Development of a Discriminant Analysis Mixed Precipitation (DAMP) Forecast Model for Mid-Atlantic Winter Storms

J. DUSTIN HUX, PAUL C. KNAPPENBERGER, PATRICK J. MICHAELS, AND PHILIP J. STENGER

State Climatology Office, University of Virginia, Charlottesville, Virginia

HUGH D. COBB III AND MICHAEL P. RUSNAK

National Weather Service Forecast Office, Wakefield, Virginia

(Manuscript received 11 February 2000, in final form 29 September 2000)

ABSTRACT

The frequency of ''wintry mix'' precipitation—freezing rain and ice pellets—is considerable in the mid-Atlantic region of the United States. Despite the fact that the general conditions necessary to support the various winter precipitation types have been known for years, in that region, the proper forecast of type and duration of winter precipitation is one of the most difficult challenges in operational meteorology, with extensive public safety and economic ramifications. The purpose of this project is to report on an improved methodology for winter precipitation forecasts.

This study analyzed precipitation type and surface temperature data from NOAA's hourly surface airway observations and temperatures and heights for all mandatory and significant levels from NOAA's Radiosonde Data of North America from Washington Dulles International Airport, Virginia (1962–95), and Greensboro, North Carolina (1948–95). Precipitation that occurred within 2 h of a sounding for the months November through March was used for analysis. The upper-air data were combined to create vertical temperature profiles for each observation of precipitation type—rain, freezing rain mix, ice pellets, and snow. Those profiles were then categorized by the number of freezing levels (i.e., the number of times the sounding crossed the 0°C isotherm) and examined to determine if they could be used to isolate specific precipitation types and as a result segregate winter precipitation scenarios by forecasting difficulty.

Four basic temperature profiles were found for both Greensboro and Washington Dulles Airport during winter—zero, one, two, and three or more freezing level(s). Each of these profiles produced characteristic types of precipitation (snow, freezing rain, freezing rain mix, and rain); for each profile, either climatology or discriminant analysis was used to statistically determine precipitation type.

The results of these analyses were used to develop the site-specific Discriminant Analysis Mixed Precipitation (DAMP) models for Greensboro and Washington Dulles Airport. The variables required to run the model are the height(s) of the freezing level(s) and critical temperature(s) from a modeled or observed sounding. The DAMP models are easy for the forecaster to use and understand and provide probability guidance in situations that are difficult to resolve.

The overall classification results showed that the models were very effective for predicting precipitation type. Probabilities of detection were 98.4%, 85.8%, and 92.6% for rain, freezing rain mix, and snow, respectively, for Washington Dulles Airport, and 98.7%, 87.1%, and 89.7% for Greensboro.

1. Introduction and background

The ability to produce accurate winter precipitation type and duration forecasts is critical in regions with high frequencies of ice pellets and freezing rain. While all types of winter precipitation events are potentially disruptive, extended and widespread periods of freezing rain or freezing rain mix are by far the most destructive and hardest to predict. Because it coats exposed surfaces with a layer of ice that in some instances can exceed 2 in. (Lemon 1961; Michaels et al. 1991), freezing rain can damage structures, down power lines, break trees, and make surface and air travel virtually impossible. That, in turn, produces extremely dangerous and costly conditions for the transportation and utilities sectors, as well as the general public. As a result, predicting precipitation duration within type is exceedingly important to the user community.

In the mid-Atlantic, the frequency of the ''wintry mix'' of precipitation—freezing rain and ice pellets—is considerable (Fig. 1). Portions of the western piedmont of Virginia average more than 50 h yr^{-1} (Michaels et al. 1991; Keeter et al. 1995) and ice pellet frequencies

Corresponding author address: James D. Hux, 291 McCormick Road, P.O. Box 400123, Charlottesville, VA 22904-4123.
E-mail: jdh2r@virginia.edu

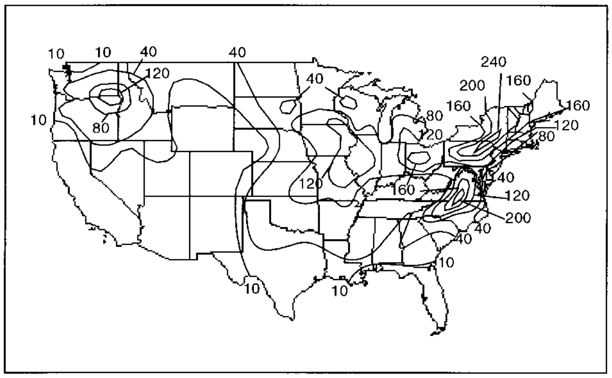

FIG. 1. The number of freezing rain observations from Sep through Apr 1982–90 (after Robbins and Cortinas 1996).

in North Carolina indicate that this maximum, though somewhat reduced, continues along the western piedmont to the South Carolina border (Musick 1991).

The general conditions required to produce different precipitation types have been known qualitatively for many years (Brooks 1920). Snow requires that the temperature of a significant portion (or the entirety) of the vertical atmospheric column is colder than 0°C. Ice pellets and freezing rain occur when an elevated warm layer coupled with a surface temperature at or less than 0°C induces partial (with ice pellets) or complete melting (with freezing rain) (Brooks 1920; Martner et al. 1993; Gay and Davis 1993).

Still, the proper forecast of type and duration of winter precipitation from the coastal plains to the mountains of the mid-Atlantic region remains one of the most difficult tasks in operational meteorology in North America. Indeed, Keeter et al. (1995) have written that ''perhaps the most challenging winter weather forecast problem in the Southeast is forecasting precipitation type.''

In the mid-Atlantic region, the onset of a winter precipitation event is often preceded by the formation of a cold anticyclone under a transient ridge that occurs in partial response to an upstream short wave passing through a longer wavelength trough (Maglares et al. 1995). As this anticyclone of southeastern Canadian or New England origin crosses the axis of the Appalachian mountains, the southward diverging cold air is trapped by the high mountains of the Blue Ridge and southern Appalachian complex, a phenomenon referred to as cold-air damming (Richwein 1980; Bell and Bosart 1988; Keeter et al. 1995). The evolution of the depth and intensity of this cold air determines the vertical temperature and moisture profile throughout the precipitation event. In particular, this cold-air damming produces a physical condition that is very difficult to resolve by straightforward interpretation of forecast model output (Richwein 1980). Bell and Bosart (1988) noted that operational forecast models of the generation tended to produce damming that was ''weaker and more short-lived than expected,'' and, although current numerical weather prediction models contain more realistic damming due to physical and resolution improvements, significant deficiencies remain.

A mixed winter precipitation event typically begins when warm, moist air overruns the dammed cold air during the developmental stages of a coastal cyclone. As the cyclone matures and progresses northward, the cold air is typically eroded away. That alters the vertical temperature profile and can lead to a change over of precipitation type. This situation presents a particularly difficult forecast in that different precipitation types can occur simultaneously within a small geographical area. The accurate placement of the rain/freezing rain/ice pellets/snow termini is critical because errors of as little as 30 km superimposed upon the dense population of the northern part of the mid-Atlantic affect the daily lives of large numbers of people (Maglares et al. 1995). Though an experienced forecaster may view this magnitude of error in a 24-h precipitation forecast a ''success,'' the public often considers that same forecast to be a failure, given the disruption that comes with such an error.

Various methodologies for distinguishing between winter precipitation types have been developed. One early method developed for forecasting precipitation type in New York City used surface temperature, the pressure (hPa) of the freezing level, and the 850-hPa temperature advection (Pandolfo 1957). Likewise, the 1000–500-hPa thickness has long been recognized as a means to differentiate precipitation type (Wagner 1957). Boundary layer potential temperature, 1000–500-hPa thickness, and 850-hPa temperature were variables that the National Meteorological Center (now known as the National Centers for Environmental Prediction) primitive equations predicted. These variables were used to develop a system that produced objective forecasts of the conditional probability of frozen precipitation in the United States (Glahn and Bocchieri 1975). Later, it was realized that many of the processes that influence precipitation type are quite shallow in depth, and the 1000–700-hPa thickness became the predictor because it was more constrained to that critical region of the atmosphere. These predictors, though easy to use, were only moderately successful.

Koolwine (1975) partitioned the 1000–700-hPa thickness to specify precipitation type over southern Ontario, Canada, by using the 1000–850- and 850–700-hPa thickness values as indicators of low-level cold air and midlevel warm air, respectively. This partial thickness approach provided a finer resolution for the thermal structure of the atmosphere. Keeter and Cline (1991) incorporated and extended this partial thickness approach in the development of objective guidance for North Carolina precipitation type prediction. This method identified precipitation type using 1000–700-, 850–700-, and 1000–850-hPa thicknesses in a combination of regression and nomogram development. The regression results were used to separate of frozen versus liquid precipitation, while the nomograms are used to predict frozen precipitation type.

Another method implemented linear screening regression to derive relationships between precipitation type and sounding characteristics (Bocchieri 1980). Instead of using partial thickness, that analysis found that the optimal parameters for precipitation type prediction were mean surface to 1000 hPa temperature; mean 500–2500-m temperature; and the calculated depths of the warm pool aloft and cold pool at the surface. The precipitation categories were liquid (rain, drizzle, and rain mixed with snow or sleet), freezing (freezing rain, freezing drizzle, and freezing rain/drizzle mix), and frozen (snow and/or ice pellets).

Although all these studies reported some success in distinguishing between frozen and liquid precipitation, they showed very little skill in predicting the type of frozen precipitation (i.e., when the observed precipitation type was snow, freezing rain, and/or ice pellets, the overall percentage of correct forecasts was only about 50%). These methods have already been exploited for just about all of their inherent information; despite such major improvements in precipitation type forecasts in mixed-precipitation events, major problems remain.

As a result, researchers have moved away from methods with limited vertical resolution and have examined ways to incorporate into the forecast more of the information provided by the sounding, whether observed or modeled. This shift in methodology was achievable because of increased computing capability concomitant with finer overall resolution in the short-range forecast models [Eta, Meso-Eta, Nested Grid Model (NGM), Rapid Update Cycle (RUC), etc.]. These studies may be subdivided into two groups: those that incorporated observations into theoretical microphysical (thermodynamic) models and those that continued to use the data to develop empirical models.

An empirical approach that has seen some success in Canada is the ''energy'' method of Bourgouin (1992), who examined 171 mixed precipitation hours from the 1989–90 and 1990–91 winters. The findings revealed that a combination of mean 1000–850-hPa temperature, mean 1000–700-hPa temperature, freezing-level height, saturation height, surface temperature, dewpoint temperature, and positive and negative energy (measured from a standard tephigram) performs better than methods using partial thicknesses or layer heights. The energy method analyzed and developed equations to distinguish between three precipitation type pairings—ice pellets versus freezing rain, rain versus snow, and ice pellets versus rain. The reported overall success rates for each pairing, based on winter 1991–92 data, were 80%, 68%, and 40%, respectively.

The hypothesis driving microphysical models is that the critical factor that can decide between freezing rain and ice pellets production is whether an ice particle will completely melt in the elevated warm layer before entering the subfreezing air beneath. In effect such models make assumptions regarding hydrometeor size and vertical velocity, and then follow the hydrometeor through the column via dynamic equations. Aircraft icing research has contributed much knowledge regarding the initial phases of hydrometeors aloft and deviations from the classical precipitation type hypothesis in winter storms (Rasmussen et al. 1992; Marwitz et al. 1997).

The first of these thermodynamic models (Czys et al. 1996) focused on discriminating between freezing rain and ice pellets by approximating the ratio of time available for melting to the time required for complete melting. That ratio was then used in concert with surface temperature to determine precipitation type. The model was tested with data from the 1990 St. Valentine's Day storm that affected much of the Midwest. While the modeled and observed areas of freezing rain corresponded reasonably well, the model underpredicted the occurrence of ice pellets. In a subsequent project, Zerr (1997) applied two heat transfer models to the ice pellets and freezing rain forecast problem. One of the models simulated the melting of a dendritic crystal, and the other, the refreezing properties of liquid droplets. He noted that the better predictor for ice pellets and freezing rain was the melting parameter.

However, the complete melting/refreezing paradigm is only 60%–70% of the story (Bocchieri 1980; Huffman and Norman 1988). In a scenario termed the ''supercooled warm rain process (SWRP)'' (''supercooled drizzle drops'' in the aircraft icing research community), freezing precipitation cases were observed in a subfreezing atmosphere (temperatures ranging from 0° to $-10°C$) when moisture decreases rapidly above the cloud top (Huffman and Norman 1988; Marwitz et al. 1997). Huffman and Norman (1988) developed a decision tree that categorized winter precipitation events into the SWRP or the classical model and then used various continuous and binary variables to determine precipitation type. No performance statistics or operational use were described for the technique.

In the study presented here the objective was to develop an improved methodology for the operational forecasting of winter mixed-precipitation type in the mid-Atlantic. Specifically, the requirements were to develop a model that is easy for the forecaster to use and understand, has the highest possible vertical resolution, incorporates climatological data from a long period of record, and provides the forecaster with probability guidance in situations that are difficult to resolve.

To that end, empirical relationships between the number of freezing levels, the temperatures from mandatory and significant levels, and other variables derived from routine National Weather Service (NWS) rawinsondes were examined with regard to precipitation type using discriminant analysis. Discriminant analysis provided the ability to separate and classify precipitation type (categorical data) based on continuous meteorological data and to produce probability estimates for group membership. The equations describing these relationships were used to develop the Discriminant Analysis Mixed Precipitation (DAMP) model. Essentially the DAMP model addresses what type of precipitation will occur during a winter precipitation event.

2. Data and methodology

Data from two distinct sources were merged to investigate the meteorological conditions necessary to support the various winter precipitation types. The first included the National Oceanic and Atmospheric Administration's (NOAA) hourly surface airways observations of precipitation type and surface temperature from Greensboro, North Carolina (1948–95) and Washington Dulles International Airport, Virginia (1962–95). All hours reporting precipitation from the months November through March were extracted for each station. Precipitation type was defined as rain (liquid rain or drizzle), freezing mix (freezing rain/drizzle or freezing rain/drizzle mixed with any other precipitation type), ice pellets, and snow (or snow/rain mix). The second dataset was the record of twice-a-day (0000 and 1200 UTC) upper-air observations for Greensboro (1948–95) and Dulles (1962–95) extracted from NOAA's Radiosonde Data of North America. These were the only two stations in the region of interest that simultaneously collected precipitation type and sounding data over an extended period of record—one that ensures that enough observations are available within and between precipitation types to establish stable distributional relationships.

For each station, these datasets were combined to ensure that the most representative upper-air observations were available for each precipitation occurrence. To accomplish that, only precipitation occurring within 2 h of an upper-air observation time (a 5-h window) was used for analysis. Within this 5-h window, each hour's precipitation type was assigned to the upper-air observation at the window's midpoint. Though this could introduce errors into the analysis in the form of different precipitation types within a 5-h window being associated with a single upper-air observation, the occurrence of this situation was rare, and precipitation type generally remained the same within each 5-h window. Additionally, in instances when any one meteorological variable was missing or not available, the entire case was excluded from analysis. Although that eliminated a large amount of data, the number of hourly observations including precipitation was sufficiently large that many hundreds of observations for each station remained—2475 and 5845 total observations for Washington Dulles and Greensboro, respectively.

Through this method, the dataset constructed for each station contained the observed precipitation type, surface temperature, and the upper-air observations of height (m) and temperature (°C) at 50-hPa increments between 1000 and 500 hPa. In addition to the height and temperature data, several other variables were derived from the sounding data. These included the calculated partial thickness (m) for each 50-hPa interval, the height(s) (m) of the 0°C isotherm (referred to as ''freezing levels'' even though 0°C is actually the melting temperature of ice, not the freezing temperature of water), and a temperature index (summation of temperatures) between each freezing level.

Discriminant analysis (Fisher 1936), a multidimensional discrimination and classification scheme, was incorporated into the examination of the relationship between precipitation type and surface/upper-air parameters. This scheme has two major goals: 1) description of group separation and 2) prediction of group membership. To quantify group separation, linear functions of the variables were used to elucidate group differences by identifying each variable relative contribution to group separation. In the next step, linear or quadratic functions were used to classify individual observations into one of the groups. [Rencher (1995) provides a complete description of discriminant analysis.]

To reduce bias during the development of the DAMP model while using all of the available data, the robustness of discriminant functions was checked using cross-validation. Cross-validation treats $n - 1$ out of n observations as a training set, develops the discriminant functions based on these $n - 1$ observations, and applies them to classify the remaining observation for n iterations. This method should achieve a nearly unbiased estimate. The model's performance was evaluated by examining the resulting classification probabilities (e.g., probability of detection and false alarm ratios). Probability of detection (POD) is the ratio of the number of correct forecasts to the total number of observations, by precipitation type in this research. The false alarm ratio is the number of correct forecasts divided by the total number of forecasts.

Although there is a constant need for increased spatial and temporal resolution in atmospheric research, many dynamic parameters are easily calculated from simple sounding data. However, a trade-off inherent in many predictive statistical analyses, as well as discriminant analysis, is limiting the number of variables to those that are informative without compromising degrees of freedom, overfitting the model, or introducing multicollinearity. In this study, various techniques were explored in the processes of variable selection and maximization of precipitation type separation. Inspecting bivariate graphs and performing discriminant analysis in stepwise mode, specifically to examine standardized coefficients and calculate partial r squares, were crucial tools for determining the most important predictor variables.

Even though several resulting variable combinations showed adequate ability to separate and predict precipitation types, simply entering the critical variables and running discriminant analyses on the entire dataset provided no improvement over existing models. The primary problems with the initial approaches were that the

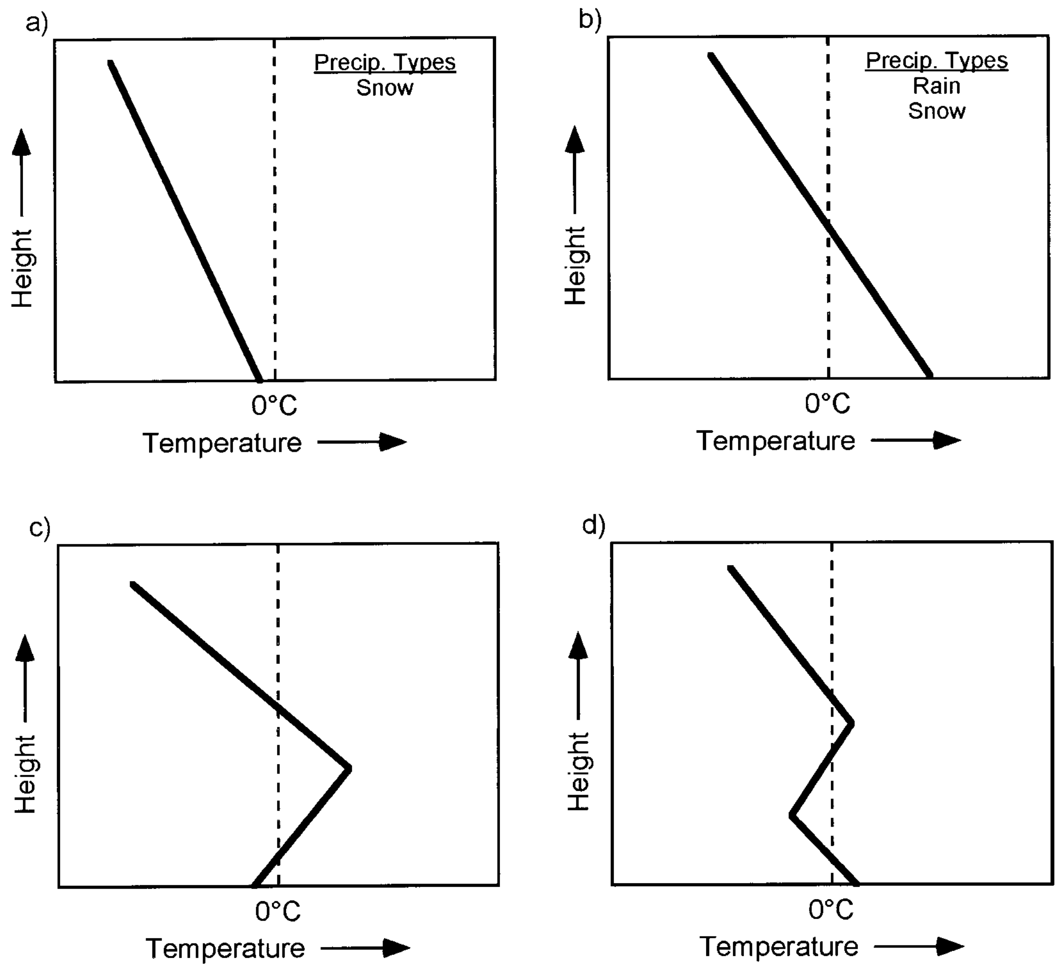

FIG. 2. The four vertical temperature profiles associated with winter precipitation types. Note that the precipitation type that occurs most often is indicated by the larger font.

number of observations of rain far exceeded observations of other precipitation types, many of the variables that were useful discriminators and predictors were also highly correlated (muticollinearity), and the resulting models were ''black boxes.'' Isolating easy and difficult forecasting situations seemed impossible.

To circumvent these problems, a new methodology was designed that differed from previous research. Though still making use of the high-resolution multivariate data, this approach no longer required the incorporation of many variables into the statistical analyses. Using some basic meteorology, the upper-air data were combined to create vertical temperature profiles for each observation of precipitation type. These profiles were then separated depending on the number of freezing levels (i.e., the number of times the sounding crossed the 0°C isotherm) and examined to determine if they could be used to isolate specific precipitation types and as a result segregate winter precipitation scenarios by forecasting difficulty. Discriminant analysis was used to further separate and classify observations within each scenario if categorizing the profiles failed to isolate precipitation types.

3. Results and discussion of the DAMP model development

There are four basic temperature profiles during the winter for both Greensboro (GSO) and Washington Dulles Airport (IAD)—zero, one, two, and three or more freezing level(s) (Fig. 2). Each of these profiles produces characteristic types of precipitation (snow, freezing rain, freezing rain mix, and rain). Note that pure ice pellets were not included as a precipitation type, and, as a result, the models were not trained on pure ice pellets, since they occurred infrequently and were largely nondisruptive when compared with freezing rain in the region. From an operational perspective, it is more important to correctly forecast any precipitation, whether pure or a mix, that contained freezing rain or pure snow than to correctly forecast pure ice pellets. Unlike other precipitation types, ice pellets prove difficult to isolate

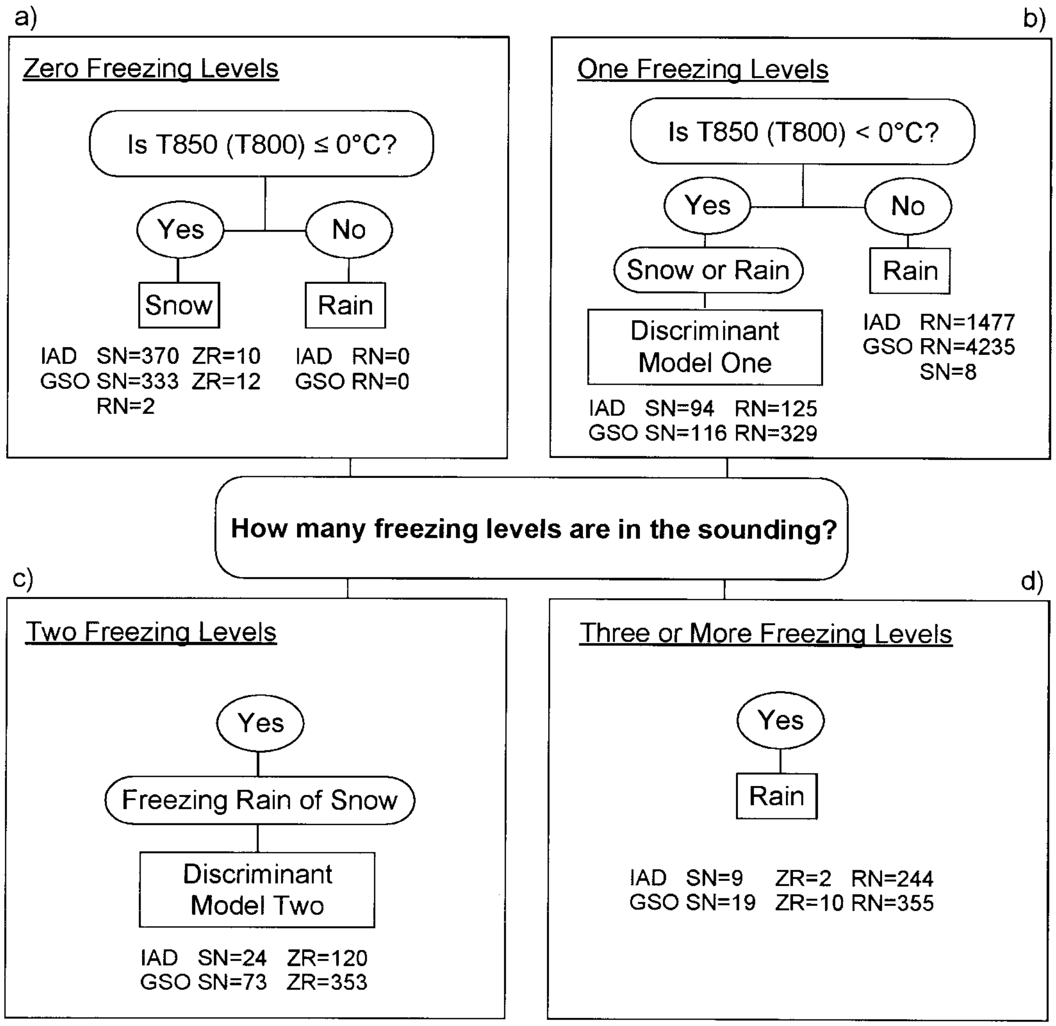

FIG. 3. The DAMP model decision tree for Washington Dulles Airport (IAD) and Greensboro (GSO). The trees are identical for both stations with the exception of the number of observations of each precipitation type (RN = rain, ZR = freezing rain, and SN = snow) isolated by each scenario, and that the critical temperature (denoted in parentheses) is different for Greensboro.

(Keeter and Cline 1991; Bocchieri 1980; Czys et al. 1996; Zerr 1997). Whereas the majority of observations of other precipitation types could be isolated to one or two sounding types, the observations of ice pellets were evenly distributed through each scenario. Additionally, the statistical analyses could rarely predict the occurrence of ice pellets and tended to include ice pellets with the precipitation type that had the most observations within each profile. That, in turn, weakened the models' abilities to correctly predict the other precipitation types.

Site-specific models (decision trees) were then built by separating the vertical temperature profiles into the four different freezing level categories and performing statistical analyses within each category (Fig. 3). The trees showed the forecaster the decisions that are made during execution of the model. A complete discussion of the DAMP model for Washington Dulles Airport follows; Greensboro is mentioned when the models were different.

a. Zero freezing levels

The decisions made by the DAMP model in the no freezing levels category (Fig. 2a) do not require the use of discriminant analysis. To forecast precipitation type in this section of the model, the only variable required was a temperature from somewhere in the sounding to determine whether the entire atmospheric column was warmer or colder than 0°C. The 850-hPa temperature (IAD) and 800-hPa temperature (GSO) were selected for this purpose because these temperatures (subsequently referred to as the critical temperatures) were the most important for discrimination in the one crossing and two crossing parts of each model and were, for simplicity, used in this situation.

In the zero freezing level category, there were no winter precipitation cases where the entire sounding (1000–500 hPa) was warmer than 0°C for either station (Fig. 3a). Conversely, when the entire column was 0°C or colder at IAD, two precipitation types were observed—snow ($n = 370$) and freezing rain ($n = 10$). The results for GSO were similar (333 observations of snow and 12 observations of freezing rain) except that two observations of rain entered this grouping. These observations of snow represented 74.4% and 60.0% of all the snow cases observed at IAD and GSO, respectively. As a result, the criteria for membership in this category were very effective in the isolation of snow. While other types of precipitation do occur in this scenario, the DAMP model was trained to forecast snow that ''climatologically speaking'' occurred 97.4% (IAD) and 96.0% (GSO) of the time.

While the two rain observations at GSO were likely due to observational or measurement errors, there were several possible explanations for the occurrence of freezing rain when the entire column is below freezing. The most likely culprits are a shallow moist layer that does not extend to the level where dendritic growth is possible (temperatures of $-12°$ to $-15°C$), supercooled water making it to the surface, or a combination of both. Czys et al. (1996) and Zerr (1997) both noted that if the hydrometeors are relatively small, then freezing drizzle could occur even if the entire sounding was colder than 0°C because cloud and fog droplets (diameter $< 100\ \mu m$) have very low freezing probabilities. The methodology incorporated by Huffman and Norman (1988) successfully segregated these SWRP cases using sounding moisture and temperature variables. However, SWRP occurred more often (30%–40%) at the stations in their research. Freezing precipitation in an entirely subfreezing atmosphere accounted for only 0.4% of all cases and 8.7% of freezing rain cases for IAD (0.2% and 3.5% for GSO). Therefore, since SWRP requires the use of moisture variables not incorporated into other nodes of the DAMP models and the number of SWRP cases were few, that distinction was not made in the current research.

b. One freezing level

The one freezing level grouping included soundings where the surface temperature was greater than 0°C, became subfreezing at some point above the surface, and remained sub-freezing (Fig. 2b). For IAD and GSO, 1697 and 4688 observations enter this section of the model. This is approximately 69% and 80%, respectively, of all observations. Again, in this part of the DAMP model the first decision to make was whether the critical temperature was greater than or less than 0°C. Over the 33 yr of IAD observations, when the critical temperature was higher than 0°C (Fig. 3b) the only type of precipitation observed was rain ($n = 1477$). This was nearly 80% of all the rain cases for IAD. Likewise, for GSO a critical temperature greater than 0°C isolated 4235 rain cases (86%) and only eight snow observations (Fig. 3b). The likelihood of receiving rain in this scenario was 99.8%. As a result, the IAD and GSO DAMP models were both programmed to forecast rain in this situation—a decision made using climatology rather than discriminant analysis.

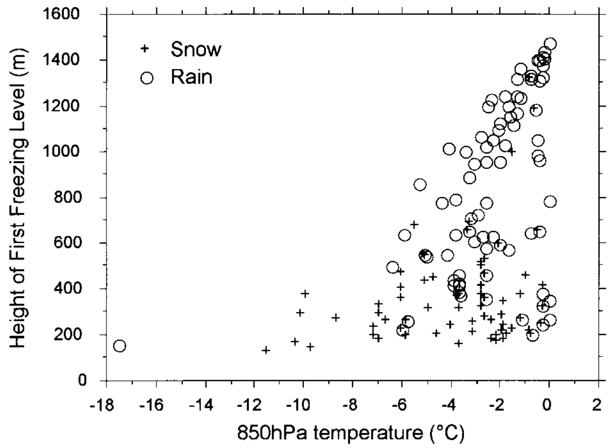

FIG. 4. The interaction of the height of the freezing level and the 850-mb temperature and the separation of precipitation type. These are the variables used by discriminant analysis in the one freezing level situation of the IAD DAMP model to distinguish between precipitation types. The equation that specifies the separation of the precipitation types is determined by discriminant analysis and this figure is intended to show the degree of complexity for this case. Note that only rain and snow occur in this scenario.

However, if the critical temperatures were subfreezing, then 125 (329) rain and 94 (116) snow cases resulted at IAD (GSO) (Fig. 3b). Since both rain and snow were common in this instance, discriminant analysis was used to resolve the precipitation type. The variables that the models required for the analyses were as follows: 1) the critical temperature and 2) the height of the freezing level. For IAD if the 850-hPa temperature was greater than $-7°C$ and the freezing-level height was greater than 600 m, rain was almost certain (Fig. 4). Alternatively, snow was the most likely result if the temperature was less than $-7°C$ and the freezing level was less than 600 m. However, there was considerable overlap in precipitation type when the temperature was greater than $-7°C$ and freezing-level height was less than 600 m. For GSO the cutoff where the occurrence of rain was almost certain appeared to be 800-hPa temperature and freezing-level height warmer than $-7°C$ and 900 m (Fig. 5), while the snow probability increaseed for 800-hPa temperature and freezing-level height colder than $-7°C$ and 900 m. The area of uncertainty was when temperature was warmer than $-7°C$ and the freezing level was less than 900 m. Obviously this situation would be moderately difficult for a forecaster to resolve because of the regions of uncertainty. But, by implementing discriminant analysis, precipitation type POD within this

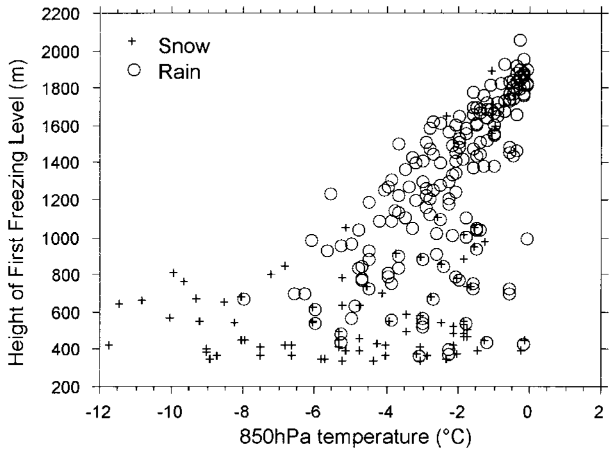

FIG. 5. The interaction of the height of the freezing level and the 800-mb temperature and the separation of precipitation type. These are the variables used by discriminant analysis in the one freezing level situation of the GSO DAMP model to distinguish between precipitation types. The equation that specifies the separation of the precipitation types is determined by discriminant analysis and this figure is intended to show the degree of complexity for this case. Note that only rain and snow occur in this scenario.

section of the model were 81.8% and 87.4% correct for IAD and GSO (Tables 1 and 2).

c. Two freezing levels

The two freezing level category (Fig. 3c) isolated nearly all the occurrences of freezing rain during the period of record for IAD (120 observations or 91%) and GSO (353 observations or 94%). Along with the freezing rain, there were 24 observations of snow that accounted for about 5% of all the snow hours for IAD. The 73 observations at GSO represented 13% of the total snow observations. The DAMP models incorporated discriminant analysis in this situation to distinguish between precipitation types. The variables determined to be the best predictors were the critical temperature and the heights of the first and second freezing levels. The critical temperature at this level (i.e., 850 hPa for IAD and 800 hPa for GSO) tended to fall between the two freezing levels and, as a result, this critical

TABLE 1. Classification results for Washington Dulles Airport DAMP model node 1. This is the one freezing level case when the 850-mb temperature is below 0°C. The overall percentage classified correctly is 81.8% (incorrectly is 18.2%). Correct percentages (in bold) are in the form of PODs. The percentages for incorrect values are false alarm ratios (FARs).

	Forecast		
Observed	Snow	Rain	Total
Snow	**76 (78.3%)**	18 (19.1%)	94
Rain	21 (16.8%)	**104 (85.2%)**	125
Total	97	122	219

TABLE 2. Classification results for Greensboro DAMP model node 1. This is the one freezing level case when the 800-mb temperature is below 0°C. The overall percentage classified correctly is 83.6% (incorrectly is 16.4%). Correct percentages (in bold) are in the form of PODs. The percentages for incorrect values are FARs.

	Forecast		
Observed	Snow	Rain	Total
Snow	**89 (75.4%)**	27 (23.3%)	116
Rain	29 (8.8%)	**300 (91.7%)**	329
Total	118	327	445

temperature was a good indicator of the amount of warm air available for melting.

For IAD, the 850-hPa temperature was the most important predictor—only freezing rain was observed above 2°C (Fig. 6). This distinction is not so clear for the 800-hPa temperature for GSO. Freezing rain occured between −4° and 9°C and snow between −9° and 7°C (Fig. 7). The interaction between the height of the first and second freezing level showed that freezing rain occurred if the height of the lower freezing level was less than 1000 m while the second freezing level was greater than 1000 m for both GSO and IAD (Fig. 8).

Without the aid of a model, that is a very difficult forecast, because the solution cannot be resolved in two dimensions (i.e., in each bivariate pairing, there are considerable regions of uncertainty). But, by incorporating discriminant analysis to examine the data in multidimensional space, the separation between precipitation types increased. The results of the discriminant analyses at this node showed that freezing rain was forecast correctly 85.8% and 87.1% of the time for IAD and GSO, respectively (Tables 3 and 4). The GSO DAMP model

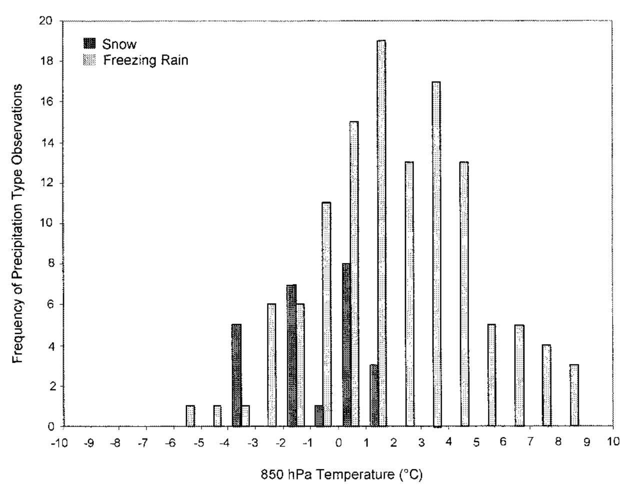

FIG. 6. The frequency distribution of snow and freezing rain for 850-mb temperatures in the IAD DAMP model's two freezing level node. The equation that specifies the separation of the precipitation types is determined by discriminant analysis using this critical temperature along with the height of the two freezing levels. This figure is intended to show the degree of complexity for this case. This critical temperature is very important for predicting precipitation type.

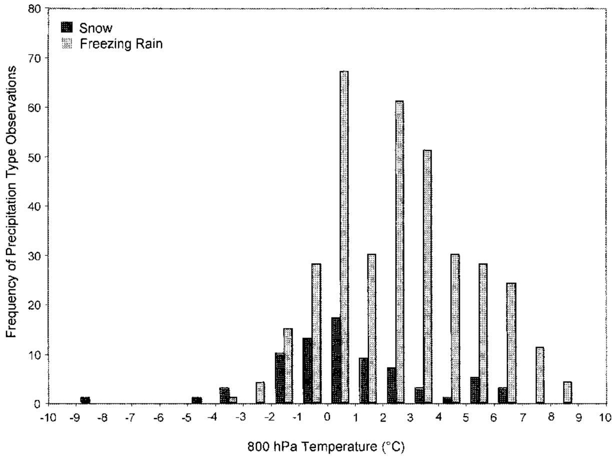

FIG. 7. The frequency distribution of snow and freezing rain for 800-mb temperatures in the GSO DAMP model's two freezing level node. The equation that specifies the separation of the precipitation types is determined by discriminant analysis using this critical temperature along with the height of the two freezing levels. This figure is intended to show the degree of complexity for this case. This critical temperature is one of the variables used by discriminant analysis to predict precipitation type.

correctly predicted snow in 73.3% of the cases (Table 4). Although, snowfall forecasts within this part of DAMP were correct only 50% of the time for IAD (Table 3), very little snow occurred under these conditions and the increased ability to predict freezing rain far outweighed the ramifications of missing snow.

d. Three or more freezing levels

The final nodes of the DAMP models were the three or more freezing level cases. Only 10.3% of the IAD precipitation observations (6.1% of the GSO observations) occurred when there were three or more points in the vertical temperature profile that crossed 0°C (Fig. 3d). Again, climatology influenced the decisions the DAMP models were programmed to make under this scenario. In this three-crossing case the DAMP models were forced to predict rain because it occurred 96% and 93% of the time for IAD and GSO, respectively.

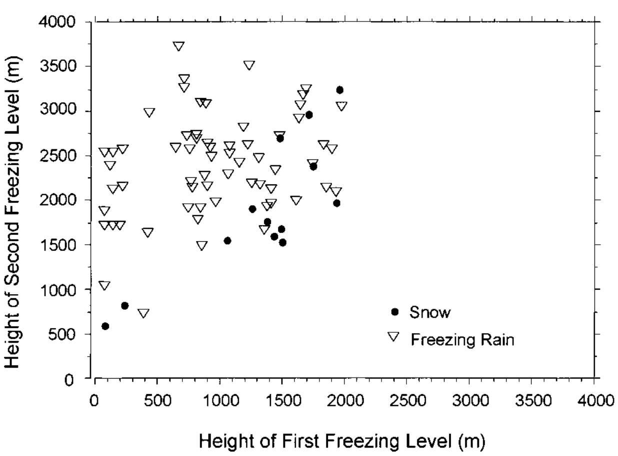

FIG. 8. The interaction of the height of the first and second freezing levels in the separation of precipitation type. These are the variables used along with critical temperature by discriminant analysis in the two freezing level situation for both DAMP models to distinguish between precipitation types. The observations presented here are from IAD. Note that only rain and snow occur in this scenario.

TABLE 3. Classification results for Washington Dulles Airport DAMP model node 2. This is the two freezing level case. The overall percentage classified correctly is 67.9% (incorrectly is 32.1%). Correct percentages (in bold) are in the form of PODs. The percentages for incorrect values are FARs.

	Forecast		
Observed	Snow	Rain	Total
Snow	**5 (50.0%)**	19 (79.2%)	24
Freezing rain	5 (4.2%)	**115 (85.8%)**	120
Total	10	134	144

e. Overall DAMP model performance

The overall classification performance results for both DAMP models indicated that a high percentage of correct precipitation type forecasts may be achieved by dividing the observations into the various profiles and as a result isolating distinct precipitation types (Tables 5 and 6). Rain forecasts were approximately 98% correct for both models. The IAD DAMP model snow forecasts were 92.6% correct and freezing rain forecasts were 85.8% correct (Table 5). Snow and freezing rain forecasts were 89.7% and 87.1% correct, respectively, for the GSO DAMP model. Neither model ever forecasts freezing rain when rain actually occurred. Further, the results indicated that when freezing rain was actually observed, the models missed the forecast by predicting rain in only 0.1% and 0.2% of the cases for IAD (Table 5) and GSO (Table 6), respectively. From an operational and public safety point of view, these results are important because the occurrence of freezing rain when rain is the forecast is very dangerous. Fortunately, the DAMP model performs very well in such disruptive and hard-to-predict situations.

TABLE 4. Classification results for Greensboro DAMP model node 2. This is the two freezing level case. The overall percentage classified correctly is 80.2% (incorrectly is 19.8%). Correct percentages (in bold) are in the form of PODs. The percentages for incorrect values are FARs.

	Forecast		
Observed	Snow	Rain	Total
Snow	**22 (73.3%)**	51 (69.8%)	73
Freezing rain	8 (2.3%)	**345 (87.1%)**	353
Total	30	396	426

TABLE 5. The overall classification results for the Washington Dulles Airport DAMP model. Correct percentages (in bold) are in the form of PODs. The percentages for incorrect values are FARs.

	Forecast			
Observed	Snow	Rain	Total	Observed
Rain	**1825 (98.4%)**	0 (0.0%)	21 (1.1%)	1846
Freezing rain	2 (1.5%)	**115 (85.5%)**	15 (11.1%)	132
Snow	27 (5.45%)	19 (3.8%)	**451 (92.6%)**	497
Total	1854	134	487	2475

TABLE 6. The overall classification results for the Greensboro DAMP model. Correct percentages (in bold) are in the form of PODs. The percentages for incorrect values are FARs.

	Forecast			
Observed	Snow	Rain	Total	Observed
Rain	**4890 (98.7%)**	0 (0.0%)	31 (0.63%)	4921
Freezing rain	10 (2.7%)	**345 (87.1%)**	20 (5.3%)	375
Snow	54 (9.8%)	51 (9.3%)	**444 (89.7%)**	549
Total	4954	396	495	5845

4. The operational use of the DAMP models

The final DAMP model is made up of a set of discriminant equations that, given a set of input parameters, output the probability of each of three precipitation types (snow, rain, freezing rain). The models take the form of a computer program that prompts users to enter the values of the required input variables that they have previously retrieved from the numerical forecast model (Eta, Meso-Eta, NGM, etc.) soundings or grids. The input parameters/variables are the height(s) of the observed crossing(s) and the critical temperature (850 hPa for IAD or 800 hPa for GSO). When these are entered, precipitation type probabilities are then output. Although the DAMP model is not built to forecast precipitation type over time, the duration of each category can be determined by successively applying the DAMP model to the output of each time step of any forecast model.

The DAMP model's dependence on the model output in an operational forecasting mode is known as a ''perfect prog'' approach—one that assumes that the model output/prognosis is perfect. An inherent problem with this approach is that errors in the numerical models enter DAMP. If the modeled heights and temperatures are identical to the observed heights and temperatures, then DAMP's performance should be unaffected. Alternatively, if the numerical forecast models are erroneous, several outcomes are possible depending on the degree to which the models depart from the actual observations and whether they occur in the borderline regions (in multidimensional space) between precipitation types. The DAMP precipitation type prognosis can be correct if the error in the numerical forecast model is within the resolution of DAMP. DAMP will be wrong if the modeled heights and temperatures erroneously output heights and temperatures that are associated with another precipitation type or if the error is outside of DAMP's resolution. The degree to which these errors effect the DAMP models' results will vary from model run to model run and must be assessed by the operational forecaster.

The DAMP model and a testing procedure were delivered to the Wakefield, Virginia, Weather Forecast Office in December 1998. During the 1998–99 winter season there were only eight mixed precipitation events and only one that was particularly disruptive and fell into the difficult forecast category. Although there were too few events to test the full effectiveness of the model, there is no reason to believe that the operational performance should deviate from developmental performance. The equations incorporated into DAMP were built upon thousands of observations, and cross-validation created stable and nearly unbiased relationships. Since, so few events occurred during the test period, any statistical analysis would not be robust in comparison to the results from model development (with observations in the hundreds and thousands depending on precipitation type). The following discussion is intended to address how the operational forecaster perceived DAMP. It is a qualitative, rather than quantitative, assessment of the model in an operational environment.

NWS forecasters incorporated the model output into their forecast discussions for each event during the 1998–99 winter season. The model predicted the precipitation type correctly in seven of the eight events. In every case the correct prediction was made 48 h before the event occurred. In the one event that was missed, the DAMP model forecast rain while freezing rain was observed; however, 1 h after the valid forecast time the observed freezing rain switched to rain and remained rain for the rest of the event. The DAMP model predicted precipitation type and duration during the 23–24 December 1998, ice storm in Virginia with 95% confidence (probability guidance), using model output for several remote locations (e.g., Charlottesville, Richmond, and Norfolk) in addition to IAD and GSO. That storm, which caused one of the largest power outages in Virginia history, left more than 380 000 Virginia Power customers without electricity, many went without power for more than a week. Although this highly successful DAMP forecast is interesting to note, this result must be replicated many times before DAMP's accuracy as a general model can be determined. However, if the models continue to perform in this manner, we can expect to be more prepared for mixed precipitation events in the future.

5. Conclusions

The methodology incorporated into the Discriminant Analysis Mixed Precipitation model development used a combination of climatology and discriminant analysis to create a very effective winter precipitation type forecasting tool, providing winter precipitation type guidance in a region where such forecasts are very difficult. Freezing level height(s), vertical temperature profiles, and basic meteorology are entered to resolve the forecasts of snow, rain, and freezing rain.

The DAMP models made better use of the available data and provided the ability to isolate and provide the forecaster with guidance in the form of POD for each precipitation type in scenarios where predicting precipitation type was normally a very difficult decision. That represents a major advantage over other current techniques. These multidimensional, physically based models proved easy for the forecaster to use: the model-decision-making process was easy to follow in virtually every case. Most important, the models did an outstanding job of predicting precipitation type and duration in mixed precipitation events. Besides achieving very high correct prediction rates for the precipitation types modeled, the most noteworthy advantage of the DAMP models was that they rarely missed the forecast of freezing rain—of particular importance for the credibility of the operational forecast.

Although the DAMP models were developed for locations (GSO and IAD) where upper-air data and surface data were collocated, very preliminary results indicated that they may retain a high degree of accuracy when applied at other locations in similar climatological regions. The IAD DAMP model has been successfully applied to events occurring in Piedmont and Tidewater locations in Virginia and North Carolina. The GSO DAMP model was suitable for higher-elevation stations in the Blue Ridge Mountains and foothills. However, because the site-specific nature of the models could present problems when applied at remote locations, future research must examine and attempt to correct this complication.

Another complication with the DAMP model that is also common to other current generation models was its inability to isolate and therefore forecast pure ice pellets. Future iterations of this model will address this problem by attempting to identify the parameter(s) that isolate ice pellets from other types of winter precipitation.

In addition to correcting problems, more refinements are planned for future iterations of the DAMP model. The first of these refinements is to determine if there are some unexplored variables that may help improve the model. Incorporation of upper-level winds and moisture variables are being considered as a possibility. Another change that may help improve the DAMP model is to identify a critical temperature (e.g., maximum or minimum temperature in certain layers) that is no longer tied to a pressure surface but perhaps to some other dynamic feature. Additionally, further automation of the DAMP models that allows for direct incorporation of numerical weather model output will provide for easier use by the operational forecaster.

Acknowledgments. This research was conducted under the Cooperative Program for Operational Meteorology, Education, and Training (COMET) Grant UCAR SS96-73653. Special thanks are extended to the Wakefield National Weather Service Forecast Office staff for their comments regarding the project and for numerous interactions that allowed us to become more familiar with the winter forecast process from their perspective, and to Robert E. Davis for his statistical advice, insight concerning winter weather, and suggestions regarding the direction of the project.

REFERENCES

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

Bocchieri, J. R., 1980: The objective use of upper air soundings to specify precipitation type. *Mon. Wea. Rev.*, **108,** 596–603.

Bourgouin, P., 1992: Criteria for determining precipitation types. *Proc. Fourth Workshop on Operational Meteorology,* Whistler, BC, Canada, AES/CMOS, 460–469.

Brooks, C. F., 1920: The nature of sleet and how it is formed. *Mon. Wea. Rev.,* **48,** 69–73.

Czys, R. R., R. W. Scott, K. C. Tang, R. W. Przybylinski, and M. E. Sabones, 1996: A physically based, nondimensional parameter for discriminating between locations of freezing rain and sleet. *Wea. Forecasting,* **11,** 591–598.

Fisher, R. A., 1936: The use of multiple measurement in taxonomic problems. *Ann. Eugen.,* **7,** 179–188.

Gay, D. A., and R. E. Davis, 1993: Freezing rain and sleet climatology of the southeastern USA. *Climate Res.,* **3,** 209–220.

Glahn, H. R., and J. R. Bocchieri, 1975: Objective estimation of the conditional probability of frozen precipitation. *Mon. Wea. Rev.,* **103,** 3–15.

Huffman, G. J., and G. A. Norman Jr., 1988: The supercooled warm rain process and the specification of freezing precipitation. *Mon. Wea. Rev.,* **116,** 2172–2182.

Keeter, K. K., and J. W. Cline, 1991: The objective use of observed and forecast thickness values to predict precipitation type in North Carolina. *Wea. Forecasting,* **6,** 456–469.

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

Koolwine, T., 1975: Freezing rain. M.S. thesis, Dept. of Physics, University of Toronto, 92 pp.

Lemon, P. C., 1961: Forest ecology of ice storms. *Bull. Torrey Bot. Club,* **88,** 21–29.

Maglares, G. J., J. S. Waldstreicher, P. J. Kocin, A. F. Gigi, and R. A. Marine, 1995: Winter weather forecasting in the eastern United States. Part I: An overview. *Wea. Forecasting,* **10,** 5–20.

Martner, B. E., J. B. Snider, R. J. Zamora, G. P. Byrd, T. A. Niziol, and P. I. Joe, 1993: A remote-sensing view of a freezing-rain storm. *Mon. Wea. Rev.,* **121,** 2562–2577.

Marwitz, J., M. Politovich, B. Bernstein, F. Ralph, P. Neiman, R. Ashenden, and J. Bresch, 1997: Meteorological conditions associated with the ATR72 aircraft accident near Roselawn, Indiana, on 31 October 1994. *Bull. Amer. Meteor. Soc.,* **78,** 41–52.

Michaels, P. J., P. J. Stenger, P. C. Knappenberger, and D. E. Stooksbury, 1991: Virginia ice storms. *Southeast. Climate Rev.,* **2,** 11–17.

Musick, D. R., 1991: A case study of a prolonged sleet event 16–17 February 1987 and a climatology of sleet events for North Carolina 1949–1989. M.S. thesis, Dept. of Marine, Earth, and Atmospheric Sciences, North Carolina State University, 61 pp.

Pandolfo, J. P., 1957: An objective method for forecasting precipitation type during the winter months at New York City. *Bull. Amer. Meteor. Soc.,* **38,** 571–574.

Rasmussen, R., and Coauthors, 1992: Winter Icing and Storms Project (WISP). *Bull. Amer. Meteor. Soc.,* **73,** 951–974.

Rencher, A. C., 1995: *Methods of Multivariate Analysis.* John Wiley and Sons, 296–349.

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

Robbins, C. C., and J. V. Cortinas, 1996: A climatology of freezing rain in the contiguous United States: Preliminary results. Preprints, *15th Conf. on Weather Analysis and Forecasting,* Norfolk, VA, Amer. Meteor. Soc., 124–126.

Wagner, A. J., 1957: Mean temperature from 1000 to 500 mb as a predictor of precipitation type. *Bull. Amer. Meteor. Soc.,* **38,** 584–590.

Zerr, R. J., 1997: Freezing rain: An observational and theoretical study. *J. Appl. Meteor.,* **36,** 1647–1661.