data could be displayed on the screen at any desired time. Furthermore, any significant discrepancies between such observations and the forecast issued for that time could be computed automatically and exhibited on the computer screen, prompting the user for an upgrade decision.

SYSTEM OVERVIEW

Figure 5 provides a schematic overview of the current system: raw radiosonde (balloon) and surface data are received from NWS via satellite communication link each morning and evening. These data are processed at WELS Weather Central to produce numerical weather forecasts saved in computer memory at 3-hr intervals. The forecasts are customized for statewide regions. Road weather data can be processed by the system, provided that access to such data is available on a routine basis. Formatted forecast data to feed the interactive GUI are piped to users via modem. At user locations with at least a 386 computer and sufficient memory and hard disk capacity, Windows and WELS software are installed to receive and display these data. End users at these locations have full access to forecast manipulation tools, but, if they so desire, they can ask Weather Central to perform such manipulations and provide them with the updated end results.

Minimum hardware configuration for on-site weather and terrain displays and forecast adjustments by the user are a 386 computer (25 or 33 MHz) with math coprocessor, 8 megabytes of RAM, an 80-megabyte hard disk, a mouse, and a modem link to WELS Weather Central or to a licensed location where the numerical weather predictions are generated. Performance is greatly enhanced on a 486/50 or 66 MHz machine. Software requirements are Microsoft Windows 3.1 and WELS ROADWEATHER PRO software and license. The computer at the user's location need not be dedicated exclusively for weather forecasting; it can be used for all other reporting, accounting, and other such tasks.

Experiences with this system configuration and the results of extensive tests during the 1991–1992 winter are described in great detail by Reiter et al. in a final project report to the Strategic Highway Research Program (SHRP) (*3*).

ACKNOWLEDGMENTS

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