6.2 POST-PROCESSING WEATHER PREDICTION MODEL OUTPUT IN THE UNITED STATES NATIONAL WEATHER SERVICE: MODEL OUTPUT STATISTICS FROM 1972 TO 2012

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1. INTRODUCTION

Two events significant to the development of post-processing weather prediction model output began and ended 1972. In January, a probability of precipitation (PoP) forecast product valid over the conterminous United States (CONUS) replaced a subjective product made by forecasters at the National Meteorological Center (NMC). This new product was developed by application of the Model Output Statistics (MOS) approach and was the first MOS product valid for the entire CONUS. While development of the MOS approach had been initiated in the late 1960's, the December 1972 paper by Bob Glahn and Dale Lowry (Glahn and Lowry 1972b) defined MOS and demonstrated that post-processing the output of numerical weather prediction models would improve public and aviation weather forecasts.

Within the National Weather Service (NWS), NMC (later reorganized in 1995 as the National Centers for Environmental Prediction or NCEP) was responsible for the development and implementation of the numerical weather prediction models. However, the creation of MOS, subsequent refinements, and development of operational guidance products were the responsibility of the NWS's Techniques Development Laboratory or TDL (later reorganized and renamed the Meteorological Development Laboratory (MDL) in 2000).

In this paper, we review four decades of post-processing development done within TDL/MDL. The focus is on weather guidance products relevant to the public and aviation community. Section 2 of the paper reviews background important to the reader's understanding. Section 3 describes computer limitations that hindered post-processing during the 1970's through the 1990's – barriers that seem foreign to a user of weather guidance in the 21st century. Sections 4 – 14 concentrate on different eras of model guidance. Finally, Section 15 provides the author's personal reflection.

2. BACKGROUND

Both NMC/NCEP and TDL/MDL underwent organizational restructuring during the four decades discussed in this document. For the sake of continuity and ease of understanding references in other documents, we have attempted to use the organizational name or acronym appropriate at the time the particular model or guidance product was implemented.

The focus is on public and aviation weather guidance products. Included are forecasts of maximum (max) and minimum (min) temperature; air temperature and dewpoint at the 2-m observing height; wind speed and direction at the 10-m anemometer height; cloud cover and ceiling height; precipitation occurrence and amount; types of precipitation (liquid, freezing, or frozen) during winter events; snow amount; visibility; and obstructions to vision. During the 1970's and early 1980's, TDL developed a number of specialized MOS products in response to internal NWS requirements or requests from external users. These products included forecasts of convective wind gusts; marine winds; max/min temperatures, vertical temperature soundings, precipitation occurrence, and precipitation amount for the Bonneville Power Administration; tower wind profiles for the Savannah River Laboratory; air temperature, evapotranspiration, soil temperature, and sunshine for agricultural weather interests; solar energy and sunshine; and aircraft turbulence. While these guidance products were quite innovative, most were eliminated by the mid-1990's as requirements changed and will not be discussed here.

In this paper, we have emphasized development of guidance for forecast projections of 60 h or less. In the 1970's, numerical weather prediction (NWP) was in its infancy, and NWP models tended to focus on projections of two days or less. During this era, the NWS released official public weather forecasts twice daily at approximately 0900 to 1000 UTC and 2100 to 2200 UTC. Sometimes, a late-morning update forecast was issued. The early morning and late afternoon release times enabled official forecasts to be available for publication in the next issue of the daily newspaper or for use in the morning or evening television news programs. Table 1 shows the standard time for the NWS forecasts of public weather. Note that the nominal forecast projection tended to fit the definition of valid periods for forecasters in the Eastern Time Zone. A forecaster in the Mountain or Pacific Time Zones would need to adjust the forecast to conform to the local day or night period.

Several other factors help in understanding the emphasis on the development of "short-range" guidance products during the 1970's and 1980's. First, the forecast issued to the public at 2100 UTC for the "day after tomorrow" was often termed the "outlook" for that day and was less credible than forecasts for the three earlier periods. Secondly, the public forecast at 0900 UTC for "tomorrow night" might not even be mentioned in a radio or television broadcast. Thirdly, with limited computer resources, NMC was restricted in its ability to run a model from 0000 UTC initial conditions to predict the weather a week

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Table 1. Standard valid periods of the NWS public weather forecasts during the 1970's, 1980's, and much of the 1990's. The column denoted "Fcst. Issued" indicates the approximate time that the local forecasters issued their forecast.

Fcst. Issued	Valid Period	Nominal Fcst. Projection
0900 UTC	Today	12-24 h after 0000 UTC
	Tonight	24-36 h after 0000 UTC
	Tomorrow	36-48 h after 0000 UTC
	Tomorrow Night	48-60 h after 0000 UTC
2100 UTC	Tonight	12-24 h after 1200 UTC
	Tomorrow	24-36 h after 1200 UTC
	Tomorrow Night	36-48 h after 1200 UTC
	Day after Tomorrow	48-60 h after 1200 UTC

or more in advance. These factors meant that TDL's work focused on short-range forecasts. Some limited guidance was, however, developed for the 3- to 5-day projections to support "medium-range" forecasting.

The deadlines for issuance of a local forecast meant that a surface observation of 0800 or 2000 UTC was the latest available for a scheme to post-process NMC model output and transmit the guidance to local forecasters. Was enough time available for the observation to be decoded, used in a post-processing scheme, transmit the resulting guidance product to the local forecast office, and enable the human forecaster to process the information? TDL often decided on developmental procedures according to the "best" estimate of when the product generation software might run operationally.

During the 1970's, as MOS products became operational, dissemination of the guidance encountered serious obstacles. Communications of alphanumeric products took place through the Kansas City Weather Message Switching Center (WMSC), a facility operated by the Federal Aviation Administration (FAA). These products were sent to teletype machines; transmission speeds were rated in terms of hundreds of bauds (a baud being one bit per second). Bandwidths were small, particularly in light of modern standards that consider transmission speeds in terms of megabytes per second. Alphanumeric bulletins were limited in the NWS by restricting quantity and types of statistical forecasts to be transmitted.

Graphics displaying MOS guidance during the 1970's and early 1980's were transmitted via facsimile machines. Products were sent at a scheduled time. As a general rule, few, if any, open slots existed in the schedules. Usually, addition of a new product required removal of an older one. Relatively few MOS products were available in graphical form until the 21st century.

Computer resources (Section 5) were also limited. The net result of these various constraints slowed development of post-processing. Implementation of new products faced hurdles, and dissemination of those products often called for innovative solutions and trade-offs between competing products. What seems strange or convoluted today was normal in the environment of the 20th century.

3. A NEW POST-PROCESSING APPROACH -- MOS DEFINED, TESTED, AND IMPLEMENTED

At the first AMS conference on statistical meteorology, Bob Glahn presented a new approach to post-processing objectively forecasts from NWP models (Glahn and Lowry 1968). He noted that statistical and dynamical approaches to weather forecasting should be merged, despite a history of growing independently of each other. While "classical" and "perfect prog" approaches had been tried with varying degrees of success, what became known as MOS was described thusly: "*The predictand is related statistically to the variables actually produced by numerical models. This method builds in the biases and inaccuracies of the numerical model and for predictive purposes seems to be the most desirable of the three methods. However, development of these relationships requires a history of the numerical model forecasts, and for the technique to be useful the numerical model should have undergone little change during the period over which the historical sample was collected and still be essentially the same when the technique is used.*"

In June 1966, NMC implemented a 6 layer primitive equation (6LPE) model (Shuman and Hovermale 1968) on a CDC 6600 computer. At first, the 6LPE made forecasts out to 36 h, but by October 1969, the model generated forecasts to 48 h twice daily, and TDL began to archive model output. Two features of the 6LPE were noteworthy. First, the 6LPE fields were available at initial model time (0000 UTC and 1200 UTC), and at 12-h forecast intervals to the end of the model run. Secondly, the 6LPE surface boundary layer was 50 hPa in depth or roughly 500 m. With a lack of temporal and vertical resolution in the numerical model, a statistical interpretation system could add information to the forecast process.

Two years later, in June 1968, TDL implemented the Sub-synoptic Advection Model or SAM (Glahn et al. 1969) that generated forecasts at hourly resolution and with a spatial resolution approximately ¼ that of the 6LPE. SAM was designed to use the latest surface observations as initial conditions. With output from these models, TDL began testing the MOS concept. The MOS acronym first appeared in 1969 (Glahn and Lowry 1969) in a technical memorandum describing development and testing of statistical regression equations to predict the probability of precipitation (PoP). The development of MOS PoPs from a combination of the SAM and 6LPE models was so successful that the first operational MOS facsimile product, namely, PoPs for the eastern United States, was implemented in February 1969. By May 1969, MOS PoPs for 79 stations were available in alphanumeric format on the Service "C" teletypewriter circuit. More details about SAM and the contributions of the model to development of the MOS concept can be found in Glahn (2020). Since SAM was run only over the eastern U.S. and only for projections of 1 to 17 h after the latest available surface observation, the model had limited applicability for generating PoPs beyond the first period of the public forecast.

The landmark paper by Glahn and Lowry (1972b) summarized much of the work done to develop the SAM/PE MOS approach. Efforts to develop SAM/PE equations were focused on objective forecasts of PoP, wind direction and speed, max temperature, cloud amount, and conditional probability of frozen precipitation. Equations for predicting PoP, surface wind, and frozen precipitation were eventually developed, tested, and implemented. For relatively brief durations, operational guidance products were generated from these equations. However, the primary contributions of the Glahn and Lowry paper were to establish MOS as a viable post-processing technique, to demonstrate rudimentary developmental guidelines for MOS work, and to note both optimism and caution about the value of combining the NWP models with a statistical interpretation of model output.

3.1 Regression procedure for developing forecast equations

Multiple linear regression was the approach first used. In the TDL MOS application, the dependent variables or predictand data (local weather observations) were correlated to independent variables (predictors) obtained from an NWP model, previous surface observations, and geographical or climate information. Multiple least squares linear regression, specifically the forward selection screening technique, was applied to obtain the relationship between the predictand and predictors. The resulting equation was of the form:

$$\boldsymbol{Y} = a_0 + a_1X_1 + a_2X_2 + \ldots + a_kX_k.$$

$\boldsymbol{Y}$ is the estimate of the predictand variable, k represents the number of predictors in the equation, a_0 is the regression constant, a_i (i=1,…,k) are the regression coefficients, and X_i (i=1,…,k) are the predictors. The regression coefficients were obtained from the developmental sample by minimizing the mean square error between the estimate of the predictand and the actual value. This process maximized the reduction of variance, another measure of the goodness of fit of the regression equation. The first predictor selected was the variable that gave the greatest reduction of variance. The next predictor selected was the variable responsible for the greatest additional reduction of variance when combined with the first predictor. The process continued until a user-specified number of terms were included in the equation, or until no variable remaining in the set of potential predictors added a user-specified amount to the reduction of variance.

If the predictand can only be one of two states, for instance, precipitation or no precipitation, then the predictand can be expressed mathematically as 1 for precipitation or 0 for no precipitation. In this case, the regression equation gives an approximation of the relative frequency of precipitation, that is, the PoP, when the predictors take on their combined values. In the original PoP development, all predictors were binaries, that is, values of 0 or 1, depending on whether the value of the predictor exceeded a user-specified cutoff or not. Miller (1964) called this Regression Estimation of Event Probabilities (REEP). In this procedure, probability can be negative or exceed 1.0.

When the predictand is an observation of an event like cloud cover that can take on x states (for example, clear, scattered, broken, or overcast), then the predictand can be expressed as x binary variables, each of which is set to 0 or 1. As before, individual probabilities can be negative or exceed 1.0. However, if the same predictors were used in the x equations, then the sum of the probabilities equals 1.0. For multiple predictands, the screening algorithm was modified so that predictors were selected on the basis of maximizing the additional reduction of variance for any one of the predictands. The chosen predictor was then used in the equations for all predictands, though the coefficients were calculated independently for each predictand.

3.2 General guidelines for MOS development

The work described in Glahn and Lowry (1972b) established standards that were followed by other MOS developers until better solutions were adopted. For instance, in the initial PoP development, all predictors were binary variables. Separate PoP equations were developed for three periods, namely, 1200-1800 UTC, 1800-2400 UTC, and 1200-2400 UTC. Unlike later PoP developments, the equations for the two 6-h periods and the 12-h period were developed independently of one another. Though the authors desired to develop individual equations for each station (single-station approach), the small developmental sample precluded this method. Instead, a "generalized-operator" equation was developed in which predictors and predictands for all stations were combined into one sample, one equation was developed for each projection, and then each equation was applied to every station for which PoP was desired. The unique predictor values at for each site meant that the PoPs were also unique. The quality of the PoP guidance, as with all MOS developments, was established by comparing MOS PoPs to some standard reference, in this case forecasts made by NMC or local forecasters. The developmental sample was divided into two seasons, defined as summer (April – September) and winter (October – March). While the nomenclature was later modified to refer to warm and cool seasons, respectively, the concept of using seasonal stratification for MOS development was established.

The development of MOS equations for wind direction and speed established several other principles. First, a dependent sample of approximately 200 cases at each station was deemed sufficient to develop single-station MOS wind prediction equations. Second, since wind direction is expressed in degrees from due north, direction represents a circular function going from 0 to 360. While a wind of 350 degrees and a wind of 10 degrees are only separated by 20 degrees, this relationship is not easily represented by linear regression. Wind direction can, however, be represented by the u (east/west) and v (north/south) vector components, and separate equations were developed for the u and v components. Forecasts of u and v were then used to predict wind direction. Third, while wind speed can be calculated from MOS forecasts of the u- and v-wind components, Glahn (1970) showed that this estimate of the wind speed, on average, underestimated the actual wind speed. Thus, a separate MOS relationship was developed for wind speed. Fourth, the latest available station observation of the wind was an important predictor for the MOS equations. Fifth, specific geostrophic wind variables from the SAM model judged important to predicting wind speed and direction were forced into MOS regression equations as predictors to enhance consistency between the model and guidance. Lastly, MOS forecasts generated from an independent data sample were verified and compared to those made subjectively for the aviation terminal forecasts. The verifications showed the usefulness of the MOS technique.

Initial efforts to predict calendar day max temperature ("today's" max) via MOS were made from output variables of the 0700 UTC SAM and the 0000 UTC 6LPE model. Developmental data were stratified into warm and cool seasons, and multiple linear regression equations were developed for each season and each station. Initial testing began in April 1969 and continued until September 1971. The MOS max temperature equations were updated every 6 months prior to testing on the forthcoming warm or cool season. Both continuous and binary variables were included as possible predictors. Though tests were conducted on a small sample of stations, several important conclusions resulted from the study. First, the optimal number of predictors in the forecast equations was eventually set to 10. Second, the MOS max temperature forecasts exhibited monthly biases over a season. Use of the first harmonic (cosine and sine) of the day of the year as potential predictors removed most of this bias. Third, not all of the bias was eliminated; the authors speculated that some bias could have been due to changes made to the 6LPE over the period that the developmental sample was collected. Lastly, the MOS system was comparable in accuracy to the perfect prog Klein-Lewis temperature guidance (Klein and Lewis 1970), but was less accurate than the official max temperature forecasts.

Work in developing a MOS system to predict cloud amount had just begun when Glahn and Lowry (1972b) was written. In initial work on clouds, single-station multiple linear regression equations were developed from a coded predictand indicating total cloud cover, that is, clear, partial obscuration, thin scattered, scattered, thin broken, broken, thin overcast, overcast, or obscured. The predictand observations were valid at 1200, 1500, 2100, and 2400 UTC, and predictors included the latest available surface observation (0700 UTC).

Finally, some development on predicting the conditional probability of frozen precipitation (PoFP(P)) had occurred. The predictand was taken from a subset of the developmental data, namely, cases when precipitation was occurring at a specified hour. The primary predictor in the forecast equations was a variable indicating the probability of frozen precipitation occurring as a function of the predicted 1000 – 500 hPa thickness. Using predictor variables derived from model output and representing physical processes important to the occurrence of the predictand became quite common in MOS development. All other predictors were binary variables, and the generalized operator approach was used to develop the forecast equations. In testing on independent data, Glahn and Lowry noted a bias in the PoFP(P) probabilities. The authors speculated that a change made in the 6LPE during the developmental sample could have been responsible.

In the early 1970's, work on forecasting ceiling height was also underway (Bocchieri and Glahn 1972). Other MOS developmental principles were adopted. For instance, the idea of using predictors valid only at the predictand site became the standard. In the nascent developmental and operational MOS system, the complexity of using predictors from a network of stations was not justified by verification results. In the MOS system, forecast model fields were archived on a grid and then interpolated to a station for use in regression. This feature allowed manipulation of model forecasts, such as smoothing or creating derived variables during the developmental process, rather than making decisions about predictor variables as model data were archived.

While multiple linear regression was to be used for predicting ceiling height, small samples and the rarity of low ceilings meant that developmental data were pooled and that development of generalized-operator equations was necessary. The question as to the type of predictors to use was not settled; experiments were conducted with various combinations of observations and forecasts from the 6LPE and SAM models. Since ceiling height is a quasi-continuous variable, the predictand definition was not obvious either. Two approaches were tested. In one, equations were developed simultaneously to predict the probabilities of five mutually exclusive and completely exhaustive categories of ceiling height. A separate equation was derived for each category; the same predictors were used in each equation, but the coefficients and constants varied among equations. The categorical forecast was selected from the predicted probabilities by an appropriate algorithm. In the second approach, the ceiling height was transformed by a function designed to emphasize the lower ceiling heights, and the transformed value was treated as a continuous variable. Either the REEP approach or standard regression was applied to develop forecast equations for the binary or continuous predictand, respectively.

Development and testing focused on ceiling height forecasts valid at 1200, 1800, and 2400 UTC, which represented 5-, 11-, and 17-h projections, respectively, from the SAM start time. In what became a standard model for TDL developers, the verification on independent data was designed to:

- determine the optimal number of predictors;
- select the optimal combination of observed and model predictors;
- choose the predictand definition that best fit user needs;
- compare the objective forecasts with an appropriate standard; and
- determine the best approach for transforming probabilities into categorical guidance.

Extensive tests on predicting ceiling heights showed that the best approach to choosing a categorical forecast depended on the verification score being used to evaluate the guidance. For instance, maximizing percent correct was not beneficial if some categories represented rare events. In this case, the bias[1] became a concern. The developer needed to select a meaningful verification score and tune the categorical system accordingly. Eventually, a "utility matrix" was created to produce biases between 0.98 and 1.02 for ceiling height. An iterative "trial and error" approach was used to obtain this minimum bias matrix. The practice of minimizing bias in categorical guidance products was widely adopted within TDL, but the challenge of selecting a categorical forecast from probabilities was a recurring issue.

The Glahn and Lowry paper (1972b) summarized the MOS approach, use of screening regression, and development of rudimentary PoP, wind, and max temperature guidance from the SAM/6LPE models. Eventually, more extensive MOS guidance in terms of elements and national coverage became available, but the effort that went into developing the prototype operational MOS system laid the groundwork for what was to follow and showed that MOS was a valuable prediction tool, particularly when probabilities were needed. In general,

- the predictand definition was critical;
- sample sizes determined whether single-station or generalized-operator equations were developed;
- probabilities could be used to generate categorical guidance;
- predictors from both model forecasts and station observations were effective;
- equations should sometimes be developed simultaneously for multiple predictands;
- equations should be updated seasonally.

Some evidence was presented to indicate that 6LPE model changes may have affected the quality of the MOS guidance. The last paragraph of the paper summarized future challenges that faced TDL in developing methods to post-process output from numerical weather prediction models: *"Progress in objective weather forecasting within the next few years will come through the combining of numerical and statistical models. Due to the development of new, and the modification of old, numerical models, data samples containing numerical model output are a perishable commodity. Therefore, considerable prior planning and organization will be necessary in the operational implementation of MOS products*."

4. THE MOS SYSTEM INFRASTRUCTURE

By the early 1970's, the MOS approach was the method of choice for providing objective guidance from the combination of numerical and statistical models. As noted in Section 3, a formal organization of software and data bases was necessary for efficient implementation of MOS products. TDL became successful in MOS development and implementation because digital data bases were established and quality-controlled, software was written in a systematic and documented fashion, and TDL staff members used their meteorological expertise to develop and improve guidance products within an established framework.

Bob Glahn had done much of the early programming and testing of statistical concepts within TDL. After NMC implemented the 6LPE model on the CDC 6600 computer, this machine hosted initial TDL model and observational databases, MOS developmental programs, and operational processes. Bob Glahn led the effort to create the software and archives, writing most of the developmental software and concentrating on MOS development from the SAM and 6LPE models. With the creation of

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[1] Bias is defined as the number of categorical forecasts (F) of the event relative to the number of observed events (O), that is, the bias equals F/O. A desirable or "minimum" bias is 1.0.

other NWP models such as the TDL Atmospheric Trajectory (AT) model (Reap 1972), MOS equations relied on both the 6LPE and AT models. At this point, a unified developmental structure with standardized software was necessary. The need for databases, archive processes, software, and developmental procedures to be thoroughly documented was also evident. The MOS system on the CDC 6600 is described in Glahn (1973b).

In 1972, NMC began testing numerical weather prediction models on a new IBM 360/195 mainframe computer. The IBM mainframe had a distinct word architecture and operating system. Facing the removal of the CDC machine, TDL staff converted all programs and archives to run on the IBM computer. A revised and enhanced MOS system was established on the IBM 360/195 by 1974 (Glahn 1974). For the next 20 years, this MOS system (later designated as MOS-1974) was the foundation of NWS MOS guidance. While the MOS system was frequently modified, the basic architecture remained unchanged.

The introduction to the MOS-1974 manual described what MOS is, why a system was essential, and how the documentation was to be maintained. Chapter IV listed the models for which grid point archives were established. When NMC implemented new models, TDL established archives to extract subsets of the model grid and output variables. Chapter VI of the manual described surface observation data obtained from the National Climatic Data Center (NCDC). In the early years of MOS, these observations provided nearly all predictand variables. Hourly observations recorded at 3-h intervals from 0000 UTC to 2100 UTC at approximately 260 sites in the United States were available. NCDC had done quality-control on the observations. Because quality of observations was critical to the success of MOS, TDL did subsequent quality-control via a mix of automation and human judgment.

The TDL hourly observation archive (Chapter X) begun in December 1976 deserves special mention. This archive became one of the most essential databases in TDL. Early in MOS development, the value of hourly, rather than 3-h, surface observations was recognized. These observations were needed for all available stations with as much of the meteorological information as could be saved. On the IBM 360/195, NMC had established hourly files containing all the surface aviation reports (SA's) that reached NMC. Files of synoptic reports were also available. A project was established within TDL to access the NMC files and save the data in a suitable format. After the archive was established, a team of TDL meteorologists and programmers worked to create a thorough quality-control procedure for the data. Encoding of the hourly SA's was not always done properly, reporting standards were not consistently followed, the meaning of some reports was ambiguous, precipitation amounts were sometimes not reported though precipitation had occurred, reports sometimes indicated unrealistic meteorological conditions, and so forth. The extensive automated quality-control process that ensued was critical to later development of statistical guidance products. In subsequent years, as TDL expanded the network of MOS stations, refined predictand definitions, and embarked on new projects to generate guidance valid at hourly resolution, the hourly data archive proved invaluable.

A standard format for MOS program write-ups and a lab-wide requirement to document software made the TDL software documentation (Glahn et al. 1975) an essential reference for every MOS developer. In 1979, Bob Glahn issued software standards (Glahn 1979a) that every TDL employee was to follow. These standards prescribed internal program documentation, use of variable names, and so forth. The rationale for standards was summarized thusly: "*The objectives of the TDL standards are to enhance clarity, testability, maintainability, and person-to-person and computer-to-computer transferability of software throughout its life cycle.*"

The importance of the MOS infrastructure can't be over-emphasized. New employees, many with little or no statistical background, were hired for the MOS effort. Within 6 months, these employees were trained and could productively develop and test MOS products with some degree of confidence. The development and implementation of new products were possible because a defined path was available to define predictands and test ideas. The quality-control of both model and observational databases meant that a developer was reasonably confident that developmental data were correct. Error rates in developing and implementing operational products were minimized. Cooperative education students came to TDL and assisted senior-level meteorologists in developing new products. In short, TDL had a productive environment for developing and implementing statistical guidance.

5. COMPUTER RESOURCES

During the early years of MOS, computer resources were scarce and primitive by modern standards. DiMego et al. (2004) documented the processing speed of NWS computers during the 1900's and early 2000's. When the IBM 704 was bought in 1957, peak processing speed (floating point operations per second or flops) was 8 Kflops. In 1960, the IBM 7090 increased this to 67 Kflops. In 1963, a speed of 100 flops was reached with the IBM 7094. In 1966, the CDC 6600 had a speed of 3 Mflops. Finally, in 1972, the IBM 360/195 reached speeds of 18 Mflops. For comparison, in 2014 a new supercomputer at the University of Maryland was capable of 300 trillion (300 teraflops) operations per second (M. Weil 2014) – a speed approximately 100 million times faster than the CDC 6600 on which the first MOS system was developed.

Programming until the late 1970's was done on punched cards. Control information used as input to programs was created by key-punching data on input cards. For years, disk storage space was either unavailable to developers or was rationed. Programs were stored in decks of cards. A careless computer operator could undo weeks of development work by dropping a deck of cards on the terminal room floor. When disk storage space became available, quantities were small. Disks were mounted on a spindle as needed. If an operator was unavailable, the user's program could not run. Time-sharing devices which allowed a developer to program directly on the computer without punch cards were unavailable until the IBM 360/195 had been installed and adequate disk storage had been obtained.

Archives needed for MOS development were stored on magnetic tape. A tape contained 40 to 140 Mbytes, according to tape density and length. Length was often variable, especially if a tape had been broken and repaired. Tapes could be broken or mishandled by operators. Stories abounded about tapes going bad after a certain length of time.

Since NWS computers were first and foremost for weather prediction and operational products, computer usage was restricted. With the advent of the IBM 360/195, a queuing system was established for developmental jobs. Jobs that required small amounts of memory, short runtime, and no external resources were first in the queue. Jobs that required large amounts of memory, long runtimes, and external resources were last. In this environment, a small job was defined as one that required 256 Kbytes of memory. The maximum amount of memory available was 600 Kbytes. Compare that with the standard desktop computer available today with 4 or more Gbytes of memory.

For a MOS developer, checkout or compilation of a development job might require 256 Kbytes of memory and 1 minute or less of runtime. Usually, the turn-around for such a job was within a day. A MOS regression program that developed equations for a large number of sites might not run until a weekend had passed. It was not uncommon for a developer to submit a job on Monday morning and receive the results the subsequent Monday!

6. PEATMOS – THE GROWTH OF MODEL POST-PROCESSING

By the early 1970's, with the MOS infrastructure in place and the 6LPE model twice daily producing forecasts of the atmospheric circulation out to 48 h in advance, TDL began developing MOS guidance for the public weather forecast periods described in Table 1. Because SAM was limited in its geographical and temporal coverage, SAM-based MOS products were eliminated in September 1973. However, as noted earlier, the three-dimensional atmospheric trajectory (AT) model (Reap 1972) had been implemented in response to an NWS mandate to improve forecasts of convective weather. Using output from the PE model, the AT model generated forecasts of temperature, dew point, stability, and net vertical displacement out to 24 h in advance for the CONUS. The AT fields became another possible source of predictor information for the MOS system, and the PEATMOS acronym was born.

Implementation of PEATMOS weather guidance began in 1972 and continued throughout the 1970's. At the same time, NWS efforts to modernize operations meant changes in computer resources and numerical weather prediction models; MOS weather guidance evolved to keep pace with changing requirements. By December 1973, the 6LPE was running operationally on the IBM 360/195. By November 1975, three IBM machines were available for operations and development. In January 1978, the 6LPE would be modified to have a mesh length of 190.5 km and a seventh layer, and would be run operationally over the Northern Hemisphere to a forecast projection of 84 h from 0000 and 1200 UTC initial conditions. The model was then designated the 7LPE.

In 1971, NMC implemented the Limited-area Fine-mesh Model (Howcroft and Desmaris 1971) to generate guidance earlier in the forecast cycle. In its physics and numerics, the LFM was similar to the 6LPE model but with a grid mesh length of 190.5 km, instead of 381 km. The LFM ran over a smaller area than the approximately hemispheric 6LPE, and LFM boundary conditions were controlled by the 6LPE. For a few years, the LFM produced forecasts out to 24 h. By early 1975, the LFM was producing forecasts for projections out to 36 h, and, by early 1976, LFM forecasts were available twice daily to 48 h. The operational LFM ran significantly earlier than the 6LPE. With increased accuracy over the CONUS compared to the 6LPE, particularly during the first 36 h of the forecast period, the NWS decided that the regional LFM would become the primary model for the earlier forecast projections while the 6LPE/7LPE would be the numerical model for the extended forecast periods. Thus, by the mid-1970's, the LFM became available for use in MOS development. The presence of both the 6LPE and LFM resulted in a diverse blend of MOS products being implemented in the later years of the 1970's.

The evolution of MOS products during the 1970's is confusing. For that reason, the discussion in the rest of Section 6 is restricted to PEATMOS products. Section 7 is devoted to products generated during the transition from PEATMOS to LFM MOS.

6.1 Probability of Precipitation (PoP)

The first PEATMOS facsimile chart for the CONUS was implemented in January 1972 (NWS 1971) for 12-h PoP ending 24, 36, 48, and 60 h after initial model time. This product replaced subjective NMC PoPs. The chart was a four-panel graphic issued twice daily at 0721 and 1921 UTC. Figure 1 shows one of the PoP panels. In NWS 1971, two items were noteworthy. First, the fact that the graphic was produced twice daily for four periods "allows a 12-hr backup for each of the first three periods" in case of machine failure. Secondly, information was provided to the forecaster so that he/she could use the PoP guidance in an intelligent fashion.

Lowry and Glahn (1976) described testing that went into developing PEATMOS PoP equations. The predictand was defined to be the occurrence of liquid-equivalent precipitation of 0.01 inches or greater during the 12-h period ending 24, 36, 48, or 60 h after the initial model times of 0000 or 1200 UTC. Observations were available as predictands from 234 stations in the CONUS. The REEP procedure was used to relate the predictand to model predictors. The resulting MOS equations gave the probability of the precipitation event occurring. Seasonal stratification of developmental data meant that equations were developed for both warm (April-September) and cool (October-March) seasons. If possible, operational equations were redeveloped before the start of a 6-mo season.

At first, one year of data (October 1969 – March 1970) was available for development, with testing being done on the October 1970 – March 1971 period. Only one cycle of model forecasts, namely 0000 UTC initial time, was used for derivation of the prediction equations; however, the same equations were applied to both cycles for test purposes. The regionalized-operator approach was used, that is, data were pooled for all the stations in a relatively homogeneous region, and one equation was developed for that region for each projection. Regions were selected subjectively after considering the relative frequency of the precipitation event, given a certain value of 6LPE relative humidity forecasts. Predictor variables on the archive grid were modified by 5-, 9-, 13-, or 25-point spatial smoothers before interpolation to each station. More smoothing was applied as the forecast projection increased.

As additional seasons were added to the developmental sample, equations were developed for both 0000 and 1200 UTC cycles. The developmental regions became smaller so that prediction equations were better tuned to the stations. An error introduced in the 6LPE in October 1969 caused a dry bias in the model; the error was corrected in September 1970 (NWS 1970). Data for the October 1969 – September 1970 period were eliminated from testing and development. By October 1972, PoP equations were available for each cycle, the list of binary predictors had expanded to include multiple cutoffs, and timing biases in the 6LPE model meant that binary predictors offered to the regression were valid at multiple times for the same predictand projection. By the warm season of 1973 (NWS 1973c), tests showed that 12-term PoP prediction equations were optimal. The warm season of 1975 (NWS1975b) saw the expansion of the predictor list to include continuous and binary predictors as well as the sine and cosine of the day of the year. This evolutionary development of PoP, particularly the effort to redevelop the MOS equations before the start of each cool or warm season, was a prototype for development of other MOS products. The idea of adding more data, decreasing the size of the regions for development purposes, and making useful adjustments to the predictor list drove implementations during the 1973 – 1975 period.

6.2 Conditional probability of frozen precipitation – the logit model

The logit curve was introduced to the MOS system (Glahn and Bocchieri 1975) with the development and implementation of guidance to predict the *conditional* probability of frozen precipitation (PoFP(P)). The predictand in this case was the occurrence of either snow or sleet (ice pellets) at a specific hour, ***conditional*** on the occurrence of precipitation being reported. This definition required that all non-precipitation cases be eliminated from the developmental sample. MOS equations were developed for specific hours, namely, 12, 24, 36, and 48 h after both 0000 and 1200 UTC. Precipitation reports from approximately 234 sites in the CONUS were available in the developmental sample.

The logit technique (Brelsford and Jones 1967, Jones 1968) was used in the PoFP(P) development in two ways. First, 50% values at each of the stations in the developmental sample were estimated from 6LPE model output of 1000-500 hPa thickness, 850-hPa temperature, and boundary layer potential temperature. These 50% values represented the value of a meteorological quantity at which the chance of frozen precipitation occurring in a precipitation event was 50%. The 50% value was found by fitting an S-shaped curve (the logit curve) to the 6LPE model forecasts and the occurrence or non-occurrence of frozen precipitation. In this process, Y was the dependent variable (1, for frozen precipitation; 0 for non-frozen), X was the independent variable (the 6LPE model variable), and the probability of Y was expressed by:

$$P\{Y=1|X\} = (1+\exp(a+bX))^{-1}.$$

The logit model estimated parameters a and b by maximum likelihood. Once the logit curve was known, then solution of the equation for X when the probability was 50% (X = -a/b) yielded the 50% value. This value provided station-specific information; the logit equation gave a simple, one variable estimate of the probability of frozen precipitation from any value of X. Because 50%

values were developed for each station and the sample of model data was small, 6LPE model forecasts for projections valid at 0600, 1200, 1800, and 0000 UTC were pooled for the derivation. Only about 186 stations in the dependent sample had enough reports to estimate these 50% values.

The second application of the logit model came in combining predictors to form a prediction equation with multiple variables. The logit program did not select predictors by screening. Hence, a set of variables was selected by the developer for each projection, differences from the 50% values were computed for the 6LPE model variables, and then these deviations along with the station elevation and the sine/cosine of the day of the year were used as predictors. Multiple projections of the 6LPE variables were included for each guidance projection. The developmental data for all stations were pooled and one generalized-operator equation of the form:

$$P\{Y=1|X_1,X_2,\ldots,X_n\}=(1+\exp(a+b_1X_1+b_2X_2+\ldots+b_nX_n))^{-1} ,$$

was derived to predict the probability of frozen precipitation. Categorical guidance was determined by selecting the category (frozen, non-frozen) with the highest probability. Unlike probabilities generated from regression equations, logit-based probabilities were inherently constrained between 0.0 and 1.0.

The first PoFP(P) system was implemented in November 1972. At that time, the probabilities were available (NWS 1972) as dashed isopleths on hand-drawn PoP facsimile charts (not shown). New “Service C” teletype bulletins (FOUS12) containing the PoP and PoFP(P) for 152 sites in the CONUS also became available twice daily at approximately 0720 and 1920 UTC. In December 1972, the PoP/PoFP(P) became computer-drawn (Fig. 2). Symbols representing the prediction of snow or liquid precipitation were plotted at station locations when the PoP was $\geq$ 45%. Snow was predicted when PoFP(P) exceeded 50%. In February 1973, new PoFP(P) equations developed from an additional year of dependent data were implemented (NWS 1973a).

In February 1976 (NWS 1976e, Bocchieri and Glahn 1976), the PoFP(P) system (now designated PoF) was again updated. Major changes included the addition of two more winter seasons of 6LPE output to the dependent sample, the inclusion of the 1000–850 hPa thickness as a potential predictor, availability of additional observations (0300, 0900, 1500, and 2100 UTC) to derive 50% values for four variables predicted by the 6LPE model (the same three variables used in the original development plus the 1000-850 hPa thickness), a better method for selecting predictors to be included in the logit prediction equations, and addition of 18-, 30-, and 42-h projections to the list of the original four predictand projections (12, 24, 36, and 48 h after 0000 and 1200 UTC). Tests comparing the REEP approach to the logit technique showed that logit produced more accurate guidance. However, the REEP approach could be used as a first guess for the appropriate predictors in the logit process. In this PoF development and implementation, the generalized-operator approach was used so that only 14 equations were necessary to produce the guidance for two cycles and seven projections.

6.3 Maximum/minimum temperatures

Some mention of the “perfect prog” approach used within the NWS for many years is relevant before discussing the implementation of PEATMOS max/min temperature guidance. In the K-L perfect prog method (Klein and Lewis 1970), specification equations were developed to relate the observed max or min temperature to **observed** or **analyzed** atmospheric conditions like upper-air heights or temperatures. In operations, these specification equations were applied to **forecast** output from an NWP model. In contrast, MOS equations related a meteorological variable like observed max temperature to **predicted** variables from an NWP model. These equations were applied to **forecast** output from the same or nearly the same model. The latter approach seemed inherently more accurate because MOS accounted for certain systematic model biases, model predictability of atmospheric variables, and the decrease in model skill with increasing projection.

In September 1968, perfect prog forecasts of max/min temperature were first disseminated in a teletype bulletin for 131 stations in the conterminous U.S. (Klein and Lewis 1970). The max/min temperature guidance was valid for periods approximately 24 to 60 h in advance. As in MOS development, perfect prog equations were developed by multiple linear regression and from data stratified by season. Unlike the MOS approach, a field or network approach was used to obtain the predictors for the equations; a predictor for a particular station may have been atmospheric conditions hundreds of miles away from the station of interest. Both max and min temperature specification equations were developed from observations that lagged the nominal time of occurrence of the max or min.

The K-L perfect prog system had one interesting advantage over MOS. Since only one set of equations was developed for the max and one set for the min, these equations were used at both forecast cycles and for any appropriate forecast projection. In operations, observations were replaced by model forecasts (both the numerical model and the prior perfect prog max or min forecast) as the forecast projection increased. This “bootstrap” approach meant that the perfect prog forecast system could be used for longer-range projections as long as appropriate variables were available from the NWP model. The bootstrap method meant that in later years MOS forecasts could be substituted for the K-L perfect prog forecasts when appropriate or useful.

In August 1973, following unsuccessful attempts to improve the perfect prog max/min system (Klein and Marshall 1973) and experiments showing the superiority of MOS max/min guidance (Klein and Hammons 1975), the NWS implemented MOS max/min temperature guidance for the same four projections (Table 1) available in the perfect prog system. Similarly, MOS max/min temperatures were valid for local calendar day (midnight to midnight, local time). Unlike PoPs, PoF, and earlier SAM/PE MOS efforts, MOS max/min temperature equations (Klein and Hammons 1975) included 0000 and 0600 UTC or 1200 and 1800 UTC observations (according to the forecast cycle) as potential predictors for the first forecast period. Model predictors for all four projections included 6LPE and AT variables. The AT variables were exclusively 24-h forecasts. The 6LPE variables were valid at 12, 24, 36, and 48 h after initial model time with the exception of precipitable water valid at 18, 30, and 42 h after initial model time. All model variables were smoothed with either a 5- or 9-point smoother. The sine and cosine of the day of the year were included to represent the annual variation in the normal max/min temperature. Ten-term equations were optimal, and the new MOS system generated max/min guidance for 228 sites in the CONUS, a substantial increase over the 131 stations in the K-L system. Equations were developed for both warm and cool seasons. Because observations were used at most stations as predictors for the first period guidance, the possibility existed that during daily operations predictor observations for MOS stations were missing. This potential glitch necessitated the development of two sets of guidance equations for the first projection, that is, a primary set using all potential predictors including observations, and a secondary or backup set using only model and climatic predictors.

The operational output of the PEATMOS max/min guidance system underwent a number of changes after the initial August 1973 implementation. At first, max/min guidance for 135 stations was transmitted on NWS Service C in the FMUS1 bulletin. Forecasts for another 93 stations were available in the FOUS 28 message sent on the FAA's WMSC Request/Reply circuit; the guidance for the other 135 sites was also available on this circuit. By February 1975, the format of the max/min temperature bulletin on Service C was modified to combine the temperature forecasts with the MOS PoP and PoF forecasts (NWS 1974d). The new bulletin now called FOUS12 (Fig. 3) eliminated the need for the other bulletins.

A four-panel facsimile chart displayed a mixture of the MOS max/min guidance (135 sites in the CONUS) and the K-L perfect prog guidance (5 sites in the CONUS and 11 cities in southern Canada). By October 1974, the computer-generated isotherms on this chart depended on analysis of MOS guidance at 228 sites and the K-L guidance at 16 sites (NWS 1974b).

In August 1975, additional 6LPE data enabled development of max/min equations for 3-mo seasons (spring (March – May), summer (June – August), fall (September – November), and winter (December – February)), and resulted in improved guidance (Hammons et al. 1976). Extensive testing had led to substantive changes in potential predictors, including the addition of observations as predictors for the second valid period (approximately 24-36 h after initial model time) and use of both first and second harmonics of the day of the year to capture seasonal trends in temperature. A 25-point smoother was applied to many of the model predictors, particularly when 48-h model forecasts were being used to predict the fourth period max or min temperature. The predictand was still the calendar day max/min, and 10-term equations remained optimal.

6.4 Surface winds

For winds, MOS equations developed from the 6LPE model were first implemented in May 1973 (NWS 1973b, Carter 1975) and were available for 233 stations in the FOUS22 bulletin on the Service A request/reply circuit. Guidance was valid at 12, 18, 24, 30, 36, 42, and 48 h after 0000 or 1200 UTC. The 0600 or 1800 UTC observations were included as potential predictors for the 12-h projection. Inclusion of observations as predictors necessitated the development of backup equations that used only model predictors and climatic terms. Model predictors included forecast variables that influenced surface winds such as winds in the low and mid troposphere and atmospheric stabilities. The sine and cosine of the day of the year and twice day of the year were included to simulate seasonal variation in wind speed. The developmental sample was divided into warm (April – September) and cool (October – March) seasons. Unlike earlier work with surface winds, the MOS equations were developed simultaneously for both the u- and v-wind components **and** the wind speed. This simultaneous derivation meant that predictors in the forecast equations for the three predictands (u, v, and speed) at a specified projection were the same, though the equation coefficients and constants differed. For this development, the 6LPE boundary layer wind components and speed valid at the same time as the predictand were forced to be the first three predictors in the equations. All equations were single-station and contained ten terms.

Early experience showed that strong winds were underforecast by MOS. In December 1973, a post-processing procedure was implemented to compensate for this bias (NWS 1973e). The procedure considered two MOS estimates of wind speed, namely, speed directly from the MOS equation and speed estimated from the vector sum of the u- and v-wind components. The greater of the two speeds was selected as the MOS forecast. This approach helped, but did not eliminate the problem.

In May 1975 (NWS 1975c), new wind equations were implemented. Five years of 6LPE data were available as a developmental sample, additional variables were screened as potential predictors, 12-term single-station equations became the standard, and forcing of predictors was eliminated. A new post-processing technique was also introduced to compensate for the underforecasting of the high wind speeds. The "inflation" technique had been used many years earlier with perfect prog temperatures. In the wind application, MOS forecasts of wind speeds greater than the developmental mean were increased, while those forecasts less than the developmental mean were decreased. The net result was that more strong winds were predicted with only minor changes in the overall root mean square errors.

6.5 Cloud amount

Development of MOS cloud guidance was a vexing problem because a categorical forecast needed to be obtained from the cloud probability forecasts. In 1973 (Glahn 1973a), single-station multiple regression equations were developed to predict probabilities of clear, scattered, broken, or overcast at projections of 18 and 30 h after 0000 and 1200 UTC, respectively. Predictors came from the 6LPE and AT models. Transformation of probabilities into categorical forecasts depended on the verification score assessing the utility of the forecast to the user; for clouds, maximizing the percentage correct was the goal. In this development, however, clear and overcast conditions were overforecast, that is, the bias (number predicted/number observed) was > 1.0 while scattered and broken clouds were underforecast (bias < 1.0). This undesirable characteristic was ameliorated by using a minimum bias matrix to transform the probabilities. Probabilities of clear, scattered, broken, and overcast were multiplied by values of 0.84, 1.20, 1.04, and 0.94, respectively, and the categorical forecast was the predictand category with the greatest transformed probability.

In 1974 (NWS 1974c, Carter and Glahn 1976), PEATMOS cloud guidance was implemented for the 12-, 18-, 24-, 30-, 36-, 42-, and 48-h projections after both 0000 and 1200 UTC. Single-station equations were developed from 5 years of data for about 233 CONUS sites. The dependent sample was divided into the now standard warm and cool seasons. The predictand was taken from the station's total sky cover observation roughly divided into categories of clear (clear, partial obscuration or thin scattered), scattered (scattered), broken (thin broken, broken, or thin overcast), and overcast (overcast or obscured). Equations were developed simultaneously for four binary predictands corresponding to these categories; for each category, the predictand was equal to 1 if that cloud category was reported, and was 0, otherwise. The same predictors were included in each of the four equations, but the coefficients and constant in each equation differed. The sum of the four probabilities generated from these equations equaled 1.0; however, the raw probabilities were not constrained to be $\geq$ 0.0 or $\leq$ 1.0. In the derivation of the equations, both binary and continuous predictors were used. For the 12- and 18-h projections, the latest surface observations (0600 or 1800 UTC) were included as potential predictors. Model predictors included forecasts of atmospheric moisture, temperature, stability, and winds; the model fields were smoothed by 5- 9- or 25-point smoothers according to the model forecast projection. The sine and cosine of the day of the year were also included as climatic variables. The use of observations as potential predictors for 12- and 18-h projections meant that backup equations with only model and/or climatic variables were necessary.

Categorical forecasts were obtained from the probabilities with the goal of maximizing the percent correct forecasts. Selecting the cloud category with the highest probability as the categorical cloud guidance was tried. Again the MOS guidance underforecast scattered and broken while overforecasting clear and overcast. A more sophisticated solution was designed. First, the probability forecasts for each station were inflated in a manner similar to that used for the perfect prog max/min temperature and the PEATMOS wind guidance. Subsequently, the probability forecasts were transformed by an empirically-derived minimum bias matrix. Two minimum bias matrices were derived for the cool season: one for the 0600 and 1200 UTC valid times, one for the 1800 and 0000 UTC valid times. The biases were improved with only minor changes in the percent correct scores. The PEATMOS cloud probabilities and categorical guidance were implemented in December 1974 when the guidance was added to the FOUS22 message on the request-reply circuit. While 10-term equations were developed for the cool season, 12-term equations were developed for the subsequent warm season.

6.6 Ceiling height and visibility

After testing MOS techniques to predict ceiling height and visibility, Bocchieri et al. (1974) developed the first PEATMOS ceiling and visibility guidance for CONUS sites. This first system was implemented in September 1974 (NWS 1974a). Unlike clouds, the ceiling and visibility prediction equations were developed by using the regionalized-operator approach. Predictands were valid 12, 18, 24, and 30 h after 0000 and 1200 UTC. As with clouds, observations of ceiling height and visibility were converted to binary variables by using FAA-specified categories shown in Table 2. For both ceiling height and visibility, five equations were developed simultaneously to predict the probability of each category of the event. The REEP approach was used; predictors from both the 6LPE and AT models were screened, and all predictors were binary variables. Observations at the initial model time t_0 and at $t_0 + 6$ were included as predictors for the

12-, 18-, and 24-h projections, and the sine and cosine of the day of the year were included to simulate seasonal variations. Both primary and backup equations were developed. A categorical forecast was generated by using a scoring matrix to transform the initial probability forecasts and maximize an NWS verification measure for aviation forecasts. With this implementation, the ceiling height and visibility forecasts were added to the FOUS22 message.

Table 2. Categories used for ceiling height and visibility equations.

Category	Ceiling Height (ft)	Visibility (mi)
1	≤ 100	≤ 3/8
2	200 – 400	1/2 - 7/8
3	500 – 900	1 – 2 ½
4	1000 - 1900	3 – 4
5	≥ 2000	≥ 5

In August 1975 (Carter and Glahn 1976), a new 4-panel facsimile chart (NWS 1975e) displaying PEATMOS winds and categorical cloud forecasts for 12-, 18-, 24-, and 30-h projections was implemented. For the 18- and 30-h projections, PEATMOS categorical forecasts of "flight weather" were added to the chart (Fig. 4). The flight weather categories combined ceiling and visibility forecasts (Table 3). Since the categories shown in Table 2 did not match those needed for the flight weather categories, new single-station equations were developed exclusively for this requirement.

Table 3. Categories of flight weather used for aviation forecasting. IFR defines instrument flight rules. MVFR defines marginal visual flight rules and VFR defines visual flight rules.

Flight Weather Categories	Ceiling Height (cig ht)/Visibility (vis) Conditions
IFR	< 1000 ft and/or < 3 mi
MVFR	1000 ft ≤ cig ht ≤ 3000 ft and/or 3 ≤ vis ≤ 5 mi
VFR	3000 ft < cig ht and 5 mi < vis

6.7 Probability guidance for thunderstorms and severe local storms

The prototype system pioneered by Ron Reap and Don Foster (Reap and Foster 1979) to predict probability of thunderstorms and severe local storms met requirements for guidance required by the National Severe Storms Forecast Center (NSSFC) and other specialized users. For traditional public and aviation weather forecasts, however, these early systems did not meet forecaster needs because the valid period of the guidance did not match the standard forecast periods. Yet the efforts by Reap and Foster provided a template for dealing with remote-sensed meteorological data. Care and insight were required to process these data, but such data sets proved very valuable especially when modern radar and lightning strike data sets became available. The complex predictors used by Reap and Foster to predict thunderstorm and conditional severe storm probabilities demonstrated the value of interactive and linearized predictors in the MOS scheme and provided a model for other developers. The use of interactive predictors became common in the 1990's and 2000's.

The first PEATMOS thunderstorm and severe thunderstorm probability product was implemented in May 1973 (NWS 1973d). The probabilities were instantaneous values valid 24 h after 0000 UTC; a facsimile map of probabilities was transmitted around 0800 UTC during the months of April - September. These probabilities were based on applying the MOS screening regression technique to 6LPE and AT model predictors. Predictors included forecasts such as moisture convergence and stability indices, as well as the cosine day of the year. Predictand data were based on radar reports tabulated from 0000 UTC summary maps prepared at NSSFC. Only spring (April - June) and summer (July - September) data from 1970 and 1971 were used. The radar activity was summarized within grid boxes, approximately 190 km on a side, and centered on LFM grid points. For the thunderstorm probability, the presence of a convective echo at 0000 UTC within the box defined the occurrence of an event. For the conditional severe thunderstorm probability, the occurrence of an intense line echo on the 0000 UTC summary map defined the event. For thunderstorms, only one generalized-operator equation valid for the entire grid and the complete spring-summer season was developed. For severe thunderstorms, equations were developed for the two 3-mo seasons and two separate regions (the East-Midwest and the Gulf).

In July 1973, the Manually Digitized Radar (MDR) program was implemented in the NWS Eastern, Central, and Southern Regions (NWS 1975a). The grid now used in the radar summary charts was approximately 40 nm on a side. In April 1975 (NWS 1975d), the first MOS probabilities based on using MDR reports as predictand data were implemented. For thunderstorm probabilities, the predictand was defined as the occurrence of an MDR value of 4 or greater (Video Integrator and Processor (VIP) level of 3 or greater) in an MDR block approximately 75-80 km on a side. A severe thunderstorm was defined as the occurrence in the NSSFC logs of tornadoes, hail of ¾ inch diameter or greater, or wind gusts ≥ 50 kts, conditional on an MDR value of 4 or greater in the MDR block. A radar-indicated severe cell within the MDR block was also accepted as a severe thunderstorm event. Occurring 24 h after the initial time of the 6LPE and AT models, the predictand was defined in a time window of ± 3h from 0000 UTC. As before, a generalized-operator equation was developed for thunderstorms and was valid for the 6-mo spring-summer season. For conditional probabilities of severe weather, regionalized equations for each of the 3-mo seasons were developed. In January 1976 (NWS 1976b), equations for the January - March season were implemented. Note, however, the thunderstorm and severe thunderstorm probabilities, available on facsimile during April through September, were only available on teletype during the cool season.

By the convective season of 1977, the PEATMOS thunderstorm/severe thunderstorm probability system (NWS1977f) had evolved further. The temporal window for the predictand was the period of 12 - 36 h after 0000 UTC, that is, the predictand was valid ± 12 h from 0000 UTC. The developmental period for the thunderstorm convective season was defined as March 15 - September 15. For severe thunderstorm probabilities, the spring and summer season developmental periods were modified to be March 15 - June 15 and June 16 - September 15, respectively. Reap and Foster (1979) had also developed a number of innovative predictors by using thunderstorm relative frequencies obtained from the radar data as well as severe local storm relative frequencies computed from NSSFC reports. These relative frequencies were used to indicate the climatological likelihood of the event in MDR blocks. In turn, the relative frequencies were made interactive with model variables by multiplying the relative frequencies with model-predicted stability indices, thus blending both the synoptic situation as well as the climatic likelihood of an event into a single predictor. These interactive predictors were linearized by use of a cubic polynomial transformation that essentially provided a “simple” estimate of the probability of the event for each MDR grid block. Other predictors included the product of two model variables and the use of sophisticated computed variables. The net result was the elimination of the need to develop equations for separate regions and the improvement of the thunderstorm/severe thunderstorm guidance.

6.8 MOS guidance for Alaska

Because of the MOS-1974 system design and archives, PEATMOS guidance for stations in Alaska was developed and implemented separately from the CONUS guidance. No trajectory model was run over Alaska, and only 6LPE variables and surface observations were available as predictors. Observational data were initially available for 14 Alaskan sites.

In January 1975, equations to predict the calendar day max/min temperature were implemented for the Alaskan sites (NWS 1977c). These equations were developed for the 0000 UTC and 1200 UTC forecast cycles in the same manner first used for the CONUS. The developmental data were stratified into cool and warm seasons. Ten terms were allowed in the equations; for the first projection, observations at 0600 or 1800 UTC were added as potential predictors. The guidance was available in the FMAK1 teletype bulletin.

By April 1977 (NWS 1977c), guidance for surface winds valid 12, 18, 24, 30, 36, 42, and 48 h after the 0000 and 1200 UTC initial model times was added to the FMAK1 bulletin. Unlike what was done for CONUS sites, wind equations were developed for 3-mo seasons (spring: March-May; summer: June-August; fall: September-November; and winter: December-February). Because of the persistence of weather conditions in Alaska, particularly during the colder months, observations at 0600 or 1800 UTC were used as potential predictors for the 12-, 18-, 24-, and 30-h projections. The inflation procedure was used to modify the wind speed guidance.

In June 1977 (NWS 1977g), PoP equations were implemented for 6-h periods valid 12-18, 18-24, 24-30, and 30-36 h after initial model time. PoP equations for 12-h periods were also implemented for the 12-24, 24-36, 36-48, and 48-60 h projections. Observations at 0600 or 1800 UTC were screened as potential predictors for projections to 24 h. Development of the 6-h and 12-h PoP equations was done simultaneously, as was done for the CONUS sites, to enhance consistency among the 6- and 12-h PoP values. For instance, equations for the 12-18, 18-24, and 12-24 PoPs had the same predictors, albeit with different coefficients and constants. However, in a radical departure from what was done for CONUS sites, these equations were single-station relationships, rather than regional, and were based on logistic regression rather than multiple linear regression. Moreover, the PoP equations for Alaskan sites were developed from the same 3-mo stratification of the data used for wind prediction. By September 1977, logistic regression had been used to develop PoF forecast equations, and PoF guidance was added to the FMAK1 bulletin for projections of 12, 18, 24, 30, 36, 42, and 48 h. The bulletin was available at approximately 0730 and 2000 UTC.

Finally, in the spring of 1979, the last PE-based MOS equations were developed and implemented for Alaskan sites (NWS 1979c). The max/min temperature prediction equations had been re-derived by stratifying the developmental data into the same 3-mo seasons used for CONUS sites. A MOS forecast of the calendar day max temperature valid nominally 72 h after 0000 UTC was now available. The wind, PoP, and PoF guidance were generated by updated forecast equations. Guidance for clouds (opaque sky cover), ceiling height, and visibility were added to the FMAK1 message. Unlike in the CONUS, the equations to produce the probabilities for these elements were based on cumulative predictands (for instance, < 0.1 opaque cloud cover, < 0.6 opaque cloud cover, or < 1.0 opaque cloud cover), rather than exclusive predictands. In response to suggestions from the Alaska region, equations for clouds, ceiling height, and visibility were developed for unique seasonal stratifications, that is, spring (March-May), summer (June-August), fall (September-October), and winter (November-February). Finally, the Miller-Best minimum bias model (Miller and Best 1978) was used to obtain categorical forecasts for these three elements so as to have a bias of approximately 1.0, that is, the number of forecasts of the event and the number of observations of the event would be approximately equal.

7. TRANSITION TO LFM-BASED MOS – THE ELIMINATION OF PEATMOS PRODUCTS

By 1975, two alphanumeric bulletins contained most of the PEATMOS guidance for the CONUS. The FOUS12 message displayed calendar day max/min temperature, PoP, and PoF guidance. The FOUS22 message contained wind, clouds, ceiling height, and visibility guidance. However, in December 1975, a new NWS plan for using the LFM and the NMC global model was issued (NWS 1975h). This directive required a significant change in the MOS packages: *"The objective with regard to the use of forecast models in the future is to work towards a 12- to 48-hour LFM as the primary conterminous U.S. guidance model and the 8 Layer Global Model as the guidance model for the longer range and the larger area forecasts."* Table 4 shows the planned schedules and contents of the revised MOS guidance. In short, the contents of the two bulletins were reversed, and a second pair of bulletins designated as "Early" were to be added to the MOS operational products. The LFM itself had been extended to make forecasts out to 36 h in December 1974 (NWS 1974c) when the conversion of NWS operations to the IBM 360/195 was completed. By February 1976, the LFM was making forecasts to the 48-h projection. In March 1976, after the radiosonde release time was changed to be 20 minutes earlier, the LFM could start at 0150 UTC (1350 UTC) and would take about 75 minutes to run (NWS 1976c). At this point, the requirement for earlier production of the LFM and LFM-based MOS guidance could be met.

Changes in the next several years exceeded even the original requirements. The Early FOUS12 was implemented in February 1976, and significant modifications occurred subsequently. By April 1979, the LFM-based guidance message had evolved into the primary MOS package, and the "Final" FOUS12 with its mixture of PEATMOS and LFM guidance was eliminated.

The FOUS22 had a checkered history. The Early FOUS22 message was implemented in February 1976, but contained only PEATMOS max/min and wasn't available until about two hours after the Early FOUS12 had been issued. The Final FOUS22 based on PEATMOS equations continued until March 1981 (NWS 1980a) when it was replaced by a second transmission of the LFM-based FOUS22. The only difference between the first and second transmissions of this FOUS22 was the addition of a 72-h max/min forecast based on the K-L perfect prog approach, and the second transmission of the FOUS22 was eliminated in 1982.

Because the LFM was phased in over a period of years, the availability of archived forecast data for MOS developmental purposes was uneven and posed a problem for MOS developers and users of the guidance. The challenge was met by developers in various ways, and details on individual weather elements in the subsequent sections may clarify the evolution of the MOS guidance.

Table 4. Revised NWS requirements for MOS bulletins. Times in parentheses refer to 1200 UTC cycle.

Bulletin	Transmission Time (UTC)	Input Needed	Contents
Early FOUS12	0300 (1500)	LFM, 02Z obs. (14Z obs.)	6- & 12-h PoP, PoF, clouds, ceiling, visibility, wind
Early FOUS22	0500 (1700)	6LPE, AT	Max/min temp.
Final FOUS12	0600 (1800)	6LPE, AT, LFM, 05Z obs. (17Z obs)	6- & 12-h PoP, PoF, clouds, ceiling, visibility, wind
Final FOUS22	0700 (1900)	6LPE, AT 06Z obs. (18Z obs.)	Max/min temp.

7.1 Probability of precipitation (PoP)

The first LFM-based PoPs for the 12-24 h and 24-36 h projections were available in February 1976 as part of the initial Early FOUS12 message. For the first time, 6-h PoPs for the 6-12, 12-18, 18-24, and 24-30 h periods after both 0000 and 1200 UTC were included. For 6- and 12-h PoP equations valid at projections of 24 h or less, LFM predictors and observations at t_0 + 3 (t_0 = initial model time of 0000 or 1200 UTC) were used as potential predictors. This marked the first time observations were used as predictors in PoP equations. Regionalized-operator equations were developed where the regions were chosen according to the relationship at stations between LFM mean relative humidity forecasts (or precipitation forecasts) and the occurrence of measureable precipitation at the station. Because the LFM archive for the 30- and 36-h variables did not begin until early 1975, the developmental sample of 30- and 36-h variables was insufficient for the traditional MOS approach. Instead, when the PoP equations for the 24-30 h and 24-36 h periods were developed, PEATMOS variables were used as potential predictors. LFM variables were substituted for these predictors when the equations were evaluated operationally.

The Final FOUS12 was also implemented in February 1976. The 6-h PoPs were valid for the same periods as those found in the early message, though another period (30-36 h) was added. The equations used to predict the PoPs valid at projections of 24 h or less were developed from LFM variables and observations at t_0 + 6. The equations for all PoPs valid at projections of greater than 24 h were identical to the equations used for the "Early" guidance package, except only PEATMOS variables were used in the equations.

Other significant changes to the PoP system were implemented in the next 3 years. Those changes included:

- May 1976 (NWS 1976d) – For the first time, equations to predict 6-h PoPs (for example, the 12-18 and 18-24 h projections) were developed simultaneously with equations to predict the 12-h PoP encompassing that period (for example, the 12-24 h projection). Thus, the three equations for a region used the same predictors, but the coefficients and constants differed among the equations. This technique enhanced consistency, but did not guarantee it.
- October 1976 (NWS 1976f) – The Final PoP guidance for projections out to 24 h was based only on LFM variables; PEATMOS equations for these projections were unavailable. Equations that generated the 48-60 h PoP from 0000 UTC 6LPE forecasts now used 60- and 72-h PE variables.
- April 1977 (NWS 1977d) - PEATMOS equations for the 36-48 and 48-60 h PoPs were redeveloped from 6LPE variables for use in the Final FOUS12.
- April 1978 (NWS 1978c) – For the first time, all equations used to produce the Early FOUS12 PoPs were developed from LFM forecast variables. The 30-36 h, 24-36 h, and 36-48 h PoPs were included in the Early guidance package. For the Final guidance, a mixture of LFM and PEATMOS variables were used for projections beyond 24 h. LFM-based PoPs for the 12-24, 24-36, and 36-48 h projections were added to the Early FOUS22.
- October 1978 (NWS 1978h) – LFM-based 48-60 h PoP was added to the Early FOUS22 message. For LFM-based PoP equations, observations as potential predictor were restricted to the 6-12 h projection. The PoP equations required in the Final FOUS22 for projections beyond 24 h were redeveloped from a larger sample of PE and AT model data.

7.2 Conditional probability of frozen precipitation/precipitation type

In February 1976, LFM-based equations to predict the conditional probability of frozen precipitation, now designated PoF, were implemented for the 6, 12, 18, and 24-h projections (NWS 1975g). The guidance for these projections was obtained by using LFM predictors in generalized-operator equations and was developed in the same manner as the system implemented in November 1972. Even the 50% values used in the logit regression were the same as the ones obtained from 6LPE forecasts. By September 1976, 50% values were available from LFM forecasts, and a new set of equations was developed and implemented for the Early guidance (NWS 1976e). The LFM-based PoF values were available in the Early FOUS12 issued approximately at 0400 and 1600 UTC; the PEATMOS PoF values were available in the Final FOUS12 issued about 3 hours later.

An entirely new LFM-based frozen precipitation type system was implemented in September 1978 (Bocchieri 1979, NWS 1978g). The new system, now known as the conditional Probability of Precipitation Type or PTYPE, produced probabilities and a categorical forecast for three types of precipitation, namely, frozen (snow or ice pellets), freezing (freezing rain or freezing drizzle), and liquid (rain or drizzle). A mixture of snow and ice pellets was considered frozen precipitation; any other type of mixed precipitation was considered liquid. Other significant modifications were included. For instance, observations available at t_0 + 3 were used as potential predictors for all projections, namely, 6, 12, 18, 24, 30, 36, 42, and 48 h after both 0000 and 1200 UTC. New “joint” or interactive predictors that considered the combined effects of various pairs of model variables provided forecast relative frequencies of snow or freezing rain. For the first time, equations were developed for a maximum of seven regions determined by considering the bias for forecasts resulting from a one-term joint predictor (850-hPA temperature combined with the boundary layer wet bulb temperature) equation that produced a probability forecast for snow. The developmental regions were subjectively determined after considering the bias in these forecasts, the relative frequency of the snow event, and the availability of stations in the developmental sample.

The last major change implemented in the new PoPT system was the generation of a categorical forecast of freezing rain, snow, or rain from the probabilities of the three precipitation types. The categorical forecast was determined by comparing the probability of freezing rain and snow to “threshold” values for the freezing rain and snow events. These thresholds were selected to maximize threat scores[2] for freezing and frozen events while maintaining a bias between 1.0 and 1.3. More will be said about the categorical selection in Section 8.

The new PoPT probability and categorical forecasts were added to the Early FOUS12 in the fall of 1978. The

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[2] Threat score or critical success index is defined as (H/(F+O-H) where H = no. of correct forecasts of the event, F = no. of forecasts of the event, and O = no. of observations of the event.

categorical forecasts also were plotted on the PoP facsimile chart. Both the Final FOUS12 and FOUS22 retained the older PEATMOS PoF.

7.3 Max/min temperatures; 2-m temperatures

The first max/min temperature guidance available in the Early FOUS12 and Early FOUS22 was implemented in August 1976. These forecasts were produced by substituting LFM and LFM Trajectory variables in the PEATMOS equations developed for 3-mo seasons. Because the early guidance was generated at approximately $t_0 + 4$ (t_0 = 0000 or 1200 UTC), no observations were used in the modified equations. The Final guidance remained dependent on PEATMOS variables and $t_0 + 6$ observations for the first two projections. The deterioration in the max/min guidance by using this approach was relatively small and was preferable to a lack of guidance at the earlier dissemination time.

Additional changes occurred in the Final guidance package. In December 1976, 3-mo PEATMOS equations for the 72-h max temperature from 0000 UTC were implemented (NWS 1976g), and this max temperature guidance replaced the K-L perfect prog guidance in the Final FOUS22. These PEATMOS equations had been developed from four seasons of 60-, 72-, and 84-h forecasts available from the 0000 UTC run of the 6LPE model and was the first operational "medium-range" MOS guidance. In May 1977, when the 1200 UTC version of the 6LPE model was extended to the 60-h projection, the K-L perfect prog approach was used to produce guidance for the min temperature valid nominally 72 h after 1200 UTC (NWS 1977e).

In January 1978, the PE model underwent significant changes (NWS 1977j) by the addition of a seventh layer to the model and the halving of the grid mesh length over the entire Northern Hemisphere. The implementation of the 7LPE substantially increased the runtime of the model. The Final FOUS22 guidance package was delayed by two hours during the 0000 UTC cycle in order to generate the 72-h MOS max temperature forecast. This delay was unacceptable, and in April 1978, the 72-h max temperature forecast available in the Final FOUS22 package reverted to the value generated by the K-L perfect prog approach (NWS 1978f). MOS guidance for projections beyond 60 h would not be developed again until the mid-1980's and early 1990's.

Finally, in early 1978, new LFM MOS equations to predict the calendar day max/min temperature were developed. For the first time, equations to predict the "surface" temperature (actually, the air temperature at the 2-m height of the observing instrument) at 3-h intervals from 6 to 51 h after 0000 and 1200 UTC were developed simultaneously (Carter et al. 1979, NWS 1978f) with the max/min temperature forecast equations. For example, the equations for today's max temperature from 0000 UTC were developed with the equations for the 6-, 9-, 12-, …, 24-, and 27-h surface temperatures; the equations for tomorrow's min were developed with equations for the 27-, 30-, 33-, 36-, and 39-h temperatures; and the equations for tomorrow's max were developed with equations for the 39-, 42-, 45-, 48-, and 51-h temperatures. Equations for the day after tomorrow's min were developed independently.

Several characteristics of this development were noteworthy:

- Ten-term equations were developed for each of approximately 230 stations in the CONUS.
- The simultaneous development in groups enhanced, but did not guarantee, consistency among the max/min and the 3-h temperatures. For instance, the calendar day max temperature might be predicted to be less than one of the 3-h temperatures during that same 24-h period. These inconsistencies were particularly vexing during the colder months of the year when frontal passages could produce calendar day max or min temperatures that did not occur during the normal time of day.
- Observations were used as potential predictors for the first two sets of equations. For the first time, snow cover available in observations transmitted at 1200 UTC was used as a potential predictor. This predictor was offered to the regression program in response to user complaints about the inability of PEATMOS guidance to lower temperatures appropriately when snow cover was present. Experiments in TDL demonstrated that the use of snow cover as a binary predictor was helpful, though it did not eliminate the problem completely.
- The use of observations required sets of back-up equations that only used LFM variables. During development of the back-up equations, the LFM 2-m temperature analysis valid at 0000 UTC or 1200 UTC was offered as a potential predictor. This predictor was chosen in nearly all back-up equations as a surrogate for the missing observed surface temperature.
- Two guidance values were available for the 27- and 39-h projections. Before the guidance was transmitted, the two values were averaged to give the official guidance value for the projections.
- No operational consistency check between the calendar day and 3-h temperature values was implemented.
- Comparative verifications showed that the LFM-based max/min guidance was more accurate than the PEATMOS system.

On June 1, 1978, the new LFM-based temperature guidance became available in the Early FOUS12 for the max/min and 3-h temperatures. The max/min temperature guidance for projections to 60 h appeared in the Early FOUS22. The PEATMOS max/min temperature guidance remained in the Final FOUS22.

7.4 Surface winds

The first LFM MOS surface wind guidance was implemented in February 1976 (NWS 1976a) for 6-, 12-, 18-, and 24-h projections after 0000 and 1200 UTC. Like the PEATMOS system, the equations were single-station relationships, contained 12 terms, and were developed simultaneously for the u- and v-wind components and the wind speed. For the 6- and 12-h projections, station observations available at t_0 +3 (t_0 = initial model time) were included in development as possible predictors. Wind direction was computed from the predicted u- and v-wind components; wind speeds were inflated before dissemination. Equations were developed for approximately 230 sites in the CONUS

As the dependent LFM sample increased, equations were developed for the 30- and 36-h projections. The LFM MOS winds for these projections were added to the Early FOUS12 bulletin in April 1977 (NWS 1977b). Analogously, LFM-based winds for the 42- and 48-h projections were included in the early bulletin in April 1978 (NWS 1978b). The Final FOUS12 contained PEATMOS winds until the bulletin was removed from operations in April 1979.

One additional modification to the surface winds was made in October 1979. The developer of the MOS wind guidance at that time (John Janowiak) discovered a problem when single-station equations were developed from relatively small samples, and certain predictors were highly correlated with each other and with the predictand. This problem known as multicollinearity was evident when the coefficient for a particular predictor variable was meteorologically unreasonable. When the variable was used in the prediction equation, the contribution of that variable to the overall forecast was compensated by a similar predictor with an unreasonable coefficient of the opposite sign. A minor modification to the regression program eliminated the problem, and new cool season equations were developed and implemented in October 1979 (NWS 1979d). After this, MOS developers avoided combinations of possible predictors that could lead to multicollinearity issues, and imposed stricter limits on the reduction of variance that a variable needed to explain before being included in a regression equation.

7.5 Cloud amount/ceiling height/visibility

In May 1976, the first LFM-based equations for the probability of categories of opaque cloud amount were implemented (Carter and Glahn 1976). These equations were single-station relationships that used LFM forecasts valid at 6, 12, 18, and 24 h after initial model time t_0 as potential predictors. Observations valid at t_0 + 3 were included as possible predictors for the 6- and 12-h projections. The predictands for these equations were now defined in terms of opaque sky cover (Table 5), rather than total sky cover used in the PEATMOS system.

Table 5. Categories used for cloud amount in the LFM and original PEATMOS systems.

Predictand Category	LFM (tenths of opaque cloud cover)	PEATMOS (Total sky cover)
Clear	0 - 1	Clear, thin scattered, thin broken, or thin overcast
Scattered	2 - 5	Scattered
Broken	6 - 9	Broken
Overcast	10 (or obscured)	Overcast or obscured

Once again, the manner of choosing the categorical forecast from the MOS probabilities was modified from that used previously in the PEATMOS system. Now, the MOS probabilities were inflated, and the category with the largest probability was selected as the best category. This approach was applied to both the LFM MOS and PEATMOS systems. The LFM MOS probabilities and categorical forecasts were available in the Early FOUS12 for projections from 6 to 24 h. The Final FOUS12 continued to display PEATMOS guidance for projections of 12 to 48 h.

By February 1977, a major overhaul occurred in the cloud, ceiling height, and visibility prediction systems for the LFM MOS and PEATMOS guidance (NWS 1977a). The approach of developing single-station prediction equations for cloud amount was abandoned. Instead, stations were combined into regions based on the conditional climatology of certain ceiling height categories when the LFM boundary layer relative humidity forecast was 90% or greater. These regions were then adjusted subjectively for conditional cloud amount frequencies, topography, and synoptic climatology. The regionalized-operator approach for developing cloud amount equations eliminated the possibility of stations lacking cloud forecasts because the stations were opened part-time or were closed.

In addition, the equations for opaque cloud amount and ceiling height categories were developed simultaneously. This approach increased the consistency of the cloud amount and ceiling height guidance because the same predictors were used in each of the equations for the same region and projection, though the coefficients and constants varied among categories. Consistency, however, was not guaranteed, that is, a cloud forecast of clear or scattered was possible even when the ceiling height guidance did not indicated unlimited conditions. Limited ceiling height occurred by definition with broken or overcast opaque cloud cover. The definitions of the categories for ceiling height and visibility were also revised (Table 6) after extensive discussions with the NWS regions.

Table 6. Revised categories used for ceiling height and visibility equations in February 1977.

Category	Ceiling Height (ft)	Visibility (mi)
1	<200	< 1/2
2	200 – 400	1/2 - 7/8
3	500 – 900	1 – 2 ¾
4	1000 - 2900	3 – 4
5	3000 - 7500	5 – 6
6	> 7500	> 6

Finally, two new schemes were implemented to pick the categorical forecast from the probability guidance. For cloud amount, the first part of the selection scheme was to compare the sum of the probabilities of clear/scattered with the sum of probabilities of broken/overcast. The larger sum was picked as the likely condition, and then each of the two probabilities in that group was inflated by a specified amount. At that point, the greater of the two numbers indicated the categorical forecast. A bias of 1.0 was the goal. For ceiling and visibility, threshold probabilities were determined subjectively for each category with the goal of obtaining a bias of less than 1.0 for the lower categories, and a bias of approximately 1.0 for the higher categories.

The LFM-based MOS equations to predict clouds, ceiling height, and visibility were developed for 6-, 12-, 18-, and 24-h projections. The 6-, 12-, 18-, and 24-h LFM forecasts, station elevation, and observations at t_0 + 3 were all used as possible predictors. Back-up equations that did not use observations were necessary. The LFM guidance was included in the Early FOUS12 package. By this time, the hope was that the early guidance could be transmitted at 0300 or 1500 UTC, and the Early package was often run with t_0 +2 observations.

The complete set of PEATMOS equations for 12-, 18-, 24-, 30-, 36-, and 48-h projections were redeveloped in the 1977 revision. Observations at t_0 + 6 were included as possible predictors. In addition, for the 12-, 18-, and 24-h projections, LFM variables were included along with 6LPE forecasts. Thus, the guidance in the Final FOUS12 package was neither a complete LFM nor PEATMOS product. Because of operational deadlines, the Final package was often run with observations at t_0 + 5.

In April 1978, cloud amount, ceiling height, and visibility guidance for the 30-, 36-, 42-, and 48-h projections was added to the Early FOUS12 message (NWS 1978d). However, the guidance for these elements and projections was generated by using LFM variables in the 1977 PEATMOS equations. By this time, because of changes in the PE model, the Final FOUS12 was not available until t_0 + 8 or later.

7.6 Probability of precipitation amount/categorical precipitation amount

Early in the development of PEATMOS guidance, Bob Bermowitz (1975) tested a rudimentary system to predict the probability of precipitation amount (PoPA) categories from PEATMOS variables. Verification results did not justify implementing the system. However, in October 1977, both LFM MOS and PEATMOS systems to predict PoPA were implemented (NWS 1977i) and the guidance was added to the appropriate FOUS12 bulletin. For the early guidance, probabilities for the categories of $\geq$ 0.25 inches, $\geq$ 0.50 inches, and $\geq$ 1.0 inches during the 12-18 h and 18-24 h projections were available. These probabilities were generated by regional-operator equations developed from LFM predictors. Equations were developed simultaneously for all the categories for a specific region and projection. Regions were based on a subjective analysis of the frequency of occurrence of specific precipitation amounts, given the LFM forecast of the amount. A categorical forecast was included in the bulletin. For PoPA, the categorical forecast was determined by using probability thresholds designed to maximize the threat score of each category of event, while limiting the bias in the forecast to be $\leq$ 2.0.

For the final guidance, probabilities were available for the same categories and for the same projections; the probability for the 24-30 h projection was added, and categorical forecasts for all three projections were included. Guidance was added for the 12–36 h and 36–60 h periods after 0000 UTC and for the 24–48 h period after 1200 UTC. Because 24-h periods contained more heavy rain events, the categories of rainfall events were modified to be: $\geq$ 0.25 inches, $\geq$ 0.50 inches, $\geq$ 1.0 inches and $\geq$ 2.0 inches. Model variables from the PE and AT models were used for projections to 24 h; PE model variables were used for projections beyond 24 h. Regions and categorical guidance were developed analogously to the early guidance scheme, but were based on PEATMOS data. At this time, the Early FOUS12 was available around t_0 + 3; the Final FOUS12 was available approximately 3.5 hours later.

In April 1978, the same probabilities that had been added to the Final FOUS12 were included in the Early FOUS12. However, the equations for these additional projections and categories were developed from PE variables. The guidance was generated by using LFM fields in PE-based equations. Notably, by this time, the Final FOUS12 was issued 5 hours or more after the early guidance because of the additional time required for execution of the 7LPE model.

7.7 Probability guidance for thunderstorms

In April 1978, probability forecasts of thunderstorms during the 12-24, 24-36, and 36-48 h periods after 0000 and 1200 UTC were added to the "Early" FOUS12 message (NWS 1978e). The definitions of the thunderstorm event and the overall methodology of developing the forecast equations were identical to what was used for the 12-36 h probabilities in the older PEATMOS system. However, the development of the entire package was somewhat unusual. While the 1200 UTC equations were new and were developed from LFM variables, the forecast equations implemented at 0000 UTC, including equations for the 12-36 h projection, were derived from PE data; in operations, LFM forecast variables were substituted for the PEATMOS data to obtain the guidance for the Early FOUS12 bulletin. By February 1979 (NWS 1979b), all thunderstorm probability forecasts in the Early FOUS12 were generated by equations developed from LFM data.

7.8 Conditional/unconditional probability of heavy snow

Though unavailable in the PEATMOS system, a new guidance product to predict the likelihood of heavy snow (4 inches or more) in the 12-24 h period after both 0000 and 1200 UTC was developed and implemented in October 1977 (NWS 1977h). This product was derived by using the traditional MOS multiple linear regression approach. Only LFM-based variables in continuous and binary form were used as predictors. The predictand data consisted of 6-h snowfall amounts observed at approximately 195 stations in the CONUS. The conditioning event was defined as accumulation of 0.1 inches of snow or ice pellets during a 12-h period (1200-0000 UTC, 0000-1200 UTC), and the event was a pure snow event, that is, no liquid or freezing precipitation occurred during the 12-h period. The presence of a pure snow event was determined by examining present weather reported in station observations available at 3-h intervals from 1200 to 0000 UTC or from 0000 to 1200 UTC. Once the pure snow events were extracted from the dependent sample, LFM-based equations to predict the conditional probability of snow of 4 inches or greater during the 12-h period were developed. These were regional-operator equations; regions were determined by considering the relative frequency of the heavy snow event when the LFM prediction of the 12-h precipitation exceeded 0.1 inches.

In operations, the LFM-based equations predicted the conditional probability of heavy snow (PoSH). By using the PoP, the PoSH and a weighted probability of frozen precipitation (wt'd PoF) for the same 12-h period, the unconditional probability of heavy snow was calculated as the product of those three probabilities. Finally, a categorical forecast (heavy snow: yes or no) was obtained by comparing the unconditional probabilities to thresholds determined subjectively from the developmental data. These thresholds maximized the threat score for the heavy snow event while maintaining a bias between 1.0 and 1.5. The conditional and unconditional probabilities as well as the categorical forecast were available in the Early FOUS12 guidance package, but no PEATMOS guidance was developed for PoSH.

In the fall of 1978, forecast equations needed for the PoSH guidance were updated by using two additional years of LFM data (NWS 1978i). The new PoPT system provided the conditional probabilities for the pure snow event.

7.9 Re-cap of the early/final LFM-based and PEATMOS guidance bulletins

In August 1978, NWS1978j, NWS 1978k, and NWS 1979a summarized the status of the FOUS12 (Fig. 5) and FOUS22 bulletins. The Final FOUS12 represented the apex of PEATMOS development. The Early FOUS12 represented an evolution in the LFM-based guidance, still incomplete since some of the equations needed to produce the guidance (for instance, PoPA and cloud probabilities) were PEATMOS equations using LFM forecasts as input. By this time as well, the PE model was a 7-layer model with half the grid mesh length of the original. The LFM would also undergo modifications, becoming the LFM-II in 1979 when a seventh layer was added and the original mesh length of 190.5 km was reduced to 127 km.

By the end of April 1979, the Final FOUS12 was discontinued, but the Final FOUS22 remained. In August 1980, the 7LPE model was replaced by the Global Spectral Model (NWS 1980a, Sela 1980). By December 1980, the guidance available in the Final FOUS22 proved unacceptable to the forecasters. After appropriate coordination, the Final FOUS22 was replaced in March 1981 (NWS 1981a) by the LFM-based MOS guidance found in the Early FOUS22, with an added 5th period max/min temperature based on the K-L perfect prog approach applied to the Global Spectral Model (GSM). Thus, by early 1981, PEATMOS guidance for the CONUS was completely terminated. The PEATMOS guidance for Alaska continued by using GSM variables in PEATMOS equations until an LFM-based package was developed.

8. Creating a Categorical Forecast from Probability Guidance

Several probability guidance products generated by application of the MOS technique to different NWP model have been described. These probabilities reflected the possibility of multiple states of the weather element, for example, precipitation or no precipitation; frozen, freezing, or liquid precipitation when precipitation occurs; or precipitation exceeding various critical values. Yet, the typical consumer of probability information often desires to know whether the event for which a probability is specified will occur. As evident from previous discussions, TDL tried a number of approaches to select a "best" category – "best" in the sense of optimizing a particular verification score. Early in MOS development, utility matrices or matrices designed to produce an optimal verification score were used to multiply the probability vector before selecting a "best" category. Sometimes, the probability forecasts were inflated, and the category with the largest probability was selected as the categorical forecast.

Rich Crisci (Crisci 1976) described an experiment in which he attempted to improve the categorical forecast of low visibility conditions by deriving "threshold" probabilities. The goal was to attain a forecast bias of approximately 1.0. Crisci derived his threshold probabilities by producing a set of probability forecasts on the dependent data from which the forecast equations had been developed. He then subjectively selected a first-guess threshold probability for the lowest visibility condition, applied that value to the set of probability forecasts, and made a forecast of that visibility condition when the probability of the condition exceeded the first-guess threshold. Finally, a verification of the categorical forecasts over the dependent sample was made for the lowest visibility condition. This process was repeated for multiple guesses of possible thresholds until a choice could be made as to the threshold that generated a bias of approximately 1.0. Next, the probabilities for categories 1 and 2 were combined, and the entire process was repeated to obtain a second threshold. The generation of thresholds in this manner continued until thresholds for every category but the most common (visibilities of $\geq$ 5 miles) were developed. If the sum of the probabilities never exceeded a threshold, then the most common event was selected as the categorical forecast. Crisci found some minor improvement in his test, but one can imagine the amount of time this subjective process took.

Bob Miller (Miller and Best 1978) clearly described the problem posed by the need for a categorical forecast generated from probabilities. Miller wrote: *"A threshold probability is a number between zero and one used as a cutoff in deciding which event to forecast categorically, given a set of forecast probabilities. The need for threshold probabilities is very basic: How does one convert a forecast probability distribution into a single decision that is favorable, or in some way optimum, for a given customer's operation? In decision theory, this can be done by applying a utility function to the forecast probability distribution. To many users of weather information, however, the determination of a utility function is not easy. Precise threshold probabilities can substitute for utility functions as long as the categorical forecasts match acceptable decision frequencies, but they are likewise not easily derived."* Miller and Best proposed a general threshold probability model (M&B model) that was a function of the relative frequency of the event, the multiple correlation coefficient of the regression equation used to produce the probability forecast, and an adjustment term that ranged between 0 and the inverse of the multiple correlation coefficient and that was chosen according to the desired verification score. Two specific examples of the M&B model were presented, one for obtaining a unit bias in the categorical guidance and one for maximizing the threat score of the category. Later, Miller and Best (1981) discussed another model (the beta probability density function model) that fit a density function to the distribution of guidance probabilities when the event of interest occurred or did not occur. An algorithm was then designed to pick an appropriate threshold value for maximizing a specific verification score.

Bob Bermowitz (Bermowitz and Best 1978, Bermowitz and Zurndorfer 1979) had worked on developing threshold probabilities for maximizing the threat score of dichotomous events, particularly related to the prediction of quantitative precipitation. Like Crisci's work to predict categorical visibility forecasts with a unit bias, Bermowitz described the approach then in vogue as an empirical, iterative one: "*On successive passes through the dependent data sample, threat scores are computed for categorical forecasts made by comparing the actual probability forecasts against preselected, incremented threshold probabilities. The procedure is terminated when the threat score reaches its maximum value with the accuracy of the given increments. The threshold probability associated with that maximum threat score is then subjectively evaluated to see if it should be used operationally. Usually, this involves checking the bias to make sure that it is not unacceptably high. If it is too high, a threshold value associated with a lower bias is chosen; unfortunately, this usually results in a lower threat score."* Bermowitz developed a model based on the climatic relative frequency of the event and the multiple correlation coefficient of the prediction equation; tests on quantitative precipitation guidance showed good results, and this work became part of the M&B model described above.

These objective models were incorporated into the MOS regression program; if desired, the appropriate threshold probabilities were generated when the probability equations were developed. Both Bob Bermowitz and later Ed Zurndorfer (Zurndorfer 1980) pointed out that efficiency alone recommended the use of one of these models (M & B, beta, or Bermowitz) to derive the probability thresholds needed for categorical guidance. By the beginning of the 1980's, this objective methodology for creating thresholds became the norm, and the derivation of thresholds by subjective brute force eventually ended. Another scheme would come along in the early 1990's.

9. Enhancements to LFM MOS – A Long-Lived Product

As noted in Section 7.9, additional work was required to complete the LFM MOS guidance package. During the years from 1979 until 1989, a number of changes were implemented in the LFM MOS guidance. Some of the changes were relatively insignificant, though the guidance was improved by the increase in size of the developmental sample or small adjustments in the procedures used to derive equations or categorical thresholds. Other changes, such as the development of an algorithm to estimate the daytime max and nighttime min temperature from available hourly observations, development of thunderstorm probability equations from observations of cloud-to-ground lightning strikes, and issuance of a computer worded forecast product, were noteworthy. The LFM itself was operational until February 1996, a span of nearly 25 years from inception to removal.

9.1 Probability of precipitation (PoP)

In August 1980, a new LFM MOS system to predict PoP was implemented for the CONUS (NWS 1980e). All equations in this system were developed from LFM data. Equations needed to generate the 6-h PoPs available in the FOUS12 message were added for the 42- and 48-h projections. These equations were developed simultaneously with the 12-h PoP equation for the 36-48 h projection. As done previously, the PoPs for the 12-24 and for the 24-36 h projections were developed simultaneously with the equations for the two 6-h periods that comprised the 12-h period. The developmental sample for the cool season equations for projections of 24 h or less was available from 1972-73 through 1979-80. For the 30- and 36-h projections, the developmental sample was from 1975-76 through 1979-80. For projections greater than 36 h, the sample contained data from 1976-77 through 1979-80. In addition to LFM forecasts, observations at $t_0 + 3$ were used as potential predictors for all equations valid 24 h or earlier after initial model time t_0 (t_0=0000 or 1200 UTC). All equations were based on the regionalized-operator approach, that is, stations were clustered into regions on the basis of subjectively determining how well the LFM predicted precipitation events, given the LFM mean relative humidity or precipitation amount forecasts. The data for all stations in a region were used to determine the multiple regression equation. In all, reports from 233 stations were used to generate equations.

While the LFM MOS PoP guidance was displayed in the FOUS12 message and the Early FOUS22 bulletin, the PoPs in the Final FOUS22 were still using PEATMOS equations. Around the same time in August 1980, the 7LPE model was replaced by the GSM (Section 7.9). Consequently, these PEATMOS equations were using GSM forecasts as input. TDL had tested GSM input in PEATMOS equations prior to the GSM implementation, and developers were concerned that the Final PoPs might be misleading, particularly in Alaska. A warning regarding this potential issue was issued. The concern was well-founded, and in February 1981, the Final FOUS22 was converted to contain only LFM MOS PoPs, conditional probability of snow, and max/min temperature guidance (except for the fifth period K-L perfect prog max/min). In April 1981, new warm season PoP equations developed exclusively from LFM data were implemented (NWS 1981b). The approach was analogous to that used for the cool season equations, and like the cool season equations, additional developmental data were available. The developmental sample for the warm season equations for projections of 24 h or less was available from 1973 through 1980. For the 30- and 36-h projections, the developmental sample was from 1975 through 1980. For projections greater than 36 h, the sample contained data from 1976 through 1980.

The last update to the LFM MOS PoP system for the CONUS was implemented (NWS 1990) in February 1989 and April 1989 for the cool and warm seasons, respectively. Ten years of LFM data (from October 1978 through September 1988) were available for development. Observational data were available from approximately 220 stations. Regionalized-operator equations were developed for regions established by a correlation analysis between the LFM forecast relative frequency of $\geq$ 0.01 inches of precipitation and the observed relative frequency of $\geq$ 0.01 inches of precipitation. Station observations at t_0 were included as possible predictors for PoP projections of $\leq$ 24 h. A maximum of 18 terms was allowed in the equations, and equations were developed to predict the 48-54 and 54-60 h projections for both cycles. Testing showed some improvement in the skill of this new system relative to the prior one.

9.2 Conditional probability and categorical guidance of precipitation type (PoPT)

The changes implemented in the LFM-based PoPT guidance system in September 1982 (NWS 1982d, Bocchieri and Maglaras 1983) represented a major increase in the complexity of the probability equations. In many respects, this PoPT system was one of the most sophisticated MOS systems ever implemented and subsequently provided ideas about transformation of predictors and interactions between two or more predictors that were helpful to future MOS developers. The development paralleled that of other LFM MOS upgrades, that is, more LFM data were available in the dependent sample. A slight, but significant, modification was made to the predictand definition of freezing rain, namely, freezing rain mixed with any other precipitation was defined as a freezing rain event. In contrast, for the first PoPT system, a mixture of freezing rain with another type of precipitation was defined as rain. In the new system, PoPT guidance was available for the 6-, 54-, and 60-h projections, in addition to the 12-, 18-, 24-, 30-, 36-, 42-, and 48-h projections. Station observations at $t_0 + 3$ (t_0 = 0000 or 1200 UTC) and the climatic relative frequency of snow or freezing rain were possible predictors at all forecast projections. This use of observations meant that backup or secondary equations were necessary for all projections. The logit curve was used to develop the forecast equations from predictors selected by screening regression since logit regression had no screening capability. Equations were derived for regions. Similarly, the same approach used in the 1978 implementation to obtain categorical thresholds was used in this upgrade, namely, subjectively choosing thresholds that maximized the threat score while maintaining a bias for the event (freezing rain or snow) between 0.9 and 1.1.

The major enhancement for PoPT occurred in the type of predictors used. In the original PoF system, a one-term logit equation was developed from individual thermal predictors to estimate the 50% value of snow at each station, that is, the value of the thermal field associated with a 50% likelihood of snow occurring. In the new system, certain thermal variables, namely, the boundary layer potential temperature, 850-hPa temperature, 850-hPa wet bulb temperature, 1000-850 hPa thickness,1000-500 hPa thickness, and 850-500 hPa thickness were transformed or "standardized" by a one-variable logit curve fit that accounted for the slope or spread of the logit curve as well as the 50% value. The standardized variable X_T equaled: $(X-V_{50})/S$, where X was the original variable, V_{50} represented the 50% value for freezing rain or snow as measured by a one variable logit curve, and S was the spread of the logit curve, that is, the difference between the 95 % and the 50% value of the logit curve. The standardized variables were derived for each station in the developmental sample. The second complication introduced into the PoPT system was the use of interactive predictors that modeled the joint impact of two standardized thermal fields on the probability of snow or freezing precipitation occurring. In tests on independent data, Bocchieri and Maglaras found that the new system improved over the old, particularly for the forecasts of freezing precipitation at projections of 24 h or less. This system continued in operations until the demise of LFM MOS guidance.

9.3 Max/min temperatures; 2-m temperatures and dewpoints

In April 1980, a major overhaul in the LFM MOS system to predict 2-m temperatures was implemented (NWS 1980c). For the first time, single-station equations to predict max/min temperature, 2-m temperature, **and** 2-m dewpoint were developed and implemented for approximately 230 stations. The predictands were calendar day max/min temperatures valid nominally at 24, 36, 48, and 60 h after initial model time (t_0) of 0000 and 1200 UTC; 2-m shelter temperatures valid every 3 h from 6 to 51 h after t_0; and 2-m shelter dew point valid every 3 h from 6 to 51 h after t_0. All developmental data were stratified into 3-mo seasons of spring (March – May), summer (June – August), fall (September – November), and winter (December – February) for all projections, unlike what was done in the first LFM MOS development. Regression equations were developed simultaneously for the following five groups:

- 6-, 9-, and 12-h temperatures and dewpoints;
- 12-, 15-, 18-, 21-, and 24-h temperatures and dewpoints along with today's max temperature (0000 UTC cycle) or tomorrow's min temperature (1200 UTC cycle);
- 24-, 27-, 30-, 33-, and 36-h temperatures and dewpoints along with tomorrow's min temperature (0000 UTC cycle) or tomorrow's max temperature (1200 UTC cycle);
- 36-, 39-, 42-, 45-, 48-, and 51-h temperatures and dewpoints along with tomorrow's max temperature (0000 UTC cycle) or day after tomorrow's min temperature (1200 UTC cycle); and
- day after tomorrow's min temperature (0000 UTC cycle) or the day after tomorrow's max temperature (1200 UTC cycle).

Unlike the PEATMOS development of max/min temperature equations, no trajectory model predictors were used in equation development; LFM predictors from the model's boundary layer were also eliminated. The latter decision was made to insulate the MOS guidance from changes proposed to the LFM. Up to 12 predictors were allowed for equations in the first four groups; a maximum of ten predictors was allowed for equations in the fifth group. Station observations at $t_0 + 3$ were included as potential predictors for the first three groups. For the 0000 UTC development, station observations of the 2-m temperature at $t_0 - 3$ and t_0 were added as possible predictors to capture the persistence of late afternoon temperatures from one day to the next. For the 1200 UTC development, station observations of the 2-m temperature and snow cover were included in the potential predictor list to simulate persistence of conditions affecting early morning temperatures. As done previously, the LFM analyzed 2-m temperature at t_0 served as a potential predictor and surrogate observation when actual observations at a station were missing.

Guidance for dewpoint was added to the FOUS12 message at this time. Thus, max/min temperature forecasts were available for three periods in the message, while all the temperature and dewpoint guidance from 6 to 51 h were included. Two values were available for the 12-, 24-, and 36-h projections of both temperature and dewpoint; the two values were averaged for inclusion in the message. In addition, while the simultaneous derivation of equations increased the likelihood of consistent temperatures and dew points, the possibility of the dewpoint exceeding the temperature at the same projection still existed. In that case, the temperature and dewpoint were averaged so that the resulting guidance in the FOUS12 indicated 100 % relative humidity. Finally, the first period max (or min) temperature was compared to the hourly temperature values from 6 to 27 h after t_0. If the max (min) temperature was less (greater) than any of those values, the max (min) was set equal to the greatest (least) temperature value. Analogous checks were not done for the second or third period max/min temperatures.

In the fall of 1984, consistency checks between max/min temperatures and temperatures at specific hours were modified. For the 0000 UTC forecast cycle, the value for today's max temperature was compared to 3-h temperature values from 6 to 30 h after 0000 UTC. If the max temperature was less than any 3-h values, the original max temperature was replaced by the maximum of the 3-h values. The value for tomorrow's min temperature was compared to 3-h temperature values from 30 to 51 h after 0000 UTC. If the min temperature was greater than any 3-h temperature, then the min temperature was replaced by the minimum of the 3-h values. Finally, if the max temperature guidance for tomorrow was less than any of the 3-h values for the 30- to 51-h projections, then the max temperature was replaced by the maximum of the 3-h values. For the 1200 UTC forecast cycle, analogous checks were made between tomorrow's min and max temperature forecasts and the 3-h temperatures for the 18- to 42-h projections.

One of the most significant changes made to the MOS max/min temperature guidance was implemented in the 1200 UTC forecast cycle on November 25, 1985 (Erickson and Dallavalle 1986, NWS 1985b) when equations to predict max temperatures for the **daytime** period and min temperatures for the **nighttime** period were implemented. Since the introduction of MOS max/min guidance in 1973, the MOS max/min temperatures had been valid for calendar day periods despite the fact that NWS forecasters predicted max/min values for daytime/nighttime periods. Since the calendar day extremes did not always occur at the "normal" time (middle to late afternoon for the max, and early morning to near sunrise for the min), the MOS guidance was sometimes difficult to interpret. Beginning in 1981, the NWS Line Forecasters Technical Advisory Committee (LFTAC) had annually recommended that max/min guidance be developed for daytime/nighttime periods. In fact, Erickson and Dallavalle (1986) had found that during October to March, approximately 10 % of calendar day max temperatures occurred near midnight. Nearly 25 % of calendar day min temperatures occured near midnight of the second evening, rather than around sunrise of the appropriate overnight period. During April to September when the effects of the sun are much stronger, approximately 5 % of calendar day max temperatures and 15% of calendar day min temperatures did not occur at the "normal" time.

Clearly, LFTAC's concerns were valid. Two problems existed in finding a solution. First, station observations of max/min temperature did not correspond to local daytime/nighttime periods, but to intervals specified by the UTC clock. Secondly, no definition of daytime and nighttime existed in NWS policies, and an appropriate definition was needed for the CONUS, the four seasons, and a latitude variation of 24 degrees. MOS developers had two tasks, then, to develop a daytime/nighttime predictand for MOS development purposes. Based on discussions with NWS personnel and internal perceptions of daytime and nighttime, daytime was defined as 9 a.m. – 7 p.m. Local Standard Time (LST) and nighttime as 7 p.m. – 9 a.m. LST during October through March (cool season). During April through September (warm season), daytime was defined as 8 a.m. – 7 p.m. LST, and nighttime as 7 p.m. – 8 a.m. LST. From this definition and observations of calendar day extrema and 3-h temperature values, an algorithm was developed to estimate the daytime max and nighttime min from available observations. The algorithm accepted the reported calendar day value if the 3-h temperature observations indicated occurrence during the daytime/nighttime period. Otherwise, a simple one-term regression equation was applied to the highest (or lowest) 3-h temperature during the daytime (nighttime) period to estimate a daytime max (nighttime min). Equations were developed from 3 years of data for each of the four time zones in the CONUS, for both cool and warm seasons, and for both the daytime max and nighttime min. Generally, these equations changed the extreme 3-h temperature by no more than ± 2 degrees. Now the appropriate predictand data and the necessary equations could be developed.

With minor modifications, the developmental process was essentially the same as used in the LFM MOS temperature and dew point implementation of 1980. The developmental sample was increased to be 7 or 8 years for each of the standard 3-mo seasons. Observations were only included as possible predictors for the first two groupings below. A slight modification was made so that regression equations were developed simultaneously for the following five groups:

- 6-, 9-, 12-, and 15-h temperatures and dew points;
- 15-, 18-, 21-, 24-, and 27-h temperatures and dewpoints along with today's max temperature (0000 UTC cycle) or tonight's min temperature (1200 UTC cycle);
- 27-, 30-, 33-, 36-, and 39-h temperatures and dewpoints along with tonight's min temperature (0000 UTC cycle) or tomorrow's max temperature (1200 UTC cycle);
- 39-, 42-, 45-, 48-, and 51-h temperatures and dewpoints along with tomorrow's max temperature (0000 UTC cycle) or tomorrow night's min temperature (1200 UTC cycle); and
- tomorrow night's min temperature (0000 UTC cycle) or the day after tomorrow's max temperature (1200 UTC cycle).

In operations, the two temperature (or dew point) values for the 15-, 27- and 39-h projections were averaged for the guidance. Consistency checks were also built so that the max (or min) values for the second, third, and fourth groups above were checked with the 3-h temperatures within that group. From a strict point of view, these latter checks should be based on time zone and season of the year, but that modification was not feasible. The user community never objected, and this system existed until the demise of the LFM MOS guidance nearly 10 years later.

9.4 Surface winds

In June 1980, equations to predict surface wind for CONUS sites were updated (NWS 1980d). While the procedures were essentially identical to previous developments, the LFM sample used for development was modified to include data from April 1975 to September 1979 for the 6-, 12-, 18-, 24-, 30-, and 36-h MOS guidance. Data from April 1976 to September 1979 were available for derivation of the 42- and 48-h LFM MOS equations. Single-station equations were derived for approximately 235 stations; operational requirements resulted in generalized-operator equations being developed for another 35 sites lacking adequate observations for derivation of station-specific equations. The LFM MOS wind guidance was available in the FOUS12 message issued around 0345 and 1615 UTC daily; wind direction and speed for the 12-, 18-, 24-, and 30-h projections for a subset of stations were plotted on a map of the CONUS issued on facsimile and on the NWS AFOS (Automation of Field Operations and Services) system.

A more significant change occurred in October 1980 and May 1981 when revised wind equations were implemented for the cool and warm seasons, respectively. Janowiak (1981) had demonstrated that LFM forecasts of boundary layer winds and surface pressure could be eliminated as predictors from the wind equations without any significant change in the quality of the MOS guidance. At the time, TDL developers were concerned that proposed modifications to the LFM might have significant impact on the characteristics of the winds in the boundary layer. These new equations eliminated all boundary layer and surface pressure variables (NWS 1982a).

An update to the LFM MOS cool season equations was implemented prior to the 1983-84 cool season (Carter et al. 1984, NWS 1983e); new warm season equations were implemented prior to the 1984 warm season (Carter et al. 1985, NWS 1985a). Other than the addition of more developmental data, these equations were essentially updates of the ones implemented in 1980 and 1981. Single-station equations were available for approximately 260 sites; guidance for seven sites was generated by regionalized-operator equations. These last two updates supported the LFM MOS wind guidance system for the CONUS until the LFM was eliminated.

9.5 Cloud amount/ceiling height/visibility/obstruction to vision

In April 1980, LFM MOS guidance for probabilistic and categorical forecasts of non-precipitating obstructions to vision was added to the FOUS12 for 233 CONUS sites. Given that precipitation was not observed at a station, predictand categories were defined as haze or smoke; blowing snow, sand, dust, or spray; fog or ground fog; and no obstruction to vision. Predictors included LFM variables; observations at $t_0 + 3$; station latitude, longitude, and elevation; first and second harmonics of the day of the year; and station relative frequency of ceiling $\leq$ 1500 feet and/or visibility $\leq$ 3 mi. Regionalized-operator equations were developed from a 4-year sample for both warm and cool seasons. Because of the persistence of low visibility conditions and the difficulty of predicting obstructions to vision with no indication of the state of the underlying surface (for instance, recently fallen snow, newly plowed fields in the vicinity of the station, or ground fog), station observations were used as possible predictors at all forecast projections, namely, at 6, 12, 18, 24, 30, 42, and 48 h after the initial model time of 0000 UTC or 1200 UTC. Categorical forecasts were made by using thresholds computed from the M & B unit bias model and comparing those thresholds to cumulative probabilities of the predictand categories.

New LFM MOS systems (NWS 1981c) to predict cloud amount (opaque sky cover), ceiling height, visibility, and non-precipitating obstructions to vision were implemented in June 1981 (Carter et al. 1982a) and October 1981 (Carter et al. 1982b) for the warm and cool seasons, respectively. Changes included: addition of guidance for 54- and 60-h projections, use of LFM data for development of **all** equations, an improved threshold technique for the categorical cloud guidance, simultaneous development of visibility and obstruction to vision equations to enhance guidance consistency, better developmental regions, and larger developmental samples. Regionalized-operator equations were developed for all four elements; the regions were derived by looking at conditional climatic frequencies of specific ceiling and visibility conditions. A maximum of 20 terms was allowed in the prediction equations. Potential predictors included the same variables used in the April 1980 development of guidance for obstruction to vision. For categorical forecasts, the threshold probability technique was used; appropriate thresholds were obtained by the M & B model. A unit bias in the MOS guidance was the goal for cloud amount, obstruction to vision, and categories 3 through 6 of ceiling height and visibility. To provide better warning for categories 1 and 2 of ceiling height and visibility, thresholds for these latter categories were designed to maximize the threat score of each while allowing the bias to range between 0.7 and 1.3. The guidance was available in the FOUS12 for approximately 235 CONUS sites for the 6- through 48-h projections. The four-panel facsimile chart that displayed the "flight weather" guidance was obtained directly from the six-category ceiling/visibility guidance.

The ceiling height, visibility, and obstruction to visibility guidance systems remained the same until LFM MOS was discontinued. However, new equations for cloud amount guidance were implemented in February 1988 (NWS 1988). Unlike some of the previous developments, the cloud amount equations were once again developed independently of those used for ceiling height. While this change increased the possibility of guidance inconsistencies between categorical clouds and ceiling height, the benefits to the cloud amount system included the elimination of LFM precipitation amount as a continuous predictor but retention of precipitation amount as a binary predictor. Moreover, station observations as possible predictors were restricted to projections of 24 h or less. The developmental sample was defined as the April 1979 through September 1987 period, thus providing 8 seasons of dependent data for the cool season, and 9 seasons of data for the warm season. The categorical guidance was obtained from the probabilities by using the M & B threshold probability model and a desired categorical bias of 1.0. In testing on independent data, the new guidance produced better skill scores than the older set of equations. By this time, only 204 CONUS stations in the long-lived NCDC archive provided reliable observations. However, because the prediction equations were based on the regionalized-operator approach, guidance was issued for approximately 310 sites in the FOUS12 message for the 6- through 48-h projections. Guidance for the 54- and 60-h projections was used in the sunshine prediction product (Jensenius 1988) and in computer-worded forecast products (NWS 1983f).

9.6 Probability of precipitation amount (PoPA)/categorical precipitation amount

As mentioned earlier, some of the equations used to generate the LFM MOS precipitation amount guidance when the Final FOUS12 was removed in April 1979 had been developed from PEATMOS predictors. To produce the Early FOUS12, LFM variables were substituted for the PEATMOS quantities. In April 1980, a new MOS quantitative precipitation forecast system derived entirely from LFM variables and the first and second harmonics of the day of the year was implemented (NWS 1980b). The dependent sample for this system was a significant expansion of samples used previously. LFM predictors for 0 to 24 h, for 30 to 36 h, and for 42 to 48 h were available from October 1972, April 1975, and February 1976, respectively, through September 1979. Optimally, MOS developers wanted samples from the same period for all projections, but for LFM MOS the benefit to the MOS guidance of longer, inconsistent samples outweighed the benefit of short, consistent samples. Regionalized-operator equations were developed for PoPA; the regions were subjectively determined by considering the relative frequency of precipitation amount events.

Other changes were made. The PoPA guidance for 24-h periods was removed from the FOUS12 and was replaced by 12-h PoPA guidance for projections of 12-24, 24-36, and 36-48 h after both 0000 and 1200 UTC. Categories for these 12-h periods were identical to the precipitation amount categories used for 24-h intervals, namely, $\geq$ 0.25, $\geq$ 0.50, $\geq$ 1.00, and $\geq$ 2.00. The PoPA guidance for 6-h periods was valid for 6-12, 12-18, 18-24, 24-30, and 30-36 h after both 0000 and 1200 UTC. The 36-42 h period was added for the 0000 UTC cycle only. Categorical guidance was also included in the FOUS12 message. The categorical forecasts were determined from the probabilities by using thresholds designed to maximize the threat score. Previously chosen subjectively, these thresholds were computed objectively by using the Bermowitz and Best technique (one of the subcategories of the M & B model discussed in Section 8).

9.7 Probability guidance for thunderstorms

One of the more significant LFM MOS implementations occurred in the spring of 1983 for the thunderstorm probabilities valid 12-24, 24-36, and 36-48 h after 0000 and 1200 UTC. For the first time, the thunderstorm guidance was available for the entire CONUS (NWS 1983d), rather than just the eastern half. The MDR data for the western U.S. had become available in 1978, and the same techniques used to develop LFM MOS equations for the eastern U.S. were applied to the west. Beam blockage due to mountains caused holes in the western radar coverage, but that issue was resolved by eliminating certain MDR grid blocks from inclusion in the regression analysis. No new equations were developed for the eastern sector. Consequently, the developmental LFM sample for the eastern and western CONUS were significantly different, and the expectation was that the boundary between the guidance for the eastern and western sectors would show significant discontinuities. A spatial smoother was applied along the boundary to eliminate apparent issues. Guidance from the MOS thunderstorm probability system was now available in the FOUS12 message for all stations in the CONUS, regardless of their location.

A landmark implementation occurred in June 1986 when new 6-h thunderstorm probability forecasts for the western CONUS became operational (NWS 1986). While the immediate impact of the guidance seemed small, the implications of the work were far-reaching. Ron Reap, who developed both the PEATMOS and LFM MOS thunderstorm guidance systems from MDR data, investigated the feasibility of using lightning strike location information from lightning direction-finding stations in the western U.S. Ron (Reap 1986) had obtained from the Bureau of Land Management (BLM) an archive of over two million cloud-to-ground lightning strike locations for the western U.S. The strikes were from the summer seasons (mid-June through mid-September) of 1983-84.

Ron also had archives of MDR and satellite estimates of cloud-top infrared temperature and maximum visible brightness values. By statistically analyzing the three datasets, Ron established that the geographical positions of daily lightning frequency corresponded well with topography and with conventional climatic seasonal relative frequencies of thunderstorms. However, the lightning data also revealed that approximately 41 % of lightning strikes occurred when no radar echoes were reported. Moreover, 87 % of the strikes associated with radar echoes occurred when the reported radar intensity value was less than VIP3, that is, the minimum value assumed to be associated with thunderstorms in the eastern CONUS. These two statistics alone indicated that using MDR reports as predictands in a statistical system significantly underestimated the occurrence of thunderstorms in the western CONUS. Two important conclusions resulted:

- lightning frequencies could be used as climatic predictors in the derivation of thunderstorm probability guidance to highlight spatial and temporal detail;
- lightning strike data used as predictands in a statistical system could lead to significant improvements in thunderstorm forecasting.

The thunderstorm probability guidance described in NWS 1986 was an important first step in demonstrating the value of the lightning location data. Probabilities for the 0–6 h, 6–12 h, 12–18 h, and 18–24 h periods were generated for a grid approximately 47 km on a side and covering the western U.S. The predictand used for the regression analysis was defined to be the occurrence at any hour during the appropriate 6-h period of two or more lightning strikes in a grid block. Predictors included various fields from the LFM and LFM-based trajectory model. Developmental data covered the three summer seasons of 1983-85. Twelve-term equations were derived for each of the four forecast projections, and the same predictors were used in each of the equations to enhance consistency among forecast projections. One of the most important predictors in the equations was the linearized KF term where K was the predicted K-index from the LFM and F was the daily climatic lightning frequency for each of the 6-h periods. Thus, F represented the number of strikes per day in a specific 47-km block. The KF variable represented the large-scale flow and attendant instability (K index) interacting with underlying topographical influences. While these probabilities were not displayed in an alphanumeric message like the FOUS12 bulletin, the data were sent to forecast offices via AFOS in a packed, gridded format. Ron Reap had worked with others to develop local software to unpack and display the probabilities on an AFOS screen. Ron continued work with both Don McGorman (Reap and MacGorman 1989) and with Richard Orville (Reap and Orville 1990) to establish the credibility and utility of the lightning detection network. While Reap developed other regional forecast products in the late 1980's and early 1990's, the lightning data were not fully integrated into the MOS system until the 2000's.

9.8 Conditional and unconditional probability of snow amount (PoSA)/categorical snow amount

First implemented in October 1977, the LFM MOS system to predict heavy snow (PoSH) underwent major revisions in the fall of 1982 (Bocchieri 1983, NWS 1982c). Categorical breakpoints were redefined ($\geq$ 2 inches, $\geq$ 4 inches, and $\geq$ 6 inches) for development of forecast equations. The snow amount predictand was conditional upon the occurrence of a pure snow event (precipitation was exclusively snow and/or ice pellets) during the 12 – 24 h period after 0000 or 1200 UTC. Observations used to determine the pure snow event were restricted to observations of precipitation at 3-h intervals (for example, 1200, 1500 1800, 2100, and 0000 UTC) and 6-h snowfall reports. The new conditional PoSA equations were developed from nine winter seasons (October – March, 1972-73 through 1980-81) of LFM data. As in other LFM MOS systems of this era, LFM boundary layer forecasts were eliminated as potential predictors. Predictor variables were either unsmoothed or smoothed by a 9-point filter, and were available as either continuous or binary quantities. Regionalized-operator equations (12 terms or less) were developed by application of the REEP screening technique. These regions were determined after developing generalized-operator equations, using the equations to make forecasts on the dependent sample, and calculating the overall bias of those forecasts at individual stations. Subjective modifications to the regional boundaries were also made according to station density and relative frequency of the snow event.

Unconditional probabilities were obtained in the same manner as the original system, namely, by multiplying the conditional PoSA for a category by the appropriate 12-h PoP and the weighted probability of a pure snow event during the 12-h interval. On the dependent data, the unconditional PoSA were used to determine threshold probability values by using the subjective iterative technique. In this particular application, the goal was to find thresholds that maximized the threat score of a specific category but limited the forecast bias of that event to be $\leq$ 1.3. Thresholds were applied by comparing the unconditional PoSA for the lowest amount category to the threshold probability for that category. If the PoSA exceeded the threshold, then the process was repeated for the next category, and was continued in the same stepwise manner until the threshold for a specific category was not exceeded. If no threshold was exceeded, then the categorical forecast was for < 2 inches of snow. If all thresholds were exceeded, then the categorical forecast was for $\geq$ 6 inches of snow. The conditional PoSA, the unconditional PoSA, and the categorical guidance were added to the FOUS12 message in the fall of 1982.

9.9 Guidance for Alaska

When the 7LPE model was replaced with the GSM in August 1980, LFM MOS equations for Alaska were unavailable. The operational system was maintained by substituting GSM fields in PEATMOS equations, but the MOS guidance deteriorated. In September 1982, a new LFM MOS guidance package containing 6- and 12-h PoPs, conditional probability of frozen precipitation, max/min temperature, 2-m temperatures, 10-m winds, and cloud amount (opaque sky cover) was implemented and disseminated in the FMAK1 message (NWS 1982b). While basic techniques for developing Alaskan guidance imitated those for the CONUS, changes were made in the seasonal stratification of the developmental data, in the forecast projections, and in use of observations as predictors. The differences between the Alaskan and CONUS guidance were done after extensive coordination with Alaska Region Headquarters and with U.S. Air Force liaison officers stationed in TDL. Table 6 lists the major developmental characteristics for the new Alaskan guidance.

The changes shown were significant and conformed to the needs of the Alaskan forecasters and user community. Other changes were somewhat less important. The developmental sample consisted of LFM forecast data from September 1977 through October 1981, providing a consistent dependent dataset for all projections. The use of observations as potential predictors for most projections reflected the importance of persistence in predicting weather conditions in Alaska. The simultaneous development of equations for max/min and hourly temperatures was adjusted from that used in the CONUS. Projections for the 12-h PoPs were modified to reflect periods closer to “day” and “night” in Alaska, that is, from 1800 to 0600 UTC and from 0600 to 1800 UTC, respectively. For PoF, the definition of frozen corresponded to the original definition used in the PEATMOS system, that is, snow or ice pellets not mixed with any other type of precipitation. Freezing rain, mixed precipitation, or rain were considered liquid. Unlike in the CONUS, PoF guidance in Alaska was valid year-round. Development of the Alaskan PoF equations utilized transformations of LFM thermal variables such as the 850-wet bulb temperature and the boundary layer potential temperature. The transformation used was identical to the one used for the CONUS equations (Section 9.2). However, the Alaskan PoF equations were developed by multiple linear regression and not by the logit procedure. For cloud amount, the predictand and predictors were nearly identical to those used for the CONUS guidance, except that observations were included as potential predictors out to 54 h. In the case of the Alaska cloud amount guidance, the beta model was used to obtain threshold probabilities for the categorical forecasts with a desired bias near 1.0.

Table 6. Major developmental characteristics for the LFM MOS Alaskan system implemented in September 1982. Observations at t_0 + 3 (t_0 = 0000 or 1200 UTC) were used as predictors at all forecast projections except those in bold print. Observations were not used as predictors during the 1200 UTC cycle for the temperature projections in italics.

Guidance Element	**Seasonal Stratification**	**Forecast Projections (h)**
Probability of precipitation – PoP Regionalized equations	Fall: Sept. – Oct. Winter: Nov. – Mar. Spring: Apr. – May Summer: June – Aug.	6-h periods ending at: 12, 18, 24, 30, 36, 42, 48, and 54 h after t_0; 12-h periods ending at: 18, 30, 42, and 54 h after t_0
Cond. prob. of frozen precip. (PoF) Regionalized equations	Cool: Nov. – Mar. Warm: Apr. – Oct.	Cool: 12, 18, 24, 30, 36, **42**, **48**, and **54** h after t_0; Warm: 12, 18, 24, 30, 36, 42, 48, and **54** h after t_0
Calendar day max/min temp. Single-station equations	Same as PoP	0000 UTC: today’s max, tmrw.’s min, tmrw.’s max, day after tmrw.’s min; 1200 UTC: tmrw.’s min, tmrw.’s max, *day after tmrw.’s min, day after tmrw.’s max*
2-m Temperature Single-station equations	Same as PoP	12, 18, 24, 30, 36, 42, 48, 54 h after t_0
10-m Surface wind Single-station equations	Same as PoP	12, 18, 24, 30, **36**, **42**, **48**, and **54** h after t_0
Prob. of cloud amt. (opaque) Regionalized equations	Same as PoP	12, 18, 24, 30, 36, 42, 48, and 54 h after t_0

When the guidance was implemented in September 1982, FMAK1 was expanded from 14 to 30 stations. Figure 6 shows a sample FMAK1 message. At the same time, PEATMOS aviation weather guidance was eliminated. In February 1984, a new aviation weather message (FMAK2) was implemented for the same 30 sites, and contained probability forecasts for ceiling height, visibility, and obstructions to vision (NWS 1984).

9.10 Computer-worded forecasts

In 1976, Bob Glahn assessed progress made in automating public weather forecasts (Glahn 1976). Besides reviewing MOS operational guidance, the development of computer-worded forecasts (CWF) was reviewed. The CWF designed to support the public weather forecast issued around 0900 UTC covered three forecast periods (today, tonight, and tomorrow), and had sufficient temporal detail in PoP, conditional probability of frozen precipitation, and cloud amount to indicate whether precipitation might occur in the morning or afternoon. The conditional probability of liquid precipitation characteristics (showers, drizzle, or steady) and thunderstorm probabilities were also available. Guidance for these particular elements was developed independently of PEATMOS guidance issued to NWS forecasters and was exclusively for development of the CWF.

Three years later, a detailed description of the algorithms used to construct the automated public weather forecast was provided (Glahn 1979b). By this time, LFM MOS guidance was used in the CWF and the availability of additional MOS guidance (for example, temperature forecasts for 3-h intervals as well as quantitative precipitation forecasts permitted construction of a more sophisticated CWF. Certain guidelines had been established:

- four basic weather elements were included – wind, temperature, clouds, precipitation;
- forecasts were segmented by period – today, tonight, tomorrow – and periods were combined only for very simple forecasts;
- significant weather elements were located at or near the beginning of a segment.

While the software to construct the CWF had been built and was running on the NMC mainframe computer in 1979 (Heffernan and Glahn 1979), the plan was to transmit digital matrices and CWF's on AFOS circuits to NWS forecast offices. There, another version of the CWF software would present the forecaster with options regarding the CWF: accept verbatim, do minor edits, do a wholesale revision, or disregard. Figure 7 shows a sample CWF from 1979.

The matrix and CWF were first transmitted on AFOS circuits in the early 1980's (NWS 1983f). This documentation represented a major milestone in post-processing NWP model output since publication of a Technical Procedures Bulletin conveyed approval of a product by NWS executive management. Now the field forecasters had access not only to the digital guidance (the CWF matrix or the LFM MOS FOUS12 bulletin), but they could also see an automated worded forecast based on that guidance. While many forecasters viewed this automation as a threat, others embraced the possibilities of the new technology. By the late 1980's, AFOS had been implemented in the NWS. Not all of the original vision had been realized, however, because of inadequate communications bandwidth and limitations in local computer processing power. Despite extensive work on the CWF during the 1980's, Glahn (1989) acknowledged that complete implementation of the CWF awaited the next generation of automation at NWS field offices.

9.11 A re-cap of the LFM MOS guidance

By September 1982, the probabilities for the three snow amount categories and the 6-h precipitation type guidance were available on the FOUS12 bulletin (NWS 1982e) between September 16 and April 30. Thunderstorm probabilities based on MDR data were available year-round. In early 1983, the max/min temperature for the fourth period and the 48-60 h PoP were added to the FOUS12 bulletin (NWS 1983a). At long last, LFM MOS guidance for the CONUS was complete. Figure 8 displays the alphanumeric product dubbed "SUPERFOUS" by some to distinguish MOS guidance from FOUS messages containing direct LFM output. Improvements were later implemented in the MOS guidance available in FOUS12, but the contents of the CONUS message were complete. By the late 1980's, the operational LFM MOS system produced guidance for the 6- through 60-h projections for about 350 civilian and 150 military locations in the CONUS and Alaska (Carter et al. 1989). Figure 9 shows major events during the history of the PEATMOS and LFM MOS guidance.

Several other housekeeping tasks were completed in January 1983. The FOUS22 message was entirely removed from the NWS AFOS circuit (NWS 1983c), and the Final FOUS22 was removed from all communication circuits. The Early FOUS22, now simply called FOUS22, continued on the regular communication circuits. Issued twice daily, this abbreviated LFM MOS message contained guidance for max/min temperature, 12-h PoPs, and PoF. A new message (FOUS21) was implemented and disseminated only on AFOS (NWS 1983b). This product contained fifth period max/min temperature guidance for 131 sites in the CONUS and 12 cities in Canada. This package was produced by applying K-L perfect prog equations to the GSM and was available twice daily at approximately 0800 and 2000 UTC.

10. NGM-BASED GUIDANCE – PERFECT PROG, MODEL RERUNS, MOS

Implementation of the Nested Grid Model (NGM) epitomized model development in the 1970's and 1980's. The NGM and its attendant analysis system were developed over an extended period of time beginning in the late 1970's (Phillips 1979). The new system, named the Regional Analysis and Forecast System (RAFS), was implemented by NMC in March 1985 (DiMego 1988). Changes to the RAFS ensued as problems appeared (Hoke et al. 1989). Significant modifications included more complete parameterization of the physical processes in July 1986, and a hemispheric temperature correction scheme in October 1987. The NGM was superior to the LFM, and the user community requested statistical guidance from the NGM. Because of changes in the RAFS, however, a relatively stable sample of model output suitable for MOS development did not begin until October 1987. Since a minimum of 2 seasons of data was deemed necessary for MOS development, NGM MOS guidance could not be implemented until October 1989.

In lieu of waiting, TDL decided to use the existing MOS infrastructure to develop and implement a "modified perfect prog" system (Erickson 1988). LFM analyses of upper air observations at 0000 and 1200 UTC were used as potential predictors by interpolating LFM fields to the stations for which MOS equations were desired. Since analyses were unavailable at 0600 and 1800 UTC, 6-h forecasts from the LFM were assumed to approximate observations, and interpolated values from these variables were included as possible predictors. After other modifications were made to the traditional perfect prog approach, specification equations were developed for 204 sites in the CONUS. Predictands included daytime max/nighttime min temperatures; precipitation amount over the 0000-1200 UTC or the 1200-0000 UTC periods; and wind speed, wind direction, and opaque cloud amount at 0000, 0600, 1200, or 1800 UTC. The meteorological definitions for these variables were identical to those used for the LFM MOS system. Specification equations were converted to forecast equations by modifying the projections of the model predictors so that the temporal relationship between predictor and predictand was retained, regardless of the projection of the predictand. The new NGM-based perfect prog system was implemented in May 1987 (Carter et al. 1989) and was an interim solution to supplement the complete LFM MOS guidance.

After some discussion and experimentation, Drs. Norm Phillips and Jim Hoke, the NMC modelers responsible for developing the NGM, became convinced of the need for NGM MOS guidance. With concurrence of the responsible managers, Jim Hoke established a mechanism whereby MOS developers could rerun the NGM on the Cyber 205 super-computer for a 1-year sample of October 1986 through September 1987. Reruns began in August 1988, and were completed by December 1988. MOS equation development based on 2 years of warm season (April – September) data began immediately afterwards. This effort was a milestone, marking the first time that the operational NWS model was rerun to increase the size of a MOS developmental sample.

The process used in development of LFM MOS guidance was followed for NGM MOS with some modifications. The NGM archive was more extensive than either the LFM or PE archives, particularly in terms of the vertical structure of temperature and relative humidity. Thus, the variety of possible predictors was greater (Jacks et al. 1990a, 1990b). In the first NGM MOS system, the predictands were restricted to daytime max and nighttime min temperatures, liquid-equivalent precipitation of 0.01 inches or more in a 12-h period, 10-m wind speed and direction, and opaque cloud cover. Equations were developed for both cool (October – March) and warm (April – September) seasons. The addition of the 1986-87 model data provided three cool seasons and two warm seasons for development. Extra data from outside the seasonal limits (8 days for the cool season, 15 days for the warm season) were included to increase the dependent sample size and to smooth the transition in the guidance during the seasonal equation change. The first NGM MOS system for the warm season was implemented for max/min temperature, 12-h PoP, 10-m wind speed and direction, and opaque cloud cover on July 26, 1989. The initial set of cool season equations was implemented on October 4, 1989. Figure 10 shows a sample of the first NGM MOS alphanumeric product (FOUS14). No graphics products were available.

Additional changes were later proposed to the RAFS. Working together, NMC and TDL suspected that certain changes would significantly impact the MOS guidance. After deciding on modifications to test, NMC conducted a 4-week parallel series of model runs. TDL found that the changes would have little or no impact on the temperature, PoP, or wind guidance. However, a change in the analysis that affected the relative humidity in the upper troposphere caused a deterioration in the MOS cloud guidance. To mitigate the effects, TDL re-derived the MOS cloud equations after removing 300-hPa relative humidity as a predictor and implemented new equations in September 1990 before the RAFS was operationally modified (Erickson et al. 1991). This close collaboration between NMC and TDL was crucial to ensuring the timely implementation of the NGM MOS guidance.

The scope of the 1989 implementation was limited due to time constraints. Guidance was available only for 204 stations in the CONUS, and the predictors screened were relatively simple. The NGM MOS system would be expanded substantially in the early 1990's by adding guidance for more stations and weather elements. Major enhancements to predictors were implemented, particularly the addition of grid-binary, conceptual model, interactive, and transformed variables. A numerical method of choosing probability thresholds required for selecting a categorical forecast from guidance probabilities was designed and adopted by all developers. General guidelines meant to standardize equation development were established. The following sections summarize steps to the ultimate NGM MOS guidance package.

9.1 NGM MOS developmental considerations

In the new NGM MOS system (Dallavalle et al. 1992), three factors influenced the predictand definition: the availability of an appropriate set of observations, the predictability of the weather event inherent in the NWP model, and the need to satisfy NWS guidance requirements for public, aviation, and hydrological forecasts.

As noted, the first implementation provided guidance for only 204 CONUS sites. Later, an extensive effort was made to increase the number of individual sites for which NGM MOS guidance was provided. New sites were selected according to the availability of observed data in the TDL archives, gaps in areal coverage, NWS requirements for additional aviation and hydrological forecasts, requirements to support operations at Air Force and Army bases, and requests by forecasters. Prior to a significant implementation in the fall of 1991, the number of potential stations with NGM MOS guidance was increased to approximately 660 sites in the CONUS and 20 sites in southern Canada. Later, guidance was added for sites in Alaska.

Temporal resolution of the enhanced NGM MOS system was driven by similar considerations, namely, availability and temporal specificity of observations, temporal resolution of NGM forecasts, and NWS requirements. For example, public weather forecasts required guidance for projections of 60 h or more after 0000 and 1200 UTC. Aviation weather forecasts required guidance with as fine a temporal resolution as possible out to approximately 36 h. Yet, the NGM only produced predictions to 48 h, and TDL's NGM archive contained NGM forecasts only at 6-h intervals over the 48-h period. Still, the temporal resolution of certain guidance elements was increase, and 60-h guidance was added for most weather elements.

Developmental samples for most of the NGM MOS guidance were based upon the traditional 6-mo warm and cool seasons, with an extra 8 to 15 days of data added at the beginning and end of the season. Exceptions existed for two weather elements, namely, thunderstorms and precipitation type. For the probability of thunderstorms and the conditional probability of severe thunderstorms, developmental data were stratified into 3 seasons, namely, cool (October 16 - March 15), spring (March 16 - June 30), and summer (July 1 - October 15). For probability of precipitation type, only one season (September 15 - April 30) was used. Cool and warm season stratifications were used for temperature and dew point, unlike the LFM MOS system that used equations developed from a 3-mo seasonal stratification.

For NGM MOS, generalized- or regionalized-operator equations were developed for all elements other than temperature, dewpoint, and 10-m wind speed and direction. The regionalized-equation approach was sometimes advantageous since guidance was possible for stations within a region that had no developmental data or were added to the statistical system after equation development. For temperature, dewpoint, and wind, single-station equations were developed, although some regionalized wind equations were developed to support U.S. Air Force requirements. In general, regions were subjectively determined after considering climatic relative frequencies, topographic features, data availability, and the relationship of the predictand to critical NGM forecasts. Developers aimed to combine stations into relatively homogeneous regions.

9.2 NGM MOS Predictors

Basic NGM variables included temperature, height, relative humidity, and wind components at constant pressure levels in the low and mid troposphere. Forecasts of precipitation amount, precipitable water, and mean relative humidity from the model surface to approximately 500 hPa indicated moisture. When interpolated to the station of interest, these variables formed a basic set of predictors. Derived variables such as thickness, dewpoint, temperature advection, relative vorticity, vorticity advection, stability indices, and moisture convergence provided additional information for specific guidance elements. New derived variables, such as equivalent potential temperature, modified lifted condensation level, advection of the K-index, wind speed shear, and divergence of Q-vectors were added to the NGM MOS system. New "interactive" predictors such as the product of the vertical velocity and K-index, Total Totals index, or mean relative humidity; and the product of the mean relative humidity and K-index or Total Totals index were created for the prediction of thunderstorms and severe thunderstorms. For precipitation type, a new predictor to measure the depth of warm air over a cold surface layer was constructed. For ceiling and visibility, predictors indicating the height at which certain dewpoint depressions were predicted by the NGM were devised, and mean relative humidity in several shallow layers above the surface was computed. In general, the predictor projection was within ± 6 h of the predictand valid time. Time averages or differences over 6-h periods of NGM forecasts were also used as potential predictors.

In previous MOS developments, predictors were used as both continuous and binary variables. In the binary form, the model variable of interest, possibly from a smoothed or calculated NGM field, was interpolated to the station of interest and compared to a user-specified limit. The binary was then set to 0 or 1, depending on whether the **interpolated** model forecast exceeded the limit. This "point-binary" was helpful in creating probabilistic guidance and was a key component of the REEP technique. One problem, however, with point-binaries was that a probability forecast could show sharp temporal or spatial discontinuities based on very minor differences in the value of the model variable at a station. John Jensenius (Jensenius 1992) developed the "grid-binary" approach to eliminate these problems and still fit the relative frequency of occurrence of an event with a multiple linear regression equation. In the grid-binary approach, the value of the model variable at each **grid point** is compared to the binary limit, and each grid point is then assigned a value of 0 or 1, according to whether the grid point value exceeded the limit. The result is a field of 0's and 1's that can be smoothed if desired. This field is then interpolated to the station of interest, resulting in continuous values between 0.0 and 1.0. The grid-binary approach was quickly accepted by the NGM MOS development team, and soon grid-binary model variables replaced most point-binaries.

Station observations were included as possible predictors when persistence was important for producing guidance. Because of the operational timing of the NGM, observations at $t_0 + 3$ (t_0 = 0000 or 1200 UTC) were first used as potential predictors for the very short-range projections of most guidance elements. In later developments, observations at $t_0 + 2$ were potential predictors. For probability equations, station observations were often treated as point-binary predictors. Backup or secondary equations with no observations as predictors were available when station reports were missing.

Geographical and climatic predictors were important in the NGM MOS development, particularly as the skill of the NGM decreased with increasing projection. For regionalized-operator equations, variables such as station latitude, longitude, and/or elevation were used as potential predictors. For ceiling height and visibility, a climatology of the relative frequency of ceiling height at a specific hour being less than 1000 feet or a visibility of less than 3 miles was developed to provide individual station information in the regionalized equations. Variables like the sine or cosine day of the year or the daily hours of sunshine were used in regionalized and single-station equations to explain seasonal variations in the predictand.

9.3 Probability of precipitation (PoP)

For the NGM MOS PoP guidance system implemented in 1989, regionalized-operator equations were developed to predict occurrence of liquid-equivalent precipitation of $\geq$ 0.01 inches in 12-h periods ending 24, 36, 48, and 60 h after 0000 and 1200 UTC. A maximum of 12 terms was allowed in these equations. Regions were determined subjectively by examining topography and the correlation between the occurrence of precipitation and the NGM forecast of mean relative humidity. Model predictors for the 24-, 36-, and 48-h guidance were valid at the beginning, midpoint, and end of the 12-h period. For the 60-h guidance, model predictors from the 48-h projection were used.

By November 1992, the second set of NGM MOS PoP equations had been implemented (Su 1993), and guidance for approximately 313 stations was transmitted in the FOUS14 message (Dallavalle et al. 1992). Five seasons of developmental data (October 1986 – September 1991) were available for equation derivation. Forecast equations were developed for 6-h periods ending every 6 h from 12 to 60 h after initial model time (0000 or 1200 UTC) and for the same 12-h periods as before. A maximum of 15 terms was allowed in the PoP equations. Equations for 12-h periods were developed simultaneously with the two 6-h periods spanning the 12-h window. This approach minimized inconsistencies among the 6- and 12-h PoPs. Grid-binary predictors, especially for precipitation amount, relative humidity, and moisture convergence, were important variables in the equations. Observations were not used as predictors. Regionalized-operator equations were developed; for the first time, hierarchical cluster analysis of the correlation between the 12-h PoP predictand and 14 frequently used predictors was applied to make a first guess of the appropriate regions. Examination of the results required some subjective modification of the regions. Nearly 400 stations had precipitation reports of sufficient quality to use in equation derivation. The NGM MOS system contained approximately 660 stations by this time, but limitations in communications bandwidth allowed dissemination for less than half of the sites.

9.4 Max/min temperatures, 2-m temperatures and 2-m dew points

For the first NGM MOS implementation in 1989, equations were developed to predict daytime max and nighttime min temperatures valid nominally at 24, 36, 48, and 60 h after initial model time (t_0) of 0000 and 1200 UTC. Daytime was still defined as 8 am – 7 pm LST during the warm season and as 9 am – 7 pm LST during the cool season. Nighttime was defined as 7 pm – 8 am LST during the warm season and as 7 pm - 9 am during the cool season. The max/min temperature guidance from the 0000 UTC (1200 UTC) forecast cycle was available for today's max (tonight's min), tonight's min (tomorrow's max), tomorrow's max (tomorrow night's min), and tomorrow night's min (day after tomorrow's max). These were the same periods for which LFM MOS and the NGM modified perfect prog guidance had been available. Single-station equations were developed for 200 of the 204 sites in this initial system. Regionalized-operator equations were developed for the other four sites since the dependent data sample for these sites was inadequate for single-station equations. For the first forecast period only, surface observations of temperature, dewpoint, and wind at $t_0 + 3$ were included as possible predictors; secondary or backup equations requiring only NGM variables and climatic terms were needed when surface observations were missing. For the first three forecast periods, NGM variables valid 12 h prior to, 6 h prior to, and concurrently with the nominal guidance projection were possible predictors. For the 60-h max or min temperature equations, only 48-h NGM forecasts were used as predictors. Prior to the issuance of the max/min temperature guidance, a check of the forecasts was made to ensure that the max and min temperatures for adjacent periods were meteorologically consistent, that is, that the max temperature was equal to or greater than the min temperature for adjacent periods, and that the min temperature was equal to or less than the max temperature for adjacent periods. When two values were inconsistent, the average of the two became the max and min temperature guidance for both periods.

A second implementation occurred in October 1991. Four significant modifications were made at that time. First, the definition of daytime was modified to be 7 am – 7 pm LST year-round. The definition of nighttime was changed to be 7 pm – 8 am LST year-round. This definition deliberately overlapped one hour of day and night around sunrise and reflected opinions of the four NWS CONUS regions. Since TDL was now using its archive of hourly surface aviation observations as predictand data and since daytime max and nighttime min observations were unavailable in either hourly or synoptic observations, the TDL algorithm to generate the necessary max or min temperature values from the appropriate hourly and max/min temperature observations was redesigned. The second notable modification was the addition of sites to the MOS system resulting from the availability of hourly observations as predictands. The new predictand data set contained observations for approximately 660 sites. Thirdly, two additional years of developmental data were included so that the dependent sample spanned the period of October 1986 – March 1991. Lastly, equations were developed to generate guidance for 2-m temperature and dewpoint for projections every 3 h from 6 to 60 h after 0000 or 1200 UTC. Observations of temperature, dewpoint, and wind at $t_0 + 2$ were included as possible predictors for projections out to 27 h. The addition of temperature and dewpoint as guidance elements required that equations be developed simultaneously for groups of predictands:

- 6-, 9-, 12-, and 15-h temperatures and dewpoints;
- 15-, 18-, 21-, 24-, and 27-h temperatures and dewpoints along with today's max temperature (0000 UTC cycle) or tonight's min temperature (1200 UTC cycle);
- 27-, 30-, 33-, 36-, and 39-h temperatures and dewpoints along with tonight's min temperature (0000 UTC cycle) or tomorrow's max temperature (1200 UTC cycle);
- 39-, 42-, 45-, 48-, and 51-h temperatures and dewpoints along with tomorrow's max temperature (0000 UTC cycle) or tomorrow night's min temperature (1200 UTC cycle); and
- 51-, 54-, 57-, and 60-h temperatures and dewpoints along with tomorrow night's min temperature (0000 UTC cycle) or the day after tomorrow's max temperature (1200 UTC cycle).

In operations, the two temperature (or dewpoint) values for the 15-, 27-, 39-, and 51-h projections were averaged for guidance. Hourly temperature and dewpoint guidance values were checked for consistency with each other. Consistency checks were also enhanced so that the max (or min) values for the second, third, fourth, and fifth groups were checked with each other and then were compared with the 3-h temperatures within that group.

By early 1992, the USAF had access to the complete temperature and dew point guidance. At that time, NWS and private forecasters received only the max/min temperature guidance for the original 204 stations in the FOUS14 message. In November 1992, the temperature and dewpoint guidance became available to NWS and private sector forecasters for approximately 310 stations (Dallavalle et al.1992, Miller 1993). In the spring of 1994, the FOUS14 message was expanded to contain data for approximately 530 CONUS sites.

9.5 Surface winds

The first NGM MOS wind equations (Jacks et al. 1990a) implemented in July 1989 were developed analogously to those used in the LFM MOS system. Equations were derived simultaneously for the u- and v- (east/west and north/south) wind components and the wind speed. Guidance was valid every 6 h from 6 to 48 h after 0000 and 1200 UTC. Single-station equations were developed for 202 of the 204 sites in this first system. For the remaining two sites, regionalized-operator equations were developed. Except for the 48-h projection, potential model predictors were valid 6 h prior to, concurrent with, and 6 h after the time of the wind predictand. For the 48-h predictand, model variables at the 42- and 48-h projections were used as potential predictors. For the 6- and 12-h projections from each cycle, observations of the 10-m wind at $t_0 + 3$ were also used as possible predictors. The development of these primary equations necessitated sets of secondary or backup equations for operational use when surface observations were unavailable.

A second major implementation of NGM MOS wind equations occurred in October 1991 (Miller 1993). Two additional years of NGM output were available so that the developmental data covered the period of October 1986 through March 1991. Equations were developed for the standard cool and warm seasons; the developmental sample at the beginning and end of each season was lengthened by adding eight days of model forecasts from the adjacent season. The predictand data set was the same one used for temperature and dewpoint development and provided observations for approximately 660 sites. For the first time, wind guidance was valid every 3 h from 6 to 60 h after both 0000 and 1200 UTC. Since NGM variables were only available with 6-h resolution, this increase in temporal resolution necessitated an adjustment of the potential predictors, that is, at projections of 9, 15, 21, …, and 45 h, the averages of model forecasts 3 h prior to and 3 h after the valid predictand hour were included as possible predictors. For the 6-, 9-, and 12-h guidance projections, station observations of the 10-m wind were included as possible predictors in the primary equations.

Another major change at this point was separating the NGM MOS stations into three groups: full-time observation sites for which single-station prediction equations were to be developed; part-time observation sites important to NWS forecasters for which single-station prediction equations were to be developed; and part-time observation or closed sites critical to the USAF for which regionalized-operation equations were to be developed. Due to the diligence of the USAF liaison (Capt. David Miller) assigned to TDL from 1989 to 1993, single-station equations were developed for a substantial number of USAF or Army bases. In contrast, for the LFM MOS system, wind guidance for the military bases was generated by generalized-operator equations. With the wind guidance now based on single-station equations for many of these sites, the quality of the guidance provided both to civilian and military forecasters was enhanced substantially. As noted previously, the guidance for all required locations was available to military forecasters by early 1992. The guidance for approximately 310 stations became available to NWS and the private sector in late 1992.

9.6 *Threshold probabilities and categorical guidance*

As described in Section 8, a number of approaches had been used in TDL to produce categorical guidance from probabilities for weather elements such as cloud amount, visibility, precipitation type, quantitative precipitation, etc. The subjective threshold probabilities and cumulative probability model once used had given way to objective techniques that modeled threshold probabilities with mathematical functions. However, Capt. Dave Miller concluded that the threshold approach could be improved if a numerical algorithm was used to generate the threshold probabilities from a dependent sample of probability forecasts, that is, the same sample used to derived the forecast equations. Since the equations were derived simultaneously for different categories of the same weather element, the consistency among probabilities of the different categories was enhanced, though not guaranteed. Moreover, with multiple linear regression equations, a forecast probability did not have to be $\geq$ 0.0 and $\leq$ 1.0. Consequently, the first step in the new objective iterative approach (or the "best-miller" scheme) was to "normalize" the probabilities. For the probabilities of exclusive categories (for example, clouds), the sum of the probabilities predicted by the equations must equal 1.0. The normalization procedure begins by setting all negative categorical probabilities to 0.0, and then summing the remaining positive probabilities to find the value S. The remaining positive probabilities are "normalized" by setting the new probability value equal to the original value divided by the sum S. For probabilities of cumulative categories (for example, 12-h precipitation amount), the probability of the most common category ($\geq$ .01 inches) should be the greatest value. The probability of the second most common category should be less than or equal to this value. If not, the value of the second most common category is set equal to that of the most common category. This process continues in a stepwise manner until the probability of the rarest category (for example, $\geq$ 2.00 inches) is the least value of all the probabilities. The objective iterative approach then searches the dependent dataset via a numerical algorithm to find a probability threshold that either minimizes the bias or maximizes the threat score for every category while keeping the bias within developer-specified limits. This objective iterative approach works optimally by starting with the rarest event and then ending with the most common event. Thus, when applied operationally, the scheme first attempts to predict the rarest category; the most common category becomes the default guidance when none of the categorical probabilities exceeds a threshold. Miller (1995), Meyer et al. (1997), and Antolik (2002) describe the process used for ceiling height, visibility, and precipitation amount, respectively.

9.7 Cloud amount

For the first NGM MOS implementation, regionalized-operator equations were developed to predict the probability of opaque sky cover for projections every 6 h from 6 to 48 h after 0000 and 1200 UTC. The regions were determined by topography and the correlation at stations between cloud amount and NGM forecasts of the mean relative humidity between the surface and approximately 500 hPa. As in the LFM MOS system, the predictand for opaque sky cover (cloud amount) was obtained from 0000, 0600, 1200, and 1800 UTC station observations. Categories of clear (0 tenths), scattered (1-5 tenths), broken (6-9 tenths), and overcast (10 tenths) were obtained from cloud amount reports, and equations to predict the probability of each of the four categories for a specific region and projection were developed simultaneously. Categorical forecasts were generated from the probabilities by comparing the probabilities to three threshold values selected via the M & B cumulative probability model to produce unbiased categorical forecasts.

Predictors for this first implementation (Jacks et al. 1990b) included several relative humidity variables at specific pressure levels unavailable in the LFM MOS system. For development of the cloud amount equations, all NGM predictors were valid concurrently with the projection of the predictand. Observations at t_0 + 3 were included in the primary equations as potential predictors for the 6- and 12-h forecast projections. As noted earlier, Erickson et al. (1991) determined that a proposed change to the RAFS would negatively affect the NGM MOS cloud amount guidance. By removing the 300-hPA relative humidity from the predictors used in the guidance equations, the negative impact was ameliorated. Otherwise, the equation development was identical to that used in the first implementation. These new cloud prediction equations were implemented in September 1990.

As the NGM MOS system was being expanded in the 1991 to 1993 period, cloud amount equations were developed once more. Approximately 6 years of NGM forecasts (October 1986 – March 1993) were available in the developmental sample, and the temporal resolution of the guidance was increased to be valid every 3 h from 6 to 60 h after both 0000 and 1200 UTC. The new cloud amount guidance system was implemented in July 1993. Categorical forecasts were obtained from the four probability forecasts by using the objective iterative threshold technique with unit bias.

9.8 Probabilities of ceiling height categories/categorical guidance

For ceiling height (Miller 1995), the predictand was the occurrence at a specific hour of a ceiling less than 200 ft, 200-400 ft, 500-900 ft, 1000-3000 ft, 3100-6500 ft, 6600-12000 ft, or greater than 12000 ft. These categories were slightly different than those used for the LFM MOS guidance. The revised categorical limits reflected requirements of the NWS and the USAF as well as limitations of the new automated surface observing system (ASOS). Equations were developed simultaneously to predict the probability of each category. From the probabilities of the seven categories, a “best” category forecast was made by the objective iterative threshold scheme designed to minimize the bias.

Hourly surface observations of the ceiling height were available as predictands for approximately 440 CONUS sites. Regionalized equations were developed to predict ceiling height at 3-h intervals from 6 to 36 h after the initial model time (0000 and 1200 UTC) and at 6-h intervals from 42 to 60 h after initial model time. The dependent sample consisted of data from October 1986 through March 1992. The standard 6-mo seasons were used for development, and when feasible, 8 days of seasonal overlap were included on either side of each season. The NGM predictors were available at 6-h intervals and were valid at the same time as the predictand for the 6-, 12-, …, 48-h guidance projections. For the 9-, 15-, 21-, 27-, and 33-h projections, time-averaged model variables were used. For the 54- and 60-h guidance, 48-h NGM predictors were screened. NGM predictors included several variables new to the MOS system such as advection of relative humidity in the lower troposphere, the product of relative humidity at certain levels and either the K index or the vertical velocity, and a conceptual model indicating the height of a cloud base. Model variables were used as continuous or grid-binary quantities. Climatic variables included the monthly relative frequency of ceiling height less than 1000 ft at 0000, 0600, 1200, and 1800 UTC. These values were calculated from a 10-year sample of observations. Station latitude, longitude, and elevation were included as potential predictors. Finally, observations at t_0 + 2 hours (t_0 = 0000 or 1200 UTC) were screened as predictors for the 6-, 9-, and 12-h primary prediction equations. These variables provided an indication of persistence for ceiling height, and were often used as point-binary quantities. A maximum of 15 terms was allowed in all equations.

The ceiling height guidance was implemented on January 27, 1993. Unlike the LFM MOS guidance, in the NGM MOS message only categorical forecasts were provided. While the ceiling guidance in FOUS14 was available to the 48-h projection, the 54- and 60-h guidance was disseminated in USAF alphanumeric messages.

9.9 Visibility and obstruction to vision

For visibility (Meyer et al. 1997), the predictand was the occurrence at a specific hour of visibility less than ½ mi, ½ - 7/8 mi, 1 – 2 ¾ mi, 3-5 mi, and greater than 5 mi. For obstruction to vision, the observation was divided into three possible categories, namely, fog or ground fog, haze, or neither of these two phenomena. This definition was notably different from the “obstruction to vision” predicted in the LFM MOS system. For one thing, fog occurring in precipitation was now considered a valid obstruction in the NGM MOS system. Secondly, no attempt was made to predict blowing phenomena since observations of the ground or snow cover conditions were unavailable. Both factors were critical to determining when soil, dust, or snow were likely to become air-borne and decrease visibility. In the NGM MOS system, guidance for obstruction to vision was oriented to decreases in visibility caused by water droplets or haze particles. Equations for visibility (five categories and obstruction to vision (three categories) were developed simultaneously to minimize inconsistencies between the two types of guidance.

The guidance for visibility and obstruction to vision was valid at 3-h intervals from 6 to 36 h after t_0, and at 6-h intervals from 42 to 60 h after t_0. Predictors used were similar to those for ceiling height, except that the climatic relative frequency of visibility less than 3 mi was included as a potential predictor. Also, observations at $t_0 + 2$ were screened as possible predictors in the equations valid for the 6- through 24-h projections. The dependent data sample was one year longer (October 1986-March 1993) than that for development of ceiling guidance. Eight days of seasonal overlap were added to the warm season sample; no days were added to the cool season. Regionalized equations were developed for visibility/obstruction to vision; the regions were selected on the basis of similar climatic relative frequencies at approximately 440 sites in the CONUS. A maximum of 18 terms was allowed in these equations. Categorical forecasts were based on the objective iterative approach described in Section 10.6. For both visibility and obstruction to vision, threshold probabilities were designed to maximize the threat score while restricting the forecast bias to be in the range of 0.70 to 1.30 during the warm season, and 0.85 to 1.15 during the cool season. The NGM MOS visibility/obstruction to vision guidance was implemented in July 1993.

10.10 Probability of thunderstorms and severe thunderstorms

When the first set of equations was developed for these probabilities, lightning location data were unavailable for portions of the CONUS. In lieu of postponing the development, the predictand was defined by combining reports of thunderstorms from hourly surface observations, radar echo intensity values (MDR data), and reports from spotter networks in the NSSFC Severe Local Storms (SELS) logs (Bower 1993). As was done previously, a radar echo at Video Integrator and Processor level 3 (VIP3) was chosen to indicate occurrence of a thunderstorm. Since MDR reports were for grid blocks approximately 47 km on a side and since stations were not normally located at the mid-point of a block, the "reporting" location for a station was defined as a three by three array of blocks with the station located in the interior block. Thus, a station's hourly observation of a thunderstorm, an MDR report of VIP3 or greater within the station's area, or a SELS log report within the same area indicated thunderstorm occurrence. Reports from approximately 430 sites in the CONUS were accumulated over 6-, 12-, or 24-h periods to define the predictand. Similarly, a severe thunderstorm was defined by a station's hourly observation of a severe weather event or a SELS log report within the station's area.

Equations were developed to predict the probability of thunderstorms and the conditional probability of severe thunderstorms for 6-h intervals ending every 6 h from 12 to 60 h after 0000 and 1200 UTC (Bower 1993). Unlike the LFM MOS system, forecast equations were developed for 12-h intervals ending 18, 30, 42, and 54 h after 0000 and 1200 UTC; these intervals coincided more closely with periods of maximum and minimum thunderstorm activity in the CONUS. Equations were developed simultaneously for a 12-h interval and the two 6-h periods spanning that interval. To support NSSFC, forecast equations were also derived for 24-h periods ending 36 and 60 h after 0000 UTC. Regionalized-operator equations were available for three seasons: spring (March 16 - June 30), summer (July 1-October 15), and cool (October 16-March 15). The developmental sample extended from October 1986 through March 1991. Probability guidance for thunderstorms and severe thunderstorms was added to the FOUS14 on November 4, 1992. In October 1991 and February 1992, respectively, the thunderstorm and severe thunderstorm probabilities became available to the USAF and the NSSFC.

In November 1994, NGM MOS 24-h thunderstorm probabilities developed from lightning data and conditional probabilities of severe thunderstorms developed from SELS logs were implemented for the entire CONUS (Reap 1994). These 24-h probabilities replaced the LFM MOS system operational since the late 1970's. The probabilities were valid 12-36 h and 36-60 h after 0000 UTC, and 6-24 h and 24-48 h after 1200 UTC. The predictand data for the thunderstorm probability system was the occurrence of two or more lightning strikes within a 47-km block; the lightning strike data were obtained from lightning detection networks operated by the State University of New York at Albany, the National Severe Storms Laboratory, and the Bureau of Land Management. The sample covered the 1987-1990 period. The definition used for severe weather (conditional upon two or more lightning strikes in a grid block) was the same one used in the LFM and initial NGM MOS systems, that is, the occurrence of tornadoes, large hail (3/4 inches or greater in diameter), and/or damaging winds reported in the SELS logs. Regionalized-operator equations were available for two regions, namely, the eastern and western U.S., and for two seasons, namely, a warm (March 15 – September 30) and a cool (October 1 - March14) stratification. In contrast, severe weather equations were developed for spring (March 15 - June 15), summer (June 16 - September 30), and cool (October 1 - March 14) seasons. A categorical forecast (automated convective outlook) was also generated for the same 24-h periods by a technique documented in Reap 1994. A lack of time and staff precluded expanding this development effort to the 6- and 12-h probabilities available in the FOUS14 message.

10.11 Conditional probability of precipitation type, categorical guidance

In November 1992, the new NGM MOS probability of precipitation type (PoPT) guidance system was implemented (Erickson 1995). Four significant changes were made to the NGM MOS system compared to the LFM MOS PoPT. First, the temporal resolution of the NGM MOS PoPT was increased. Guidance was available at

3-h intervals from 6 to 36 h, and at 6-h intervals from 42 to 60 h after 0000 and 1200 UTC. Second, multiple linear regression was used to develop the MOS equations, not the logit model. Third, the predictand definition was modified. While the notion of three categories was retained from the LFM MOS system, for the NGM MOS definitions, freezing precipitation included all freezing rain, freezing drizzle, **and** ice pellet events, even if these elements were mixed with liquid or frozen precipitation. Ice pellets were moved into the freezing precipitation category for several reasons, namely, the impact on society of freezing rain or ice pellets was similar to one another; the pure snow event was uniquely hazardous and needed to be distinguished from ice pellets; the ice pellet category could not be treated uniquely because of its rarity; and an analysis of NGM forecasts showed vertical soundings for events of freezing rain and ice pellets were nearly identical. The fourth significant change in developmental procedures was that continuous, grid-binary, and point-binary variables were all used in equation development. Point-binaries were only applied to station observations, not to NGM forecasts.

The developmental sample for the CONUS consisted of NGM data for 6 cool seasons (September 16 – May 15) of 1986-87 through 1991-92. Observations were available from approximately 470 sites. Equations were developed by the regionalized-equation approach; stations were grouped in regions according to a 10-year climatology of the conditional monthly frequency of freezing precipitation and of snow, topography, and correlation of the predictand with important predictors. Station observations at $t_0 + 2$ were used as potential predictors for the 6- through 18-h projections. The NGM predictors (Erickson 1992, Erickson 1995) included several sophisticated variables. For instance, the pressure of the level where the wet-bulb temperature was below freezing was calculated. A determination was then made as to whether a layer of above freezing temperatures existed over this cold layer. Logit transforms of 850 hPa temperature, 1000-850 hPa thickness, and 850-700 hPa thickness were used to relate occurrence of snow at individual stations to continuous variables. Thus, the regionalized equations had individual station information in the predictors. Finally, the unit bias model produced categorical forecasts from the probabilities. The cumulative thresholds required were computed via the objective iterative algorithm with freezing rain treated as the rarest event.

10.12 Probability of snowfall amounts/categorical guidance

Snowfall amount guidance (PoSA) for the CONUS was implemented for over 300 sites in May 1993 (Bower 1994). A year later, guidance was extended to more than 500 sites. Forecasts were valid for 6-h periods, ending every 6 h from 12 to 60 h after the initial model time t_0 of 0000 and 1200 UTC. Guidance for 12-h periods was also generated for projections of 12-24, 24-36, 36-48, and 48-60 h after t_0. Observations of snowfall were reliably available only in the TDL archive of hourly reports collected at NCDC. Consequently, predictand data for equation development were restricted to approximately 185 CONUS sites. For 6-h periods, equations were derived to predict the probability of no snow, $\geq$ trace, and $\geq$ 2 inches. For 12-h periods, equations were developed for the events of no snow, $\geq$ trace, $\geq$ 2 inches, $\geq$ 4 inches, and $\geq$ 6 inches. All equations were developed by the regionalized-operator approach; grouping of stations into regions was done by geography, relative frequencies of snow events, and correlation at individual stations between the predictand and important predictors. The CONUS equations were restricted to a maximum of 18 terms.

The snowfall amount guidance was valid for the September 16 through May 15 season. For the equation development, NGM forecasts for the period of October 1986 through May 1992 were available. Model variables included basic fields as well as various interactive predictors; these variables were used in either continuous or grid-binary form. Because the snowfall predictand was unconditional, NGM MOS forecasts for the 12-h PoP and the conditional probability of frozen precipitation were used as potential PoSA predictors. The MOS PoP and PoF forecasts were retrospectively produced for the period of the dependent sample. Climatic predictors at stations such as hours of sunshine and relative frequency of 12-h snowfall amounts were included for all projections in order to distinguish among stations within a region. Finally, hourly observations of present weather and temperature at $t_0 + 3$ were included as potential predictors for the 6-12 h and 12-18 h projections.

The categorical guidance was obtained from the probability values by using the objective iterative threshold scheme. In this application, thresholds were calculated by maximizing threat score while restricting the bias within a certain range. For the most common snowfall category of a trace to less than 2 inches, unit bias was the goal. For all other categories and all projections out to 48 h, the bias range was 1.0 to 1.3. For projections beyond 48 h, the bias was restricted to be 0.7 to 1.0 to avoid over-predicting snow amount. The threshold procedure for PoSA went from the rarest event, namely, the greatest snowfall amount, to the least. Default categorical guidance for PoSA was no snowfall.

10.13 Probability of liquid-equivalent precipitation amount/categorical guidance

The NGM MOS guidance for probabilistic and categorical precipitation amount (QPF) was implemented for CONUS sites in October 1993. This guidance represented the first public weather product developed for QPF since 1980. Predictands for the development (Antolik 2002) were taken from hourly data reports at approximately 400 sites in the CONUS. Equations were developed for 6-h periods ending 12 to 60 h after 0000 or 1200 UTC, and for 12-h periods ending 24 through 60 h after 0000 or 1200 UTC. The equations for the 6-h probability of precipitation amount were developed simultaneously for categories of $\geq$ 0.01 inches, $\geq$ 0.10 inches,$\geq$0.25 inches, $\geq$ 0.50 inches, and $\geq$ 1.00 inches. The equations for the 12-h probability of precipitation amount were developed similarly except that a category of $\geq$ 2.00 inches was added. In the REEP multiple linear regression technique used in TDL, the predictand was equal to 1 for each category that the reported precipitation amount exceeded the lower bound, and to 0 when the lower bound was not exceeded. For the lower bound of $\geq$0.01 inches, this procedure duplicated development of PoP equations, but the second set of PoP equations was necessary for generating categorical QPF guidance. The redundant PoPs were not issued to the forecasters and were eliminated in development of GFS-based QPF during the 2000's.

Predictor data were available from 7 years of NGM forecasts (October 1986 – March 1993) and included NGM basic variables, derived variables, grid-binary variables, and geoclimatic terms. The grid-binary predictors were the most common variables used in the equations. All equations were regionalized-operator relationships. Up to 15 terms were allowed in an equation. The procedure for developing the categorical guidance from the probabilities was identical to the objective iterative approach described in Section 10.6. For QPF, Antolik (2002) aimed to maximize the threat score while producing categorical forecasts with a bias close to 1.0. The ability to maximize the threat score was related to the skill of the MOS QPF. Since the skill of the MOS guidance declined with increasing projection and the rarity of the event, that is, the greater amounts of precipitation, the thresholds for all events at the later projections were designed to maintain biases of approximately 1.0. For the earlier projections, biases up to a maximum of 1.4 were allowed for the event of 0.50 inches or more of precipitation in a 6-h period, and for the event of 1.00 inch or more of precipitation in a 12-h period. In this way, the QPF guidance was designed so that performance would be maximized when justified by the skill of the system.

10.14 NGM MOS guidance in the CONUS - FOUS14

The FOUS14 bulletin (the FWC in the NWS system) was implemented in May 1987 when the message contained modified perfect prog guidance based on the NGM. Guidance was available for 204 sites in the CONUS. In July 1989, NGM MOS guidance replaced the perfect prog values in the FOUS14 message; forecasts were available in the identical format for the same elements and stations as in the original message. Guidance for more elements and additional stations was developed during 1991 and 1992; a revised FOUS14 message was implemented in November 1992. Guidance was now issued for 313 sites in the CONUS (Dallavalle et al. 1992). The contents of the message were completed in October 1993 with the addition of QPF. Figure 11 shows a sample message. Compared to the FOUS12 (the LFM MOS message), FOUS14 contained much more information in terms of weather elements and temporal resolution. However, probabilities for QPF, snow amount, clouds, ceiling height, visibility, and obstruction to vision were not included in the message. These modifications resulted from feedback from both the NWS and private forecaster community. In April 1994, changes were made to issue the FOUS14 for 529 stations; another change in August 1995 increased the number of stations in the FOUS14 to 565 (author's notes). The FOUS14 continued in NWS operations until removal in March 2009.

10.15 NGM MOS guidance in Alaska

The first NGM MOS product implemented for stations in Alaska (Reap 1991) was developed in response to a request from the Alaska Scientific Services Division. Thunderstorm probability guidance for 12-h periods of 6-18 h and 30-42 h after 1200 UTC and18-30 h after 0000 UTC was generated. The MOS equations predicted the probability of two or more cloud-to-ground lightning strikes in a 47-km grid block during the 12-h valid periods. These periods, centered on 0000 UTC (1500 LST in Alaska), correspond to the time of maximum thunderstorm occurrence in Alaska (Reap 1991). Alaska Region had requested the guidance as an aid in predicting regions of wildfire activity caused by lightning. The predictand data were provided by the Bureau of Land Management's automated lightning detection network. The developmental sample covered 3 warm seasons (May 1 - September 30 during the 1987-1989 period. The NGM predictors were analogous to those used when the first lightning products were developed from the LFM for CONUS sectors. The new equations for Alaska were implemented in the NWS operational network in May 1990. The MOS probabilities generated from these equations were packed into the GRIdded Binary (GRIB) format and were transmitted to NWS Alaska computers for decoding, contouring, and display. Actual decoding of the GRIB messages was not implemented in Alaska until May 1991.

In October 1994, the FOAK13 message was implemented for 60 sites in Alaska. Unlike the LFM MOS message for Alaska, the format and contents of the Alaskan NGM MOS message (Dallavalle et al. 1995) were quite similar to those of the CONUS message. In general, the predictands were identical with the exceptions that 12-h PoP, 12-h QPF, and 12-h PoSA intervals were centered on 0000 and 1200 UTC, like the Alaskan thunderstorm probabilities. In Alaska, the PoPT and PoSA guidance were valid during September 1 – May 31. The other difference between CONUS and Alaskan guidance was that blowing phenomena were retained in the Alaskan MOS system for obstructions to vision.

Equations to predict wind direction and speed for the 60 sites in Alaska were developed and implemented in December 1994 (Foose 1997). This implementation completed development of NGM MOS guidance for Alaska. The Alaska NGM MOS guidance was removed in March 2009.

11. Medium-Range Forecast Guidance Based on the Global Spectral Model

TDL had developed PEATMOS equations for the 72-h calendar day max and min temperature in the 1970's (Section 7.3, 7.9), but the guidance had been replaced by K-L perfect prog forecasts because of problems with timeliness. Carter et al. (1989) described the statistical guidance for projections beyond 2 days thusly: *"The statistical guidance in support of forecasts beyond 2 days has been very limited. For many years, only perfect prog max/min temperature guidance was available for 143 locations throughout the contiguous United States and southern Canada."* Carter et al added: *"Since April 1985, 2- to 6-day MRF-based MOS forecasts of max/min temperature and PoP also have been produced daily for approximately 200 locations in the contiguous United States."*

Since November 1982, TDL had provided statistical forecasts of the calendar day min/max for the 84- through 192-h projections to NMC's Medium-Range Forecast Group (MRFG) for help in preparing the 3- to 5-day forecast package. The statistical guidance was generated by applying the K-L perfect prog equations to output from the 0000 UTC run of the Medium-Range Forecast (MRF) model. The MOS system implemented (Dallavalle and Jensenius 1985, Palko et al. 1985) in April 1985 was also intended for the MRFG, but the techniques used in development were chosen to minimize the impact of future changes planned for the MRF model (also called the Global Spectral Model or GSM). The predictands were calendar day max/min from approximately 36 to 144 h after 0000 UTC and the 24-h precipitation amount (0000-0000 UTC) ending every 24 h from 48 to 144 h after 0000 UTC. If the predictands are considered valid in terms of days with day 1 (today) denoting the initial time of the MRF model, then the calendar day max/min and the probability of 24-h precipitation amount $\geq$ 0.01 inches were valid for day 2 (tomorrow) through day 6; those periods matched the guidance requirements of the MRFG. The guidance was developed for approximately 200 stations in the CONUS, essentially the same sites used for the initial NGM MOS development. Equations were developed for the standard warm and cool seasons for max/min temperature and PoP.

The standard MOS techniques used in previous developments were modified because changes were planned to the GSM/MRF model later in 1985. The goal was to reduce differences in characteristics between the model in the dependent sample and the modified model to be implemented later. Simple model variables were chosen as predictors and were smoothed over large areas of the model grid before interpolation to stations. Time averages of thermal and relative humidity variables, the 1951-80 max/min temperature normal, and the climatic monthly relative frequency of $\geq$ 0.01 inches during the 0000-0000 UTC period were included as potential predictors. The max/min temperature equations for the same calendar day projection were developed simultaneously, thus enhancing consistency in the guidance. For these equations, the number of terms was limited to 10, and the regression procedure was halted when no potential predictor added a minimum of 0.75 % to the reduction of variance of the predictand explained by the equation. For the PoP equations, larger regions than in other MOS developments were used, the regression was stopped at a cutoff of 0.50 % in the reduction of variance, and the average value calculated from the mean relative humidity (the relative humidity from the model surface to approximately 500 hPa) at the beginning and end of the 24-h PoP period was forced into all prediction equations. Tests on independent data showed some deterioration in the bias of MOS guidance when calculated from the modified MRF model. However, the MOS guidance still improved relative to a climatic forecast, and the correlation of the MOS guidance with observations seemed to improve with the improved MRF model.

Until 1992, these systems provided the primary statistical guidance generated by TDL for projections beyond day 2, the bulk of the guidance being provided only to NMC's MRFG. In December 1992, however, a milestone was reached when a package of MRF-based statistical guidance (Jensenius et al. 1993) was implemented and issued to the forecast community. Guidance was available for daytime max and nighttime min temperatures, 12-h PoPs for 0000-1200 UTC and 1200-0000 UTC periods, and mean opaque cloudiness during the same 12-h periods. The 24-h PoP valid from 0000 to 0000 UTC was predicted by combining the appropriate 12-h PoPs (Wilks 1990). The guidance was generated from the 0000 UTC run of the MRF model and was valid for projections 24 to 192 h after 0000 UTC. Jensenius et al. (1992) described the development of the equations required for the PoP and max/min temperature guidance. These equations were based on a modified perfect prog approach similar to that used in 1987 for the first NGM-based guidance system. The predictors were selected from LFM analyses and 0-12 h forecasts, and specification equations relating station observations to analyses and the very short-range forecasts were developed. Because developmental data came from the LFM, the dependent sample was extensive (December 1983 through November 1990). For max/min temperature, the dependent sample was divided into the standard 3-mo seasons of spring, summer, fall, and winter, and single-station equations were developed for approximately 200 stations in the CONUS and 14 sites in Alaska. For PoP, the traditional warm and cool seasons were used for development, and regionalized equations were derived. Predictors were based primarily on geostrophic fields or mean temporal values; for PoP, especially, grid-binary variables were extensively used.

The specification equations were converted to prediction equations by replacing LFM variables in the specification equations with MRF variables representing the guidance projection and preserving the temporal relationship between predictand and predictor. This application of the modified perfect approach used two unique techniques. First, extensive tests were done with various smoothers on the fields of LFM data; eventually, different specification equations with different predictor smoothers were developed. Jensenius et al. had recognized that the short-wave predictability in the MRF deteriorated faster with time than that of the long-waves. Thus, smoothing of predictors over larger areas seemed like a way to make the modified perfect prog scheme behave more like MOS. Second, Jensenius et al. developed a calibration scheme to account for systematic biases in the guidance. This calibration scheme depended on converting both guidance and verifying observations to departures from normal. By verifying the original modified perfect prog guidance on a sample of independent data, a correction equation was derived to relate the calibrated forecast departure from normal to the slope of the linear regression between the uncalibrated forecast and the verifying observation. The procedure was designed to minimize the mean square error of the guidance by forcing the guidance to tend toward normal climatic conditions as the skill of the guidance declined. The calibration also removed systematic biases found in verification on independent data. In tests comparing the calibrated perfect prog max/min forecasts to the guidance already provided to the MRFG, Jensenius et al. found that calibration improved temperature accuracy by as much as 1 to 2 days. The recommendation was that 1 to 2 years of verification on independent data be done for the calibration, particularly if one of the years was highly anomalous. The calibration scheme was adaptable to MOS guidance if a significant change had occurred in the operational model supporting the guidance.

As noted earlier, guidance for the mean opaque cloud cover over 12-h periods was included in the December 1992 implementation. The mean opaque cloud cover was defined as a weighted average of hourly observations of opaque cloud cover at 3-h intervals from 0000 to 1200 UTC or from 1200 to 0000 UTC. The average was calculated by assigning a weight of 1.0 to the observations at the initial and ending hours of the 12-h interval. The reports for the three intermediate hours were assigned a weight of 2.0. However, by December 1992, a series of problems led to abandoning the modified perfect prog approach (Jensenius et al. 1995), and the regional equations for cloud prediction were based on the MOS technique applied to a sample of MRF model data. The equations used for max/min temperature and PoP guidance in the December 1992 implementation were those described in the previous paragraph. The calibration scheme was applied operationally to the guidance for max/min temperature, PoP, and mean opaque cloud cover.

In July 1993, MRF-based MOS equations to predict the mean wind speed for 12-h periods were implemented, and guidance for mean wind speed was added to the medium-range guidance package. The predictand for development of the necessary equations was calculated as a weighted average of hourly observations in the same manner as used for mean opaque cloud cover. In October 1993, the MOS conditional probability of snow – conditional on a significant precipitation event – was added to the guidance package. In this instance, for the 0000 to 1200 UTC interval, a “significant event” was defined as precipitation occurring at a minimum of two hourly reports from the 0000, 0300, 0600, 0900, and 1200 UTC group. Moreover, the two reports were separated by a minimum of 6 h. The definition for a significant event during the 1200 to 0000 UTC interval was analogous. Once a significant precipitation event was established, then each of the precipitating reports was assigned a value of 0.0 for liquid precipitation such as rain or drizzle; 0.5 for freezing rain, ice pellets, or mixed precipitation of any kind; or 1.0 for pure snow. The average of the values for the 12-h interval provided the MOS predictand. In April 1994, the modified perfect prog equations for max/min temperature were replaced by MRF MOS equations based on 3-mo seasons and approximately 5 years of developmental data. In January 1995, the MRF PoP guidance became a MOS product. In all cases, the calibration approach was retained. Jensenius et al. (1995) and Dallavalle (1996) discuss changes made in the guidance after the initial implementation of December 1992.

A sample MRF message is shown in Fig. 12 (Jensenius et al. 1993). The guidance represented the first substantial effort at producing a complete package describing weather of interest to the public at projections out to a week in advance. As requirements evolved, more detailed information became necessary, and this particular guidance package was eliminated in April 2003.

In August 1994, the same equations used in generating the medium range guidance were applied to the Aviation run (AVN) of the GSM (Jensenius et al. 1994). The AVN was run at approximately 0600 and 1800 UTC; thus, statistical guidance from this model provided the forecasters with an “early” look at expected conditions beyond the normal 60-h projection. The alphanumeric message (not shown) was identical to the one containing the medium-range guidance, except that guidance was provided only for projections of 24, 36, 48, 60, and 72 h, and 24-h PoPs and mean wind speed were eliminated. In comparisons with the 60-h NGM MOS guidance, the AVN MOS guidance for the 60-h max/min temperature was more accurate. This comparison provided impetus for development of the next generation of MOS guidance for short-range projections. The AVN guidance package was removed in April 2002, replaced by a complete short-range package of GSM-based MOS guidance.

12. An Era of Change: 1993 - 2000

In December 1993, Bob Glahn, Director of TDL, asked senior-level MOS developers to suggest design features for a new MOS development system. By 1993, the MOS-1974 system had been in use for nearly 20 years and needed replacement. The deficiencies of the system were a lack of portability, a lack of flexibility and responsiveness to new requirements, developmental software not matching software needed for implementation, non-standardization of archived model and observational datasets, binary files when ASCII files would suffice and be simpler to modify, growth of the MOS-1974 system in a non-systematic way, and a near exhaustion of reasonable ways to identify new model fields or MOS guidance elements. The lack of portability was compounded because the MOS-1974 system had run for nearly 20 years on IBM-type mainframes utilizing a proprietary operating system. While the MOS-1974 system worked efficiently on the NMC mainframe operational in 1993, the MOS-1974 system could not be ported to another computer environment without extraordinary effort. The problem was summarized (Glahn and Dallavalle 2002) succinctly: "*this 1970's system (henceforth, called MOS-1974) could not meet the NWS need for guidance for more locations, projections, and issuance times per day; from more models; and from ensembles.*"

In response to Bob's request, TDL developers designed a new variable identification scheme that would not only define the variable, but also govern computations to be made on that variable. Bob designed a new packed data format (TDLPACK) that was analogous in many ways to GRIB but with greater data compression. In addition, while GRIB only handled gridded data, TDL had archives of both gridded model data and station-oriented observational data. One of the biggest advantages of TDLPACK was its ability to pack station-oriented observations, climate values, or guidance into a GRIB-like format. That TDLPACK handled both gridded and point data (dubbed "vector" data) was a boon to the new MOS system by eliminating the need for additional archiving schemes for new observational datasets.

By the end of 1994, the MOS group was shifting all developmental efforts to creating and testing the new MOS system. However, another major change would impact these efforts. In 1995, NCEP (formerly NMC) declared a moratorium on operational changes and announced a major effort to port **all** operational processes, all necessary software, and all data sets (real-time model and observational data, archives, etc.) to the Cray operational computers. This new direction meant changes to software, adaptation to a Unix-type operating system, and conversion of all archives to new formats and storage structures. This shift had a major impact on MOS development. Converting the entire MOS-1974 system to another platform was impractical, and the MOS-1974 developmental software was abandoned. The next era of MOS development awaited the new system. In contrast, operational MOS programs and data structures essential to the NGM, AVN, and MRF MOS guidance in 1995 had to be converted. Conversion of archives was also necessary though PEATMOS/LFM MOS archives were abandoned. Fortunately, the new TDLPACK structure and software to pack and unpack both gridded and vector data were in place – a major advantage in converting TDL archives.

These two major changes were challenging enough, but others were on the horizon. The NWS modernization ongoing in the 1990's included installation of the Automated Surface Observing System (ASOS). The characteristics and information content of the ASOS instruments were different from what human observers provided. For instance, ASOS did not report clouds above 12,000 feet and no automated method was available to reliably measure snowfall amount. Thus, "complementary" satellite data were needed for the former, and "supplementary" climatic data were required for the latter. ASOS wasn't the only automated network coming on-line; automated sites (like AMOS) and mesoscale networks were implemented by the FAA, state governments, universities, or private entities. In addition, in December 1996, the standards used by the nationwide hourly aviation observing network (the "surface aviation observations") were changed to the international METAR standards as modified in the United States. Since weather observations were critical to the MOS approach, these changes meant that the MOS effort needed to adjust to the influx of new or relocated observing sites and new data sets by not only collecting data, but developing quality control tools necessary to understand and use the observations.

The changes in the surface observation system had been discussed within the NWS as part of its modernization. As implementation of ASOS began in September 1992, Unger (1992) conducted a study to determine whether the inability of ASOS to detect clouds above 12,000 feet could be ameliorated by the use of a satellite cloud cover product generated by the National Environmental Satellite Data and Information Service (NESDIS). This satellite cloud cover product estimated the coverage of high and middle clouds. Unger found, in fact, that the satellite cloud cover estimate could be used to complement the sky cover estimated by ASOS with the satellite estimated sky cover and the emissivity of the clouds. Hughes (1996) discussed MOS cloud cover and how TDL planned to use the sounder or imager data from the GOES satellites together with the satellite estimate of the effective cloud amount to judge cloud opacity. This information would then be used to complement the ASOS report and estimate the total or opaque sky cover, as needed. Fiebrich et al. (1997) studied false reports of small amounts of precipitation generated by ASOS under certain conditions of dew formation or snow melt. This report led to an algorithm implemented within TDL to check automated reports of precipitation amount. Prior to implementation of the METAR standards in 1996, TDL employees had the opportunity to suggest changes. One of those suggestions proposed observations of the daytime max and nighttime min temperatures. As a result, the ASOS system and the METAR standards were modified so that max and min temperatures were reported every 6 h at 0000, 0600, 1200, and 1800 UTC. This modification allowed further refinements in TDL algorithms that estimated daytime max and nighttime min temperatures.

Change brought challenges, but also opportunities. The MOS team had meteorologists who were interested in weather observations and used that knowledge to create new archives of surface weather observations and to influence the METAR standards implemented in 1996. The MOS team had programmers and/or system engineers who led the efforts to convert the MOS-1974 operational system to the UNIX environment required by NCEP. When NCEP turned off the IBM-type mainframes in June 1997, TDL had completed its portion of the conversion begun two years earlier. The beneficial effects of the conversion effort exceeded expectations in at least two ways: first, TDL feedback to NCEP was important in designing new operational structures for model and observational data, and secondly, the experience gained by TDL employees in making the conversion facilitated design and implementation of what came to be called the MOS-2000 system.

13. MOS-2000: A New Era

In January 2000, a landmark TDL publication titled "MOS-2000" (Glahn and Dallavalle 2000a) was issued. This document summarized what had been done within the MOS project since Bob Glahn's memorandum of 1993. Everything was new – the MOS system design, development guidelines, variable identification scheme, structure of packed data records, station dictionary, archives of NCEP model data, archives of surface and remote observational data, structure of the equation files, etc. The documentation, designed to be updated as changes occurred, exceeded 160 pages. A companion document "Computer Programs for MOS-2000" (Glahn and Dallavalle 2000b) described the new MOS software library and provided detailed instructions on using various program modules. Bob Glahn (Glahn and Dallavalle 2002) described the new system: *"A new development and implementation system has been developed for use in MDL's MOS effort. This system allows more rapid response to changing models and new requirements. Advantages of the new system compared to the old include an ID scheme that both identifies variables and controls processing, an efficient packing scheme that formats both gridpoint and station data in a similar manner, software design which allows the use of the same algorithms and general structure in both developmental and operational codes, computational subroutines which can process either gridpoint or station data and create new variables in either the developmental or operational environment, and portability of both archive datasets and developmental software between UNIX computers."* The impact of the new system was not overstated.

13.1 MOS 2000 - short-range guidance based on the global forecast system

By 1997, NCEP's Global Forecast System (GFS) was providing forecasts out to 72 h from 0000, 0600, 1200, and 1800 UTC initial conditions. The output was available at approximately t_0 + 2:45 h after initial time t_0. As part of the MOS-2000 development, TDL began a new archive of the GFS in 1997. Since part of the strategy in dealing with model changes was to archive model output with consistent spatial and temporal resolution, the GFS data were saved on a polar stereographic grid with a grid spacing of 95.25 km at 60° N. The model forecasts were output by NCEP on a 1° latitude/longitude grid, and Dr. Mark Iredell of NCEP provided TDL with software to interpolate from that grid to any arbitrary grid. Data from the GFS were available at 3-h intervals out to a projection of 72 h. The GFS archive proved to be a good testbed for building MOS-2000. By the time MOS-2000 was officially documented, work to derive and implement new GFS-based MOS equations was underway. In May 2000, a GFS-based MOS guidance package was implemented (Dallavalle and Erickson 2001a). Guidance was available for 0000 and 1200 UTC cycles at over 1000 sites in the CONUS, Alaska, Hawaii, and Puerto Rico. The station density not only represented an increase of almost 100 % coverage over NGM MOS, but was also the first time MOS guidance was available for sites in Hawaii and Puerto Rico. The new GFS MOS guidance also contained forecast projections out to 72 h. In the initial implementation, guidance was not available for all forecast elements. By July 2001, a series of implementations had completed the guidance planned for the 0000 and 1200 UTC alphanumeric short-range messages, except for categorical snowfall amount. In October 2001, implementation of alphanumeric guidance (Dallavalle and Erickson 2001b) derived from the 0600 and 1800 UTC runs of the GFS model was initiated and was completed about a year later with the exception of snow amount. When snow amount guidance was implemented in December 2003 for all four cycles, requirements for the GFS short-range guidance had also changed, and implementation of more equations extended available forecast projections from 72 to 84 h. Because of communication limitations on the alphanumeric message, guidance for the additional projections and the complete suite of MOS probabilities and categorical forecasts was restricted to binary products encoded in BUFR (Binary Universal Form for the Representation of meteorological data). The BUFR products were initially implemented in April 2001 for the 0000/1200 UTC cycles and in October 2001 for the 0600/1800 UTC cycles.

13.2 MOS 2000 – observational sources

During these initial implementations, the primary source of observations was the nationwide hourly aviation observation network, hereafter designated as the METAR sites. This network had undergone extensive changes since the early 1990's, including automation, changes in reporting standards, and addition of stations. Allen (2001a) described the challenges in using these data in development.

Other observational sources were soon incorporated into the MOS-2000 system. For instance, the occurrence of thunderstorms was specified by the National Lightning Detection Network, and the occurrence of severe weather by the national Storm Data logs (Hughes 1999, Hughes 2001). Because the NWS ASOS did not detect clouds above 12,000 ft, MDL used satellite cloud estimates (Hughes 1996) to complement the automated reports. Snowfall observations were not reported by automated sites and were not mandatory in the METAR code. The MOS team obtained cooperative observer network data from NCDC and incorporated those observations into the MOS system (Cosgrove and Sfanos 2004). MDL also transferred data from the National Data Buoy Center to include observations of wind direction, wind speed, temperature, and dewpoint at approximately 120 buoy and Coastal-Marine Automated Network (C-MAN) sites in the MOS system (McAloon 2005).

13.3 MOS 2000 – initial developmental techniques

Developmental guidelines established during the NGM MOS era were generally followed during the initial implementation of the GFS short-range guidance. Except for the probability of thunderstorms, the conditional probability of severe thunderstorms, the conditional probability of precipitation type, and the probability of snowfall amount, MOS guidance equations were developed for warm (April – September) and cool (October – March) seasons. The developmental samples for these two seasons included data between the first and last day of the season, and 15 days before the start and end of the season, if possible. Equations for all weather elements except max/min temperature, 2-m temperature, 2-m dewpoint, and 10-m wind direction and speed were developed from data combined for stations in relatively homogeneous regions. For these excepted elements, single-station equations were developed for each site in the MOS system when adequate observations (usually 200 cases or more) were available. Equations were often developed simultaneously for groupings of predictands to enhance consistency among guidance elements. GFS predictors were available at 3-h temporal resolution and with greater vertical resolution than in previous MOS developments. Both continuous and grid-binary model predictors were used. Observations at $t_0 + 3$ (t_0 = 0000, 0600, 1200, or 1800 UTC) were possible predictors for guidance out to 24 h; these observations were often treated as point-binary variables in the development of probability equations. Categorical forecasts were obtained from forecast probabilities by using the objective iterative approach to produce a bias of 1.0 on each of the probability categories or to maximize the threat score of the rarer categories while avoiding unacceptable biases in the guidance. Categorical guidance was not required for PoP, probability of thunderstorms and severe thunderstorms, and probability of precipitation occurrence.

13.4 MOS 2000 – initial predictand definitions for short-range projections

For max/min temperature, 2-m temperature, and 2-m dewpoint, the predictand definitions were identical to those in the NGM MOS development. At the METAR and marine sites, the daytime max temperature was defined as the max temperature between 7 a.m. and 7 p.m. LST. The nighttime min temperature was the min temperature between 7 p.m. and 8 a.m. LST. The min and max values were obtained via an MDL algorithm that used available hourly METAR or marine reports of temperature to estimate the extrema. Temperatures and dewpoints were valid at specific hours. Carroll (2005) described the developmental approach for the operational GFS MOS system to predict temperatures and dewpoints.

Guidance for wind direction and speed was valid at specific hours. The predictand from the METAR reports represented a 2-minute average wind direction and speed observed at the height of the anemometer, generally 10-m. The u- and v-wind components were obtained from the observed direction and speed, and equations were developed simultaneously for u, v, and speed (Sfanos 2001). For buoy and C-MAN sites, the wind direction and speed were observed at the height of the anemometer which varied among the sites from 5 to nearly 50 m. Thus, the predictand represented a non-standard wind direction and speed. McAloon (2005) discussed the approach used in the GFS MOS guidance to normalize the marine wind guidance to a 10-m height.

Probabilistic and categorical guidance for total sky cover was valid at specific hours. The predictand observations (that is, the category of total sky cover conditions) were obtained by combining METAR reports with the satellite cloud information described earlier. In the initial implementations, equations were developed to predict the probability of each of the following four categories:

- Clear: 0 octas,
- Scattered: > 0 to 4 octas of total sky cover,
- Broken: > 4 to < 8 octas of total sky cover,
- Overcast: 8 octas of total sky cover or totally obscured

.

Only the categorical guidance was included in the alphanumeric bulletin (Dallavalle and Erickson 2001a, 2001b) for projections out to 72 h. By May 2004, a change to add a fifth category (few) to total sky cover was necessary. New equations were developed and implemented to predict the probability of each of the following five categories:

- Clear: 0 octas,
- Few: > 0 to 2 octas,
- Scattered: > 2 to 4 octas,
- Broken: > 4 to < 8 octas,
- Overcast: 8 octas of total sky cover or totally obscured.

Weiss (2001) described development of total sky cover guidance. Dallavalle and Cosgrove (2005a, 2005b) described the change in the alphanumeric bulletin.

Probabilistic and categorical guidance for ceiling height was valid at specific hours. As with sky cover, hourly METAR observations complemented by satellite cloud information provided the predictand for equation development. In the initial implementations, equations were developed to predict the probability of each of the following seven categories:

- < 200 ft,
- 200 – 400 ft,
- 500 – 900 ft,
- 1000 – 3000 ft,
- 3100 – 6500 ft,
- 6600 – 12000 ft,
- 12000 ft or unlimited ceiling.

Weiss (op. cit.) described the development of the ceiling height guidance. New requirements added an eighth category to ceiling height in May 2004, namely, the 1000 to 3000 ft category was divided into two categories: 1000 – 1900 ft and 2000 – 3000 ft. Dallavalle and Cosgrove (op. cit.) described the change in the alphanumeric bulletin.

The probability of $\geq$ 0.01 inches of liquid-equivalent precipitation (PoP) occurring at a specific site was provided for 6-, 12-, and 24-h periods. The predictand observation for a 6-h period was obtained from the METAR 6-h precipitation group. Precipitation amounts for the 12- and 24-h predictands were calculated by summing appropriate 6-h values. The probabilities of $\geq$ 0.10, $\geq$ 0.25, $\geq$ 0.50, and $\geq$ 1.00 inches of liquid-equivalent precipitation (PQPF) occurring at a site were predicted for 6-, 12-, and 24-h periods. For the 12- and 24-h periods, probability guidance for a category of $\geq$ 2.00 inches was also generated. The predictand for the probability of precipitation amount (PQPF) equations was **conditional** on precipitation occurring. Since the PQPF were conditional, the MOS-2000 system used a simple algorithm to produce the unconditional probability of precipitation amount from the PoP and the PQPF. This modification eliminated the duplication of PoP guidance that existed in the NGM MOS system. Maloney (2002) describes the PoP/QPF approach used for Eta MOS; the same method was used for GFS MOS guidance.

For the first time, probabilistic forecasts of thunderstorms over the CONUS for all forecast periods were developed from lightning strikes reported by the National Lightning Detection Network (NLDN) and provided by NASA's Global Hydrology Resource Center. Since the NLDN did not detect lightning strikes far outside the land mass of the CONUS, MOS thunderstorm guidance was initially available only for the CONUS and adjacent coastal waters. Since lightning observations were random in time and space, a polar stereographic grid covering the CONUS with 47.625-km resolution at 60°N was established. A thunderstorm event was defined as the occurrence of **one** or more lightning strikes within a grid box and within the appropriate 6-, 12-, or 24-h period. Hughes (2001) describes the GFS thunderstorm probability guidance for these periods.

The severe thunderstorm predictand was defined by use of Storm Data reports, and was conditional upon the occurrence of a thunderstorm event. The same grid and time periods used for thunderstorms were used for severe weather, except that severe weather over the coastal waters was unavailable. The seasons used for developing thunderstorm and conditional severe thunderstorm probability equations were identical, that is, spring (March 16 – June 30), summer (July 1 – October 15), and cool (October 16 – March 15). Given the occurrence of a thunderstorm, a severe thunderstorm was defined as a thunderstorm with wind speeds in excess of 50 kts, hail of 0.75 inches or greater diameter, or a tornado.

Probabilistic and categorical guidance for precipitation type (freezing, snow, or liquid) were provided for specific hours. These forecasts were conditional, that is, the predictand was conditional upon precipitation occurring. The standard METAR observations valid at a specific hour were used to specify the predictand. Since automated stations do not always distinguish between precipitation types of light intensity, METAR reports of unknown precipitation were eliminated from the developmental sample. Otherwise, reports of freezing rain, freezing drizzle, ice pellets, or any mixture of these with snow or rain were considered a freezing event. Only pure snow events were categorized as frozen. Rain or a mixture of rain and snow was considered liquid. Forecast equations were developed for the September 1 – May 31 season. The precipitation type system was described by Allen and Erickson (2001).

Probabilistic and categorical guidance for visibility was valid at specific hours. The predictand observations (that is, the category of visibility conditions) were obtained from the hourly METAR reports. In the initial implementations, equations were developed to predict the probability of each of the following seven categories:

- ≤ ¼ mi,
- > ¼ - ½ mi,
- > ½ - < 1 mi,
- 1 - < 3 mi,
- 3 - 5 mi,
- 6 mi,
- > 6 mi.

Only the categorical guidance was included in the alphanumeric bulletin (Dallavalle and Erickson 2001a, 2001b) for projections out to 72 h.

By May 2004, a change to the limits of the lower four categories of visibility was necessary. At that time, new equations were developed and implemented to predict the probability of each of the following seven categories:

- < ½ mi,
- ½ - < 1 mi,
- 1 - < 2 mi,
- 2 - < 3 mi,
- 3 - 5 mi,
- 6 mi,
- > 6 mi.

Dallavalle and Cosgrove (2005) described the change in the alphanumeric bulletin.

Probabilistic and categorical guidance for obstructions to vision were provided for specific hours at 3-h intervals from 6 to 72 h after initial model time. The standard hourly METAR observations were used to specify the predictand. The predictand was defined as one of the following:

- No obstruction to vision or obstruction is solely due to precipitation;
- Haze, smoke, or dust;
- Light fog or mist (that is, fog with visibility ≥ 5/8 mi);
- Dense fog or ground fog (that is, fog with visibility < 5/8 mi;
- Blowing snow, dust, or sand.

Equations were developed to predict the probability of each of these categories; probability thresholds were used to generate categorical forecasts. Because of the difficulty of accurately predicting blowing phenomena when the characteristics of the underlying surface are unknown, the threshold procedure was designed so that blowing phenomena could only be predicted during the first 24 h of the forecast period. The condition of no obstruction was the default guidance when no threshold was exceeded.

The last element added to the GFS MOS alphanumeric message for the short-range was categorical snowfall amount. Since NWS cooperative observers take measurements of snowfall at different times, significant effort was required to evaluate what the snowfall predictand should be. Cosgrove and Sfanos (2004) found that the most common observation time was around 1200 UTC, with a secondary maximum observing time occurring around 0000 UTC. Thus, the predictand was defined as the 24-h snowfall from 0000 to 0000 UTC or from 1200 to 1200 UTC. Sets of probability equations were developed for these 24-h periods and the appropriate forecast projections. The sets of probability equations for the cooperative observer sites included one for the 24-h PoP, another set for the conditional probability of snowfall exceeding a trace in 24 h, and a third set for the conditional probability of ≥ 2 inches, ≥ 4 inches, ≥ 6 inches, and ≥ 8 inches during the 24-h period. The four conditional probability equations were developed simultaneously to enhance consistency. The three sets of probabilities were combined to produce the unconditional probability of snowfall during the 24-h period. Categorical guidance for snowfall amount was obtained by using the objective iterative approach to maximize the threat score for the snowfall events while restricting the bias between 0.9 and 1.1. Since the snowfall system depended on regionalized equations, guidance probabilities and categorical amounts could be generated for all sites in a region. The categorical forecasts were available in the short-range alphanumeric messages for 24-h periods ending at approximately 36 and 60 h after 0000 UTC; at 30 and 54 h after 0600 UTC; at 24, 48, and 72 h after 1200 UTC; and at 42 and 66 h after 1800 UTC. Guidance is available during September 1 – May 31.

A number of other MOS products were developed, but were not added to the alphanumeric bulletins. This guidance was important to local forecasters and was transmitted in BUFR products. The conditional probability of precipitation characteristics (PoPC), that is, drizzle, continuous precipitation, or showers, was available at specific hours every 3 h from 6 to 84 h after initial model time. The prediction equations were developed by using METAR observations of current weather at a specific hour, conditional upon precipitation occurring. Reports of unknown precipitation were not included in the dependent sample. The probability of precipitation occurrence (PoPO) was provided for specific hours at 3-h intervals from 6 to 84 h after initial model time. The standard METAR observation of current weather at the hour was used to define the predictand. This probability is not the same as PoP which is guidance for measureable precipitation over an interval of time. PoPO predicts the likelihood of precipitation occurrence at a specific time. Analogously, guidance for PoPO over a 3-h interval (PoPO3) was also generated; the predictand for this element was defined by the occurrence of precipitation at any one of the four hourly observations spanning the 3-h interval.

In 2006, guidance for the probability of gusts and for maximum gust speed (Rudack 2006) was developed from the METAR hourly gust observations. The first predictand, namely, a wind gust of 14 kts or greater at the 10-m anemometer level, was used to develop probability equations to predict the likelihood of the event. Probability thresholds designed to maximize the threat score for this event determined the categorical forecast. The second predictand was the reported wind gust, if the value was 14 knots or greater. This restriction limited the size of the developmental sample; essentially, the second predictand provided a conditional estimate of the reported wind gust. For the short-range GFS MOS system, gust forecasts were available at 3-h intervals from 6 to 84 h after the initial model time.

Figure 13 shows a sample GFS short-range message from the 0000 UTC cycle. After the first alphanumeric message was implemented on May 30, 2000, MDL implemented a significant number of updated equations. Some of these equations were redeveloped to take advantage of additional developmental data. Other equations corrected guidance deficiencies spotted by NWS forecasters or by MDL developers. New equations were needed in January 2002, December 2003, June 2006, and March 2010, when guidance was added for approximately 320, 145, 88, and 118 more METAR sites, respectively. While the guidance in the alphanumeric message was a subset of all possible guidance values, **all** MOS guidance was transmitted in BUFR messages modified as new elements, new predictand definitions, or new projections were added to the MOS suite. The initial BUFR messages were implemented in April 2001 for the 0000 and 1200 UTC cycles, and in October 2001 for the 0600 and 1800 UTC cycles. By September 2002, guidance to 78 h was appearing in the BUFR messages, and by December 2003, some guidance to 84 h was available in the messages. The BUFR short-range messages were redesigned in February 2005 to incorporate all available guidance.

13.5 MOS 2000 - medium-range guidance based on the GFS

The initial GFS MOS alphanumeric messages for the medium-range projections (Erickson and Dallavalle 2000) were implemented on May 31, 2000, for the 0000 UTC model run and for stations in the CONUS, Alaska, Hawaii, and Puerto Rico. Designated as the MRF bulletin, this message was designed to display much more guidance than the medium-range message of 1992. The new MRF bulletin was to contain forecasts of the daytime max and nighttime min temperatures; hourly values of the 2-m temperature and dewpoint; PoP and categorical quantitative precipitation forecasts (QPF) for 12- and 24-h periods; probability of thunderstorms for 12- and 24-h periods; mean total sky cover and maximum sustained wind over 12-h periods; conditional probabilities of freezing rain, snow, and mixed precipitation during 12-h intervals; a conditional categorical forecast of those same precipitation events; and a categorical forecast of snowfall over successive 24-h periods ending at 1200 UTC. Since the bulletin was designed to aid the forecaster by providing guidance beyond the traditional 1- to 2- day period, the guidance was available for projections of approximately 24 through 192 h after 0000 UTC, that is, the 1- to 8-day period. As an aid to the forecaster, normal max/min temperatures and climatic relative frequency of measureable precipitation in both 12- and 24-h periods were included, when available, for the 4th day of the forecast period.

In the May 2000 implementation, daytime max temperature, nighttime min temperature, 2-m hourly temperature, and 2-m hourly dewpoint guidance were available. The 2-m temperature and 2-m dewpoint guidance were valid every 12 h from 24 through 192 h after 0000 UTC. In late July 2000, the PoP and categorical QPF were added to the message. The 12-h PoP was valid every 12 h from 24 to 192 h after 0000 UTC; the 24-h PoP was valid every 24 h from 48 to 180 h after 0000 UTC (with an adjustment for sites in the Pacific). The categorical QPF was valid only to 156 h because verifications of test guidance indicated that no skill remained in the MOS QPF for projections beyond this time.

In October 2000, mean total sky cover and conditional precipitation type guidance were added to the message for 12-h periods from 24 h to 192 h. The mean total sky cover represented mean sky cover over a 12-h period categorized as three possibilities: clear (mean cloudiness < 31 %), partly cloudy (mixed clouds and clear skies or a mean cloudiness between 31 and 68 %), and overcast (mostly cloudy, a mean cloudiness > 68%). The predictand for the equations to predict the conditional probability of precipitation type was defined by examining the 13 hourly reports of observed weather between 0000 and 1200 UTC or between 1200 and 0000 UTC (Allen 2001b). A minimum of seven reports with at least three reports of precipitation was required to define a precipitation event. Any precipitation report that included freezing rain, ice pellets, or a mixture of these with another precipitation type qualified the event as a period of freezing rain. A snow event required that **all** the precipitation reports be a type of snow (snow, snow grains, etc.). A mixed rain/snow event was defined as one in which at least one of the precipitation reports was a mixture of rain and snow. Finally, a rain event required that all the precipitation reports be liquid, for instance, rain or drizzle. Regionalized-operator equations were developed and were valid for the period of September 1 – May 31. Categorical forecasts were generated by the objective iterative technique, that is, probability thresholds were developed to produce maximum threat scores while aiming for a bias between 0.98 and 1.02. The freezing category was treated as the rarest event; rain was the default choice if none of the thresholds were exceeded.

In May 2001, the probabilities of thunderstorms during 12- and 24-h periods were added to the medium-range guidance; the definition of a thunderstorm and the method of development were identical to that used for the short-range guidance.

By March 2002, NCEP had changed the GFS system so that each run of the model (at the four initial times of 0000, 0600, 1200, and 1800 UTC) was integrated out to a projection of 384 h (approximately 16 days). MDL recognized that changes were necessary to unify the heretofore segregated MOS short- and medium-range systems. A final implementation in the old paradigm for the maximum sustained wind speed was made in September 2002. The predictand for developing the necessary equations was based on the 13 hourly station observations between 0000 and 1200 UTC or between 1200 and 0000 UTC. The greatest wind speed during the 12-h period was defined as the predictand; equations were developed for each station and each projection from 24 to 192 h after 0000 UTC (Cosgrove and Dallavalle 2005).

The unification of the short- and medium-range GFS systems began in December 2003 when the categorical 24-h snowfall amount was added to both short- and medium range messages. For the medium-range message (dubbed the GFSX, see Fig. 14) issued during the 0000 UTC cycle, the categorical snowfall guidance was valid at approximately 48, 72, 96, and 120 h after 0000 UTC. New equations were implemented for max/min temperature, 2-m temperatures and dewpoints, PoP, QPF, and probability of thunderstorms. Common sets of equations were used to produce the short- and medium-range guidance messages for projections out to 84 h.

In September 2005, the MOS medium-range guidance message for the 1200 UTC cycle was added. Initially, guidance included the same elements as were present in the 0000 UTC message, except for sustained wind speed, conditional precipitation type, and mean total sky cover (Cosgrove and Dallavalle 2005). Guidance for these latter elements was to be added, when available.

As was the case with the short-range guidance, BUFR messages for the medium-range projections were implemented in April 2001 and modified as required. In October 2005, 2-m temperature, 2-m dewpoint, wind direction, and wind speed at projections every 3 h from 6 to 192 h were added to the BUFR messages, messages for the 1200 UTC cycle were implemented, and the messages underwent a substantial revision to reflect the evolution of the medium-range guidance.

13.6 MOS 2000 – adjustments and improvements to station guidance

A number of changes were made to the MOS system during 2006 through 2012 that affected both the short- and medium-range guidance. For instance, the original thunderstorm probability equations used a predictand based on lightning strikes occurring in an approximately 48-km grid. In April 2006, new thunderstorm probability equations (Hughes and Trimarco 2004) based on an approximately 40-km Lambert conformal grid were implemented for both the short- and medium-range projections.

In June 2006, the inflation procedure applied to the wind speed guidance was modified to eliminate changes to wind speeds predicted to be less than the mean value observed during development. For nearly 3 decades, the traditional approach had been to increase speeds greater than the mean and to decrease speeds less than the mean, thus generating a greater number of calm or near calm winds. The 2006 modification eliminated the overforecasting of light winds. In July 2006, wind direction and speed guidance became available in the medium-range products for projections every 3 h from 12 to 192 h in advance. Because of the availability of these time-specific forecasts, the process for predicting the greatest sustained wind speed in 12-h periods was modified. Instead of independent equations to predict the sustained wind speed, the maximum sustained wind speed was the greatest of the five wind speeds predicted during the 0000 - 1200 or 1200 – 0000 UTC window (Cosgrove and Dallavalle 2005).

In June 2007, total sky cover guidance for the short-range was replaced with opaque sky cover guidance (Yan and Zhao 2009). Equations to predict the probability of clear, few, scattered, broken, and overcast conditions (with the same octa breakpoints as used for total sky cover) were developed by using an estimate of opaque, rather than total, sky cover. For both total and opaque sky cover, the Effective Cloud Amount (ECA) given by the Satellite Cloud Product (Kluepfel et al. 1994) was used to complement ASOS cloud reports. The algorithm for opaque sky cover was modified by Yan and Zhao to account for the presence of translucent clouds that indicated greater total sky cover than opaque sky cover. For public and aviation weather prediction, opaque sky cover conditions were of primary importance. This development also reverted to single-station equations for cloud cover, when feasible. This modification reversed the regional-equation approach in use for approximately 3 decades.

In May 2008, thunderstorm probability equations to predict thunderstorms for 3-, 6-, 12-, and 24-h periods in Alaska were implemented (Shafer and Gilbert 2008). These equations were developed from a sample of lightning data over Alaska. The approach was analogous to that used in the CONUS with the lightning strikes being located on a 48-km grid over Alaska. The probability guidance was added to both the short- and medium-range alphanumeric messages, as appropriate. All guidance values were added to the BUFR messages.

New equations were implemented in March 2010 to generate precipitation type guidance for both the short- and medium-range projections. Shafer (2010) used an extended developmental sample of GFS model output, logit 50% values, transformed predictors, and high-resolution climatologies (Baker et al. 2009) to develop regionalized-operator equations. In tests on independent data, these equations produced guidance with notable improvement over the older guidance developed in the early 2000's. Also, in March 2010, the daytime max temperature for Alaska was redefined as the max temperature during the period of 5 a.m. to 8 p.m. LST. Similarly, the nighttime min temperature definition was changed to be the min temperature during the 5 p.m. – 11 a.m. LST period. Definitions for daytime max/nighttime min temperature remained the same for all geographic sites outside Alaska (Maloney et al. 2010).

13.7 MOS 2000 - short-range guidance for islands in the western Pacific

NWS responsibilities to support forecast operations in Guam and other islands in the western equatorial Pacific Ocean required that MDL provide MOS guidance for these locations. To do a MOS development, MDL established a new archive of GFS model variables valid on a mercator grid with 80-km resolution and encompassing the western Pacific. This archive was done retrospectively from NCEP run history archives and was similar to the primary GFS archive in terms of temporal and vertical resolution. In April 2005, MDL implemented wind guidance for Midway Island and Pago Pago, American Samoa. This marked the first time MDL had developed guidance for a station in the Southern Hemisphere. In June 2005, wind guidance was added for 13 more locations in the western Pacific (Su 2005a, 2005b). In April 2007, PoP and PoPO forecasts (Su 2007) were added to guidance messages for the 15 island sites. In September 2008, temperature and dew point guidance were also included in the short-range message. In November 2013, total sky cover and ceiling guidance completed the planned message (Su et al. 2013) for the 0000 and 1200 UTC forecast cycles

14. Gridded MOS

The vast majority of MOS products generated during the 20th century were alphanumeric bulletins. These bulletins contained only a small percentage of the forecast guidance potentially available. Graphics for the CONUS of max/min temperature, probability of precipitation, some thunderstorm probabilities, and, for several years, flight weather guidance, existed for limited projections. When these graphics displayed isopleths of temperature or of probabilities, the contours were based on values at 225 to 250 stations analyzed by the Cressman successive correction scheme (Cressman 1959) on a polar stereographic grid with approximately 90 km resolution (author's notes). Communications bandwidth and processing power available to local NWS forecast offices dictated the restrictions on graphics.

As processing power and storage capacity increased, the Internet flourished, MOS developers realized the value of "pictures" displaying the vast array of MOS guidance, and NCEP displayed abundant model forecast graphics on the Internet, the MOS team began to post graphics on the internet in the late 1990's and the early 2000's. For instance, in April 2002, graphics of the new GFS and GFSX guidance were displayed on web pages. However, like the alphanumeric bulletins, the graphics had neither the resolution nor the flexibility to aid the forecaster in generating forecast products for a wide variety of users at a resolution satisfying user requirements. True gridded products, that is, products in a standard digital form, were needed.

14.1 NWS evolution – requirements for gridded (binary) guidance

When the NWS declared the National Digital Forecast Database (NDFD, Glahn and Ruth 2003) operational in late 2004 (Glahn 2005), a new era had begun in which official NWS products were available in digital form on high-resolution grids covering the United States, parts of the eastern Caribbean, and sectors of the western Pacific. NWS forecasters generated these grids through use of the Interactive Forecast Preparation System (IFPS, Ruth 2002). Forecasters edited or manipulated grids to generate the final product; however, optimal interaction required that an initial grid with the proper resolution and some of the desired predicted features be available. Candidate grids for initialization included output from an NWP model "downscaled" to the NDFD grid resolution, a grid created during a previous forecast cycle and valid at the same time ("continuity"), or grids for the NDFD forecast elements created by NCEP. Yet another solution was to use forecast grids created by the MOS approach. The challenge became one of adapting MOS to meet the NWS requirement for high-resolution gridded guidance.

14.2 Adapting MOS requirements for high-resolution guidance

In the traditional use of the MOS technique, observations at specific observing sites are related to NWP model variables, previous observations, and geo-climatic data, such as terrain elevation or the climatic average of the event of interest. The resulting forecast equations are used operationally to generate an objective interpretation of the underlying NWP model in terms of weather elements that forecasters include in their daily forecast products.

An historical sample of observations at specific observing sites is essential for this usage of MOS. For certain weather elements such as temperature, dewpoint, or wind speed, the historical sample of observations and model data is adequate to derive “single-station” equations for each station in the MOS system, each forecast cycle, and each projection. The single-station equations generate guidance that is highly tuned to the specific observing site. For other weather elements, such as PoP, observations of the event of interest are often inadequate to develop stable forecast equations. Consequently, observations and forecast model data for stations in a relatively homogeneous area are combined to develop equations that can be applied to any of the stations in that area. Often, geo-climatic variables such as station elevation or the relative frequency of the observation of interest are used to provide additional station specificity. In general, the “regionalized-equation” approach does not produce guidance as tuned to individual sites as the single-station equations. A “generalized-operator” equation is developed when all data from a large, heterogeneous area, such as the CONUS, are combined in the developmental sample. Geo-climatic variables may be used to compensate for the lack of tuning to individual locations.

One possible approach, then, to the problem of developing high-resolution MOS guidance is to derive regionalized or generalized-operator equations that can be applied to every “site” or grid point on the high-resolution grid. This approach requires that the equations be developed by using NWP model data and geo-climatic variables that provide good site specificity. Because guidance generated in this way is less accurate than guidance generated by single-station equations, a variant on this approach is to combine guidance produced by equations for individual sites with guidance made by generalized-operator equations. One way to combine the two sets of guidance is to analyze the single-station guidance with the generalized-operator guidance serving as a first-guess background field. Successful analysis requires that as many observing sites as possible be included in the MOS system and that the analysis scheme use high-resolution geo-climatic data to adjust for terrain, land use, or water influences.

Another approach to providing high-resolution MOS guidance is to obtain observational data at each grid point and use those data in equation development. With in situ observations, of course, this density of reporting sites is not possible. However, the use of remote-sensing data as a source of observations makes this approach feasible. Remote-sensing data, random in space and time, can be projected on a grid of regularly spaced points for a specific interval of time. By using this developmental method, MOS guidance is valid for a grid of some prespecified resolution. Hughes (2001) described GFS-based MOS thunderstorm guidance where this approach was applied.

14.3 Station observations

As discussed previously, the standard source for MOS guidance at stations was the MDL archive of hourly surface observations at METAR sites throughout the U.S., the Caribbean, and the western Pacific. In addition, C-MAN and buoy data for marine sites as well as NWS cooperative observer reports had been obtained to provide observations along coastal regions and in areas where few aviation reports were available. Initially, in 2005, approximately 1500 METAR sites, 120 marine sites, and 5500 cooperative observer sites were added to the MOS system (Dallavalle and Glahn 2005). Particularly in the western CONUS, the spatial density of sites was still insufficient to support guidance at 5-km resolution.

For a better sample of temperatures and winds, MDL obtained archived reports from the MesoWest station network (Horel et al. 2002). According to Horel et al., the MesoWest network in 2001 included weather information at over 2800 sites in the western CONUS. MDL elected to use sites primarily from the Remote Automated Weather Stations (RAWS) and the Snowpack Telemetry (SNOTEL) networks. For the most part, observations from state department of transportation networks were ignored because of concerns about siting and representativeness of the reports. Most of the MesoWest sites reported hourly temperatures; some also reported wind speed, wind direction, wind gusts, and relative humidity.

Two other sources of data contributed to the expanded set of MOS sites in the western CONUS. In the late 1990’s, the NWS Office of Hydrology asked MDL to provide max/min temperature guidance for a number of locations in the NWS Northwest, Missouri Basin, and Colorado Basin River Forecast Centers (RFCs). The RFCs provided the observations for the sites of interest, and MDL, in turn, developed and disseminated the guidance for use in RFC operations. In addition, in 2004, the California-Nevada RFC provided hourly temperature data for approximately 200 sites in the Sierra-Nevada Mountains that seemed unavailable in the MesoWest network. When all data were quality-controlled and all possible sites were included, by early 2006 the MOS system in the western CONUS consisted of approximately 300 METAR/marine sites, 1325 cooperative observer sites, 1175 MesoWest sites, and 80 RFC sites (Fig. 15).

14.4 Remote-sensing observations

The second approach to providing high-resolution MOS guidance is to use remote-sensing data from radar, satellite, or lightning detection networks. As discussed earlier, observations from the lightning detection network were used in developing GFS-based thunderstorm probabilities for a grid. Hughes and Trimarco (2004) described changes in the thunderstorm guidance when the resolution of the grid on which the lightning strikes were located was changed from approximately 48 to 40 km. Antolik (2004) discussed the use of radar and gauge precipitation estimates to create a gridded MOS product providing probability of precipitation amounts on a high-resolution (4 km) grid over the CONUS. Shafer and Gilbert (2008) described the development of thunderstorm guidance over Alaska by using lightning strike data on a 48-km grid as predictand values in the MOS regression scheme. With the availability of high-resolution geo-climatic datasets such as terrain elevation, slope, aspect, land/water coverage, land use, and land characteristics, the possibility of creating interactive predictors between these variables and NWP model fields and then generating forecasts on a high-resolution grid was a logical extension of MOS techniques used previously. Sheets et al. (2005) and Trimarco et al. (2005) described the use of geographical information systems in preparing geo-climatic data for use in MOS development.

14.5 Creating gridded MOS forecasts

Glahn and Dallavalle (2006) presented approaches to providing MOS guidance on the same grid used for the NDFD. To summarize, three approaches were possible:

- analyze the MOS site-specific guidance on the NDFD grid;
- use regionalized MOS equations developed from site-specific observations, and apply the appropriate equation at each grid point of the NDFD grid;
- develop MOS equations from observational data available at each grid point of the NDFD grid.

In fact, the MOS team developed regionalized equations for elements such as temperature and winds (the second approach), but accuracy and details seen in the guidance were unacceptable. Remote-sensing observations when mapped to a grid and used as predictands in equation development was a variation of the third approach. However, unless the predictand grid was identical to the NDFD grid, additional processing of guidance was necessary to get the resolution of the NDFD grid. The first approach was feasible, if guidance was available at enough sites to resolve important meteorological features, and if a sophisticated analysis program was available to preserve and/or infer those important features.

As indicated previously, stations had been added to the GFS MOS system. Moreover, Bob Glahn (Glahn et al.1985) had previously developed a sophisticated analysis program for the Local AFOS MOS Program (LAMP). The code was adapted from analysis techniques described by Bergthorssen and Doos (1955) and by Cressman (1959); Bob Glahn called the LAMP code the BCD analysis in recognition of the three individuals. Bob now added a level of sophistication to the BCD code so that land and water gridpoints and stations were treated differently, and variations in the guidance dependent on elevation were adjusted by using available data. This latter adjustment essentially provided a three-dimensional character to the analysis and attempted to account for vertical variations of a meteorological quantity in complex terrain. The new analysis approach was named the BCDG technique.

Glahn et al. (2009) described the BCDG scheme used to analyze MOS forecasts on the 5-km NDFD grid. The extension of the BCD analysis to the BCDG approach was initially comprised of three components, namely, the use of the forecasts themselves to specify the variations of a meteorological quantity like temperature with elevation (called the vertical change with elevation or VCE), the designation of each grid point as land, inland water, ocean water, or shoreline (both land and inland water), and a contour-following smoother that was designed to smooth analyzed grid values when elevation changed only slightly, and yet the local details in the analysis were judged to be important.

Like all BCD (or successive correction) analysis schemes, the BCDG scheme had an extensive array of options that could be employed to analyze MOS guidance. These included the first-guess, radius of influence, number of passes to use in the analysis, elimination of site-specific guidance outside the range of expected values, type of correction to use, careful treatment of vertical lapse rates indicating temperature inversions, and the contour following smoother. The designation of grid points as representing land, inland water, ocean water, or a combination of land and inland water meant that three analysis schemes were used in the BCDG technique with accompanying complexity for each. This designation of grid points and the need for high-resolution terrain fields highlighted the necessity of geographical information systems to obtain the requisite data. Glahn et al. (2009) used analysis of the MOS max temperature forecasts as an example of the power of the BCDG approach. This example also highlighted the need for additional quality-control options to enforce meteorological consistency in the analyzed MOS guidance. For instance, the max temperature value at a grid point must be equal to or greater than the hourly temperatures at the same grid point during the simultaneous daytime. Similarly, the hourly dewpoint at a grid point must be less than or equal to the temperature at the same grid point and hour. These types of checks were built into the post-processing of the site-specific MOS guidance, but they were also necessary for the analyzed MOS guidance. Figure 16 is an example of the gridded MOS temperature field over the western CONUS.

The elimination of MOS guidance that seemed outside the bounds of "reasonable" was necessary to avoid bulls-eyes in the analysis. When the MOS team added cooperative observer and MesoWest sites to the MOS system, extensive quality-control checks were instituted to eliminate stations that seemed to report "unusual" values. "Unusual" was defined to be average values or standard deviations of the observations that were seemingly inconsistent with those of neighboring sites. As will be seen in the next section, elimination of more sites was necessary.

Finally, the BCDG software featured a consensus approach that included two members. The final analysis was the average of the MOS guidance analysis valid at the same projection and obtained from the current and previous forecast cycles.

14.6 Implementation of gridded MOS

On August 15, 2006, gridded MOS became operational (Glahn et al. 2009) on the CONUS 5-km NDFD grid for daytime max temperature and nighttime min temperatures out to 7 days; 2-m surface temperature, 2-m surface dewpoint, 2-m relative humidity, and 10-m wind speed and direction at 3-h intervals out to 192 h; 3-h probability of thunderstorms at 3-h intervals out to 84 h; and 6- and 12-h probability of precipitation and of thunderstorms out to 192 h. On June 5, 2007, opaque cloud cover and wind gusts at 3-h intervals out to 192 h, 24-h categorical snow amounts out to 132 h, and 6- and 12-h quantitative precipitation amounts out to 156 h were added to the gridded MOS package. Other changes followed:

- December 2007: new land/water mask, and precipitation amount analysis; sites with questionable guidance removed;
- June 10, 2008: gridded MOS for Alaska on the 3-km NDFD grid: guidance for max/min temperature; 3-h temperature, dewpoint, and relative humidity; 3-, 6-, and 12-h thunderstorm probabilities;
- August, 2008: consensus wind forecasts for CONUS ended;
- December 2008: guidance added to gridded MOS for Alaska: 6- and 12-h probability of precipitation; 3-h wind direction, speed, and gusts; and 3-h total sky cover;
- January 2010: guidance added to gridded MOS for Alaska: 6- and 12-h quantitative precipitation amount and 24-h snowfall;
- January 2010: 24-h snowfall amount guidance for additional projections to 156 h available for CONUS and Alaska;
- November 9, 2010: gridded MOS available for Hawaii on the 2.5 km NDFD grid.

See https://www.nws.noaa.gov/mdl/synop/changes.php for additional details.

Gilbert et al. (2009) discussed some of these changes with particular emphasis on the value of forecaster comments aiding improvement of the gridded MOS package. Since the first MOS products were implemented in the 1970's, the input of the user community was a critical component of the guidance improvement process. The other critical component was verification of the MOS guidance in comparison to the human forecasts. Ruth et al. (2009) showed errors of the 1- and 2- day forecasts for max/min temperature and PoP since the late 1960's and how both the local forecasts and objective guidance improved over a nearly 40-year period. At the time the Ruth analysis was done, forecasts for day 2 were as accurate as the forecasts for day 1 approximately 10 to 15 years earlier. Ruth et al. also found that gridded MOS was providing good guidance to the forecasters for projections out to a week in advance and that the skill of the gridded MOS was comparable to that of the human forecaster.

14.7 High-resolution MOS guidance

On February 27, 2012, an experimental package of gridded MOS guidance became available on the CONUS 2.5 km grid. On March 13, 2012, a true high-resolution PoP and quantitative precipitation product (Charba and Samplatsky 2011) replaced the traditional station-based gridded MOS PoP and quantitative precipitation guidance products. The improved high resolution guidance was a landmark development. Guidance was generated by equations developed from archived stage IV national mosaic precipitation data that combined radar and gauge estimates with human quality-control at the RFC's. These improved estimates were available on a 4-km grid and provided predictand data for MOS development. High-resolution observed data obtained from a combination of remote-sensing and in situ measurements, detailed climatic frequencies of precipitation amounts, geographic information available via geographical information systems, and interactive predictors that preserved both the model and underlying climatic influences validated the MDL claim that the MOS approach would generate skillful high-resolution guidance if high-resolution predictand data were available.

Gilbert et al. (2015) summarized the MOS system as it existed after the implementation of the gridded guidance. At that point, MOS guidance was produced for more than 11,000 sites in the U.S. and its territories, and on grids as fine as 2.5 km resolution. Accordingly, the guidance required "7 hours a day of run time on the NWS production supercomputer, 150132 lines of executable code, and 3.7 million unique statistical equations" – a far cry from the early 1970's when the MOS system produced a few rudimentary bulletins and consisted of approximately 3,000 equations.

15. FINAL THOUGHTS

I was fortunate enough to be a member of the NWS from December 1973 through October 2006. During my first year, I was a meteorological intern with the Forecast Division of NMC. Among other lessons, I learned two aspects of NWS culture that served me well at work and in life. The first was that the operational weather product was our top priority. The product had to go out. If that meant an intern had to sprint down a hall to deliver a chart to the fax room by the deadline, so be it. If a shift went overtime because of weather or sickness, that was part of the job. The customer, namely, the field forecaster and ultimately the U. S. citizen, was our primary obligation. Always pay attention to the important stuff. The second lesson was that when lacking reliable data (for instance, analyzing weather maps over the Pacific Ocean or Siberia), follow continuity.

For the next 32 years, I was a developer, programmer, implementer, supervisor, and branch chief with TDL/MDL. Obviously, I saw a lot of change during that time. But one thing was always true, namely, that NWS employees were committed to their job and were mission-driven. I was fortunate to work with so many dedicated people. The MOS system required substantial help from NMC/NCEP, the NWS communications staff, NWS program managers, and Regional Headquarters in order to implement products. We sometimes disagreed, but the field forecasters and the products were ultimately everyone's concern. The field forecasters helped us in TDL/MDL to create better products with their questions, concerns, and suggestions.

Without doubt, the increase in computer resources and the advance of technology (remote-sensing observations, GIS, etc.) were absolutely essential to the success of MOS. I have a hard time comprehending the numbers of MOS equations and products now available, especially compared to the 1970's and 1980's. But improvements in post-processing NWP variables were also due to the human factor, namely, the leadership and vision of the people in charge of the NWS at the highest levels, and the perseverance of NWS employees. We in TDL/MDL were fortunate to work for Dr. Bill Klein in the 1970's, and for Dr. Bob Glahn who served as director from 1976 through 2012. Bob's vision, organizational skills, and perseverance were absolutely essential to the success of MOS. I can honestly say that I enjoyed working with my TDL/MDL co-workers.

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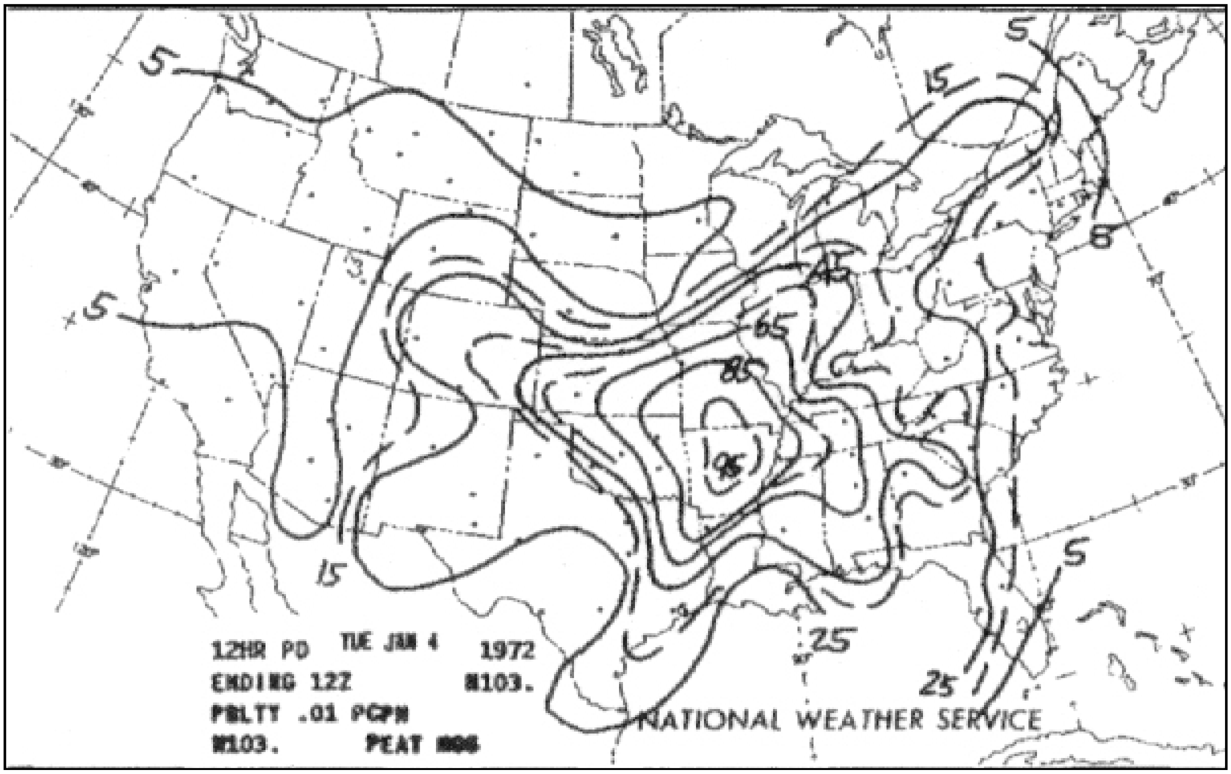


Figure 1. One of the first PEATMOS National Facsimile (NAFAX) charts for the probability of 0.01 inches or more of liquid precipitation (PoP) in a 12-h period. This chart was issued during the 1200 UTC forecast cycle on January 3, 1972. The PoP guidance was valid for the 12-24 h projection ending at 1200 UTC on January 4, 1972. Note that the isolines and labels were hand-drawn.

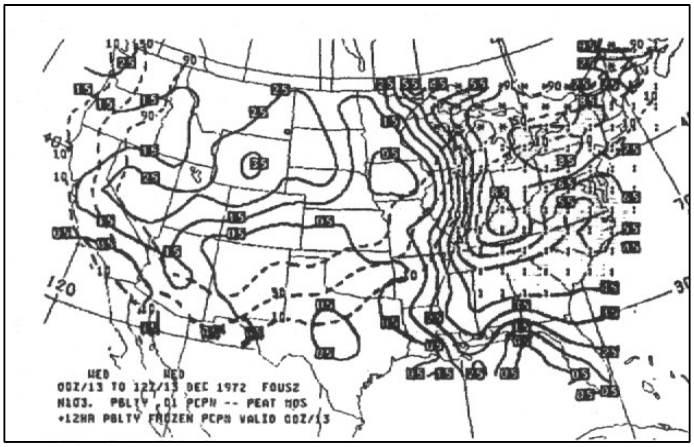
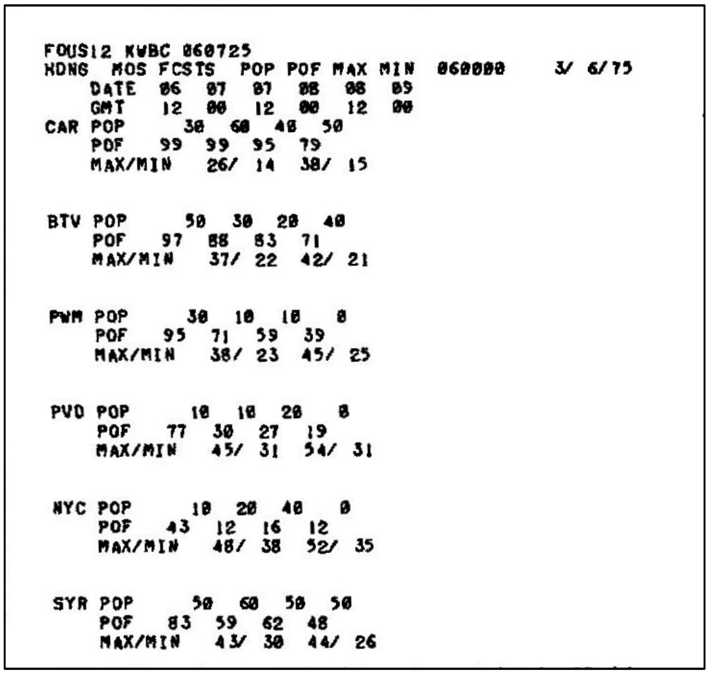


Figure 2. A panel from a four-panel facsimile chart displaying PoPs (solid lines) and probability of frozen precipitation (dashed lines). Where the PoP exceeds 45 %, the snowflake represents a categorical forecast of snow. The raindrops represent a forecast of rain. Note that unlike Fig. 1 generated at the beginning of 1972, this graphic is machine-drawn.



```
FOUS12 KWBC 060725
HDNG  MOS FCSTS  POP POF MAX MIN  060000    3/ 6/75
    DATE  06  07  07  08  08  09
    GMT   12  00  12  00  12  00
CAR POP      30  60  40  50
    POF   99  99  95  79
    MAX/MIN   26/ 14  38/ 15


BTV POP      50  30  20  40
    POF   97  88  83  71
    MAX/MIN   37/ 22  42/ 21


PWM POP      30  10  10   0
    POF   95  71  59  39
    MAX/MIN   38/ 23  45/ 25


PVD POP      10  10  20   0
    POF   77  30  27  19
    MAX/MIN   45/ 31  54/ 31


NYC POP      10  20  40   0
    POF   43  12  16  12
    MAX/MIN   48/ 38  52/ 35


SYR POP      50  60  50  50
    POF   83  59  62  48
    MAX/MIN   43/ 30  44/ 26
```

Figure 3. The FOUS12 message in 1975 based on PEATMOS equations.

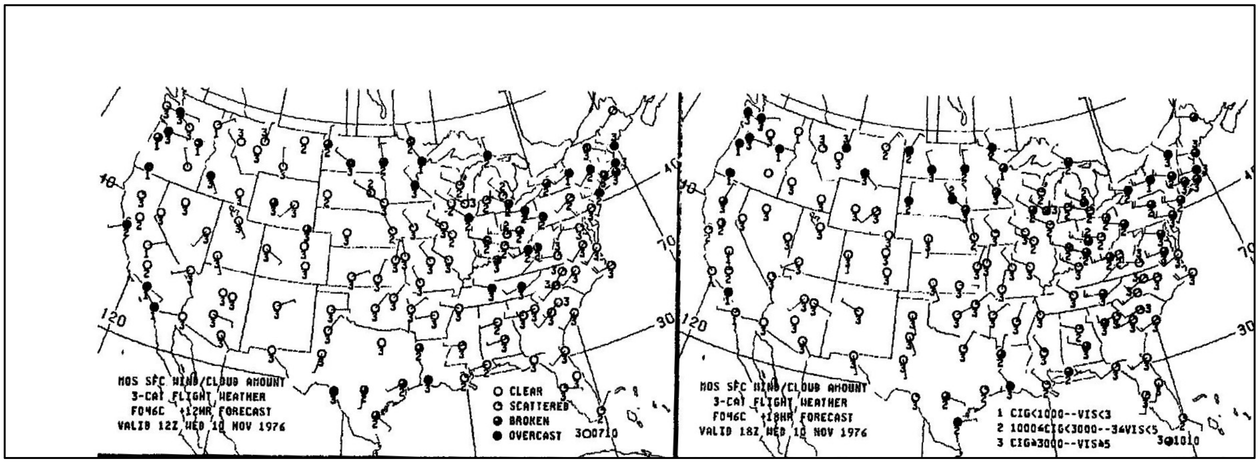
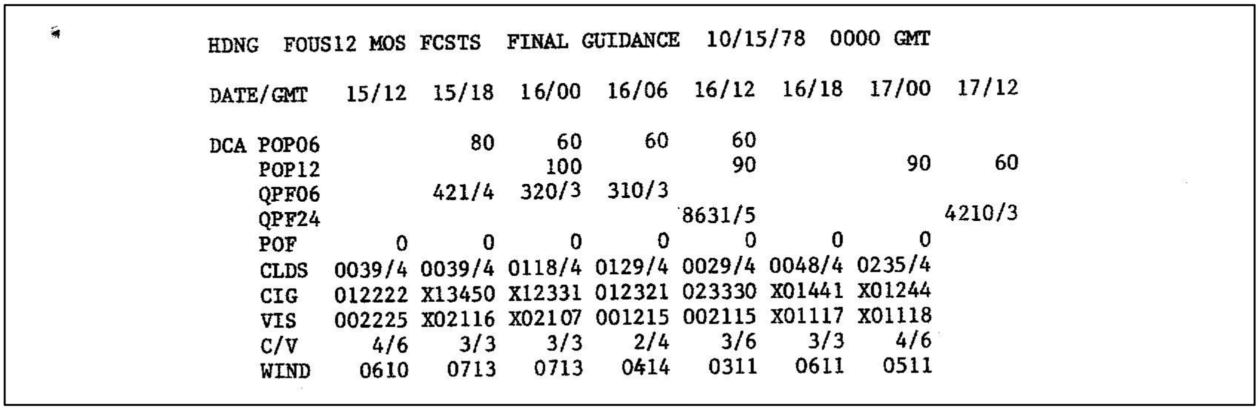
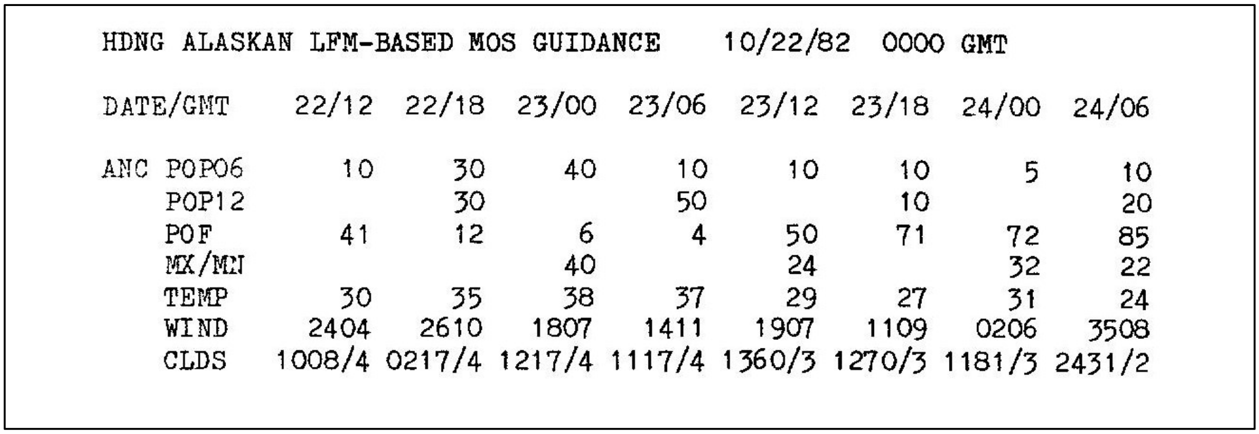


Figure 4. Two panels of the 4-panel facsimile chart displaying the MOS cloud cover, wind direction and speed, and flight weather (combined ceiling height and visibility conditions) for the 12- and 18-h forecasts from 0000 UTC on November 10, 1976. The MOS guidance was based on PEATMOS equations.



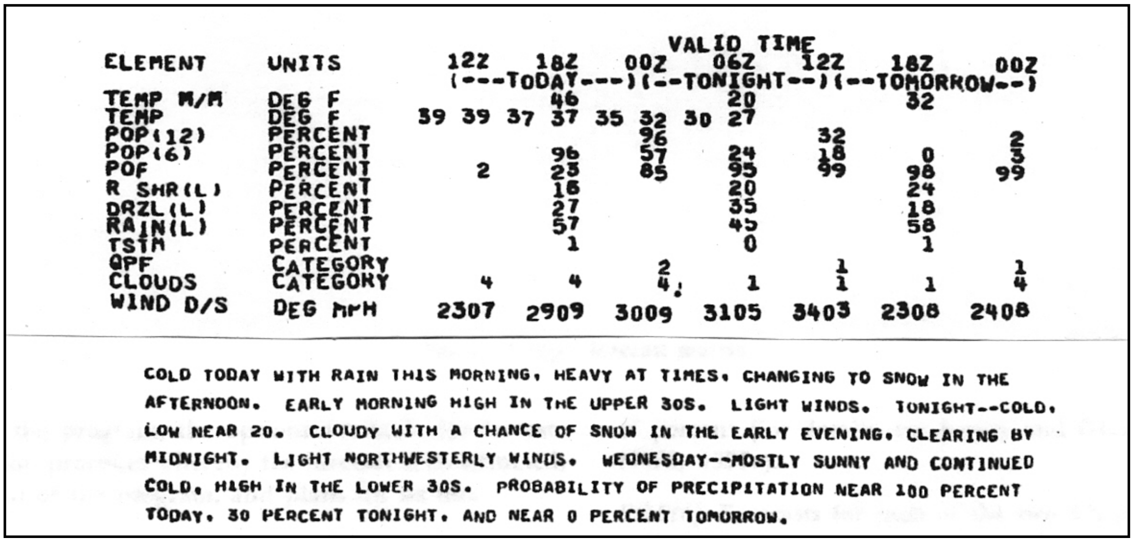
```
HDNG  FOUS12 MOS FCSTS  FINAL GUIDANCE  10/15/78  0000 GMT

DATE/GMT       15/12   15/18   16/00   16/06   16/12   16/18   17/00   17/12

DCA POP06                 80      60      60      60
    POP12                        100              90              90      60
    QPF06              421/4   320/3   310/3
    QPF24                                     8631/5                  4210/3
    POF            0       0       0       0       0       0       0
    CLDS      0039/4  0039/4  0118/4  0129/4  0029/4  0048/4  0235/4
    CIG       012222  X13450  X12331  012321  023330  X01441  X01244
    VIS       002225  X02116  X02107  001215  002115  X01117  X01118
    C/V          4/6     3/3     3/3     2/4     3/6     3/3     4/6
    WIND        0610    0713    0713    0414    0311    0611    0511
```

Figure 5. The PEATMOS FOUS12 in 1978. This was the high-water mark of MOS guidance developed from the PE and atmospheric trajectory models. Note that guidance for clouds, ceiling height (CIG), and visibility (VIS) displayed probabilities and categorical values.



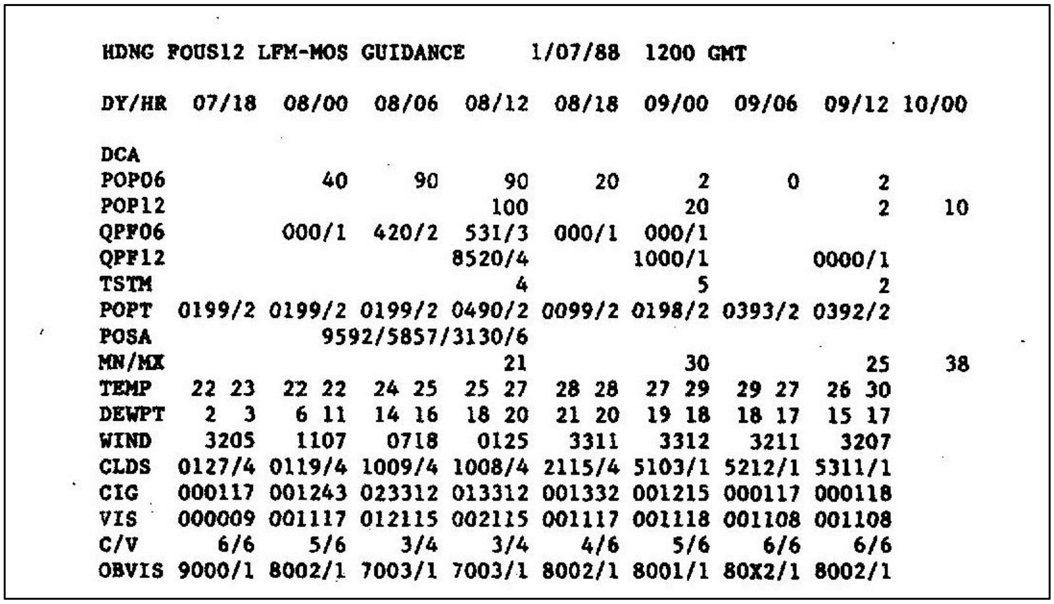
```
HDNG ALASKAN LFM-BASED MOS GUIDANCE     10/22/82  0000 GMT

DATE/GMT       22/12   22/18   23/00   23/06   23/12   23/18   24/00   24/06

ANC POP06         10      30      40      10      10      10       5      10
    POP12                 30              50              10              20
    POF           41      12       6       4      50      71      72      85
    MX/MN                         40              24              32      22
    TEMP          30      35      38      37      29      27      31      24
    WIND        2404    2610    1807    1411    1907    1109    0206    3508
    CLDS      1008/4  0217/4  1217/4  1117/4  1360/3  1270/3  1181/3  2431/2
```

Figure 6. FMAK1 message containing LFM-based MOS guidance for Anchorage, AK.



```
                                                  VALID TIME
ELEMENT       UNITS           12Z     18Z     00Z     06Z     12Z     18Z     00Z
                            (---TODAY---)(--TONIGHT--)(--TOMORROW--)
TEMP M/M      DEG F                   46              20              32
TEMP          DEG F       39  39  37  37  35  32  30  27
POP(12)       PERCENT                         96              32               2
POP(6)        PERCENT                 96      57      24      18       0       3
POF           PERCENT          2      23      85      95      99      98      99
R SHR(L)      PERCENT                 16              20              24
DRZL(L)       PERCENT                 27              35              18
RAIN(L)       PERCENT                 57              45              58
TSTM          PERCENT                  1               0               1
QPF           CATEGORY                         2               1               1
CLOUDS        CATEGORY         4       4       4       1       1       1       4
WIND D/S      DEG MPH       2307    2909    3009    3105    3403    2308    2408

     COLD TODAY WITH RAIN THIS MORNING, HEAVY AT TIMES. CHANGING TO SNOW IN THE
     AFTERNOON.  EARLY MORNING HIGH IN THE UPPER 30S.  LIGHT WINDS.  TONIGHT--COLD.
     LOW NEAR 20.  CLOUDY WITH A CHANCE OF SNOW IN THE EARLY EVENING. CLEARING BY
     MIDNIGHT.  LIGHT NORTHWESTERLY WINDS.  WEDNESDAY--MOSTLY SUNNY AND CONTINUED
     COLD. HIGH IN THE LOWER 30S.  PROBABILITY OF PRECIPITATION NEAR 100 PERCENT
     TODAY. 30 PERCENT TONIGHT. AND NEAR 0 PERCENT TOMORROW.
```

Figure 7. Computer-worded forecast generated from LFM MOS guidance (shown) in 1979.



```
HDNG FOUS12 LFM-MOS GUIDANCE      1/07/88  1200 GMT

DY/HR  07/18  08/00  08/06  08/12  08/18  09/00  09/06  09/12 10/00

DCA
POP06            40     90     90     20      2      0      2
POP12                         100            20             2    10
QPF06         000/1  420/2  531/3  000/1  000/1
QPF12                      8520/4        1000/1        0000/1
TSTM                            4             5             2
POPT  0199/2 0199/2 0199/2 0490/2 0099/2 0198/2 0393/2 0392/2
POSA              9592/5857/3130/6
MN/MX                          21            30            25    38
TEMP   22 23  22 22  24 25  25 27  28 28  27 29  29 27  26 30
DEWPT   2  3   6 11  14 16  18 20  21 20  19 18  18 17  15 17
WIND     3205   1107   0718   0125   3311   3312   3211   3207
CLDS  0127/4 0119/4 1009/4 1008/4 2115/4 5103/1 5212/1 5311/1
CIG   000117 001243 023312 013312 001332 001215 000117 000118
VIS   000009 001117 012115 002115 001117 001118 001108 001108
C/V      6/6    5/6    3/4    3/4    4/6    5/6    6/6    6/6
OBVIS 9000/1 8002/1 7003/1 7003/1 8002/1 8001/1 80X2/1 8002/1
```

Figure 8. The LFM-based MOS guidance message for Washington, D.C. issued from the 1200 UTC cycle on January 1, 1988.

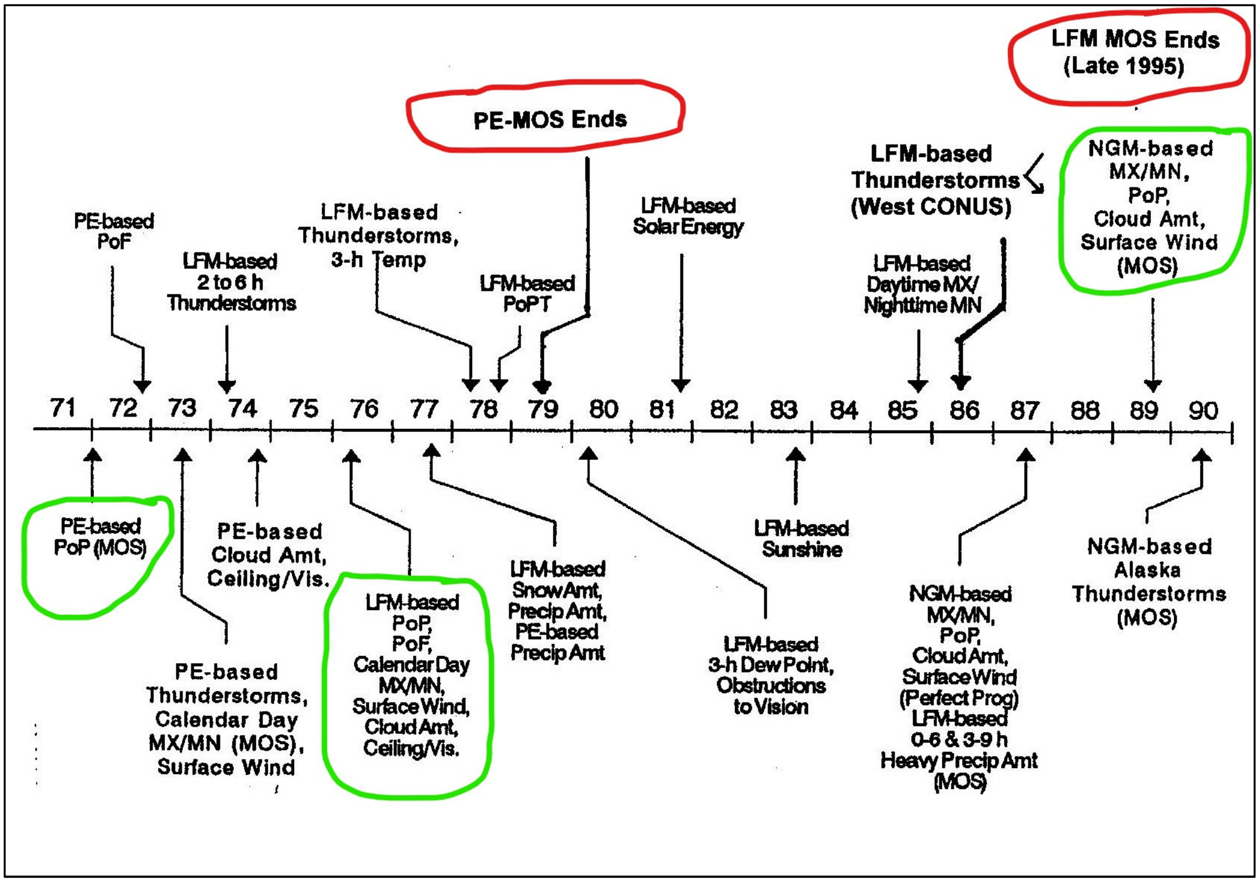
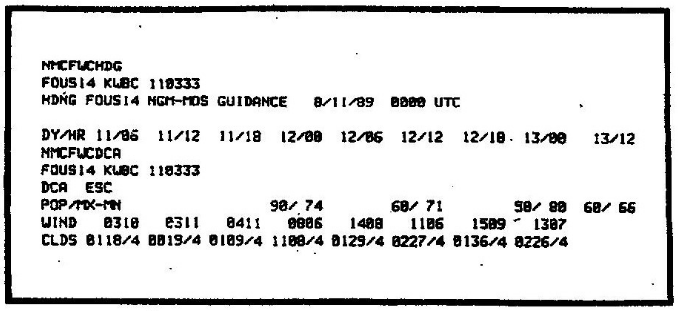
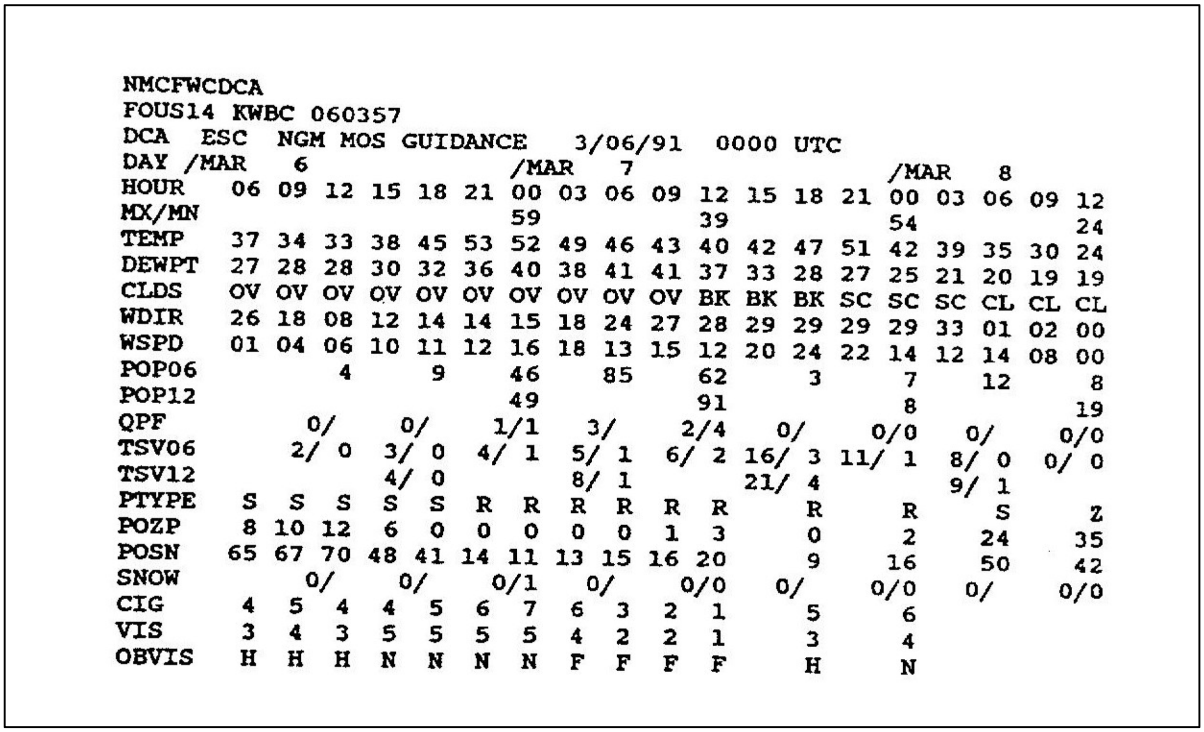


Figure 9. Significant milestones in statistical development between 1972 and 1990. The following abbreviations are used for the weather variables: PoP: probability of precipitation; PoF: conditional probability of frozen precipitation; PoPT: conditional probability of precipitation type; MX/MN: maximum/minimum temperature; Cloud Amt: probability and categorical cloud amount guidance; Vis: probability and categorical surface visibility guidance; Precip Amt: probability and categorical quantitative precipitation guidance; Snow Amt: probability and categorical snow amount guidance; 3-h Temp: air temperature at 2-m elevation ("shelter" temperature) and valid at 3-h intervals; 3-h Dew Point: dew point at 2-m elevation and valid at 3-h intervals. The green outline indicates the start of guidance from a particular model. The red outline indicates termination of the guidance.



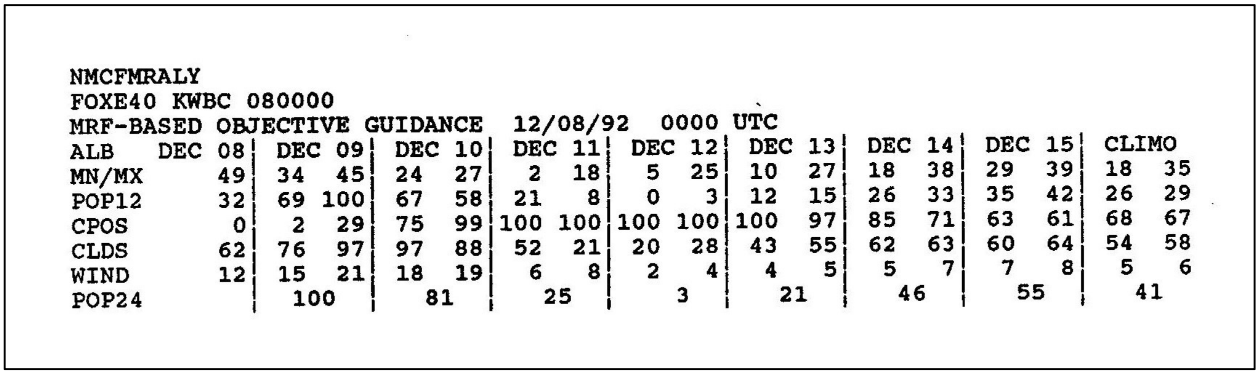
```
NMCFWCHDG
FOUS14 KWBC 110333
HDNG FOUS14 NGM-MOS GUIDANCE   8/11/89  0000 UTC

DY/HR 11/06  11/12  11/18  12/00  12/06  12/12  12/18  13/00   13/12
NMCFWCDCA
FOUS14 KWBC 110333
DCA  ESC
POP/MX-MN                   90/ 74        60/ 71        50/ 80  60/ 66
WIND   0310   0311   0411   0806   1400   1106   1509   1307
CLDS 0118/4 0019/4 0109/4 1100/4 0129/4 0227/4 0136/4 0226/4
```

Figure 10. NGM-based MOS guidance (FOUS14) when first implemented in 1989.



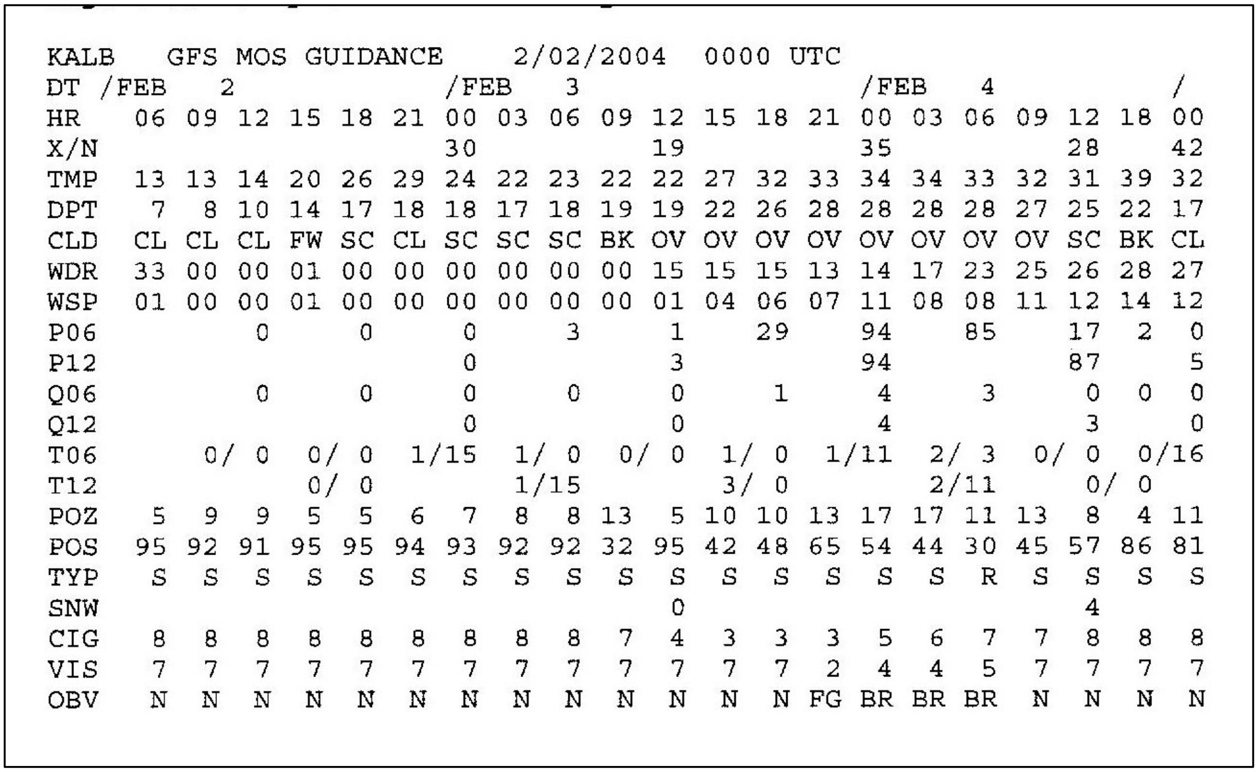
```
NMCFWCDCA
FOUS14 KWBC 060357
DCA  ESC  NGM MOS GUIDANCE   3/06/91  0000 UTC
DAY /MAR     6             /MAR   7                /MAR   8
HOUR     06 09 12 15 18 21 00 03 06 09 12 15 18 21 00 03 06 09 12
MX/MN                      59          39          54          24
TEMP     37 34 33 38 45 53 52 49 46 43 40 42 47 51 42 39 35 30 24
DEWPT    27 28 28 30 32 36 40 38 41 41 37 33 28 27 25 21 20 19 19
CLDS     OV OV OV OV OV OV OV OV OV OV BK BK BK SC SC SC CL CL CL
WDIR     26 18 08 12 14 14 15 18 24 27 28 29 29 29 29 33 01 02 00
WSPD     01 04 06 10 11 12 16 18 13 15 12 20 24 22 14 12 14 08 00
POP06           4     9    46    85    62     3     7    12     8
POP12                      49          91           8          19
QPF           0/    0/    1/1   3/    2/4   0/    0/0   0/    0/0
TSV06        2/ 0  3/ 0  4/ 1  5/ 1  6/ 2 16/ 3 11/ 1  8/ 0  0/ 0
TSV12              4/ 0        8/ 1       21/ 4        9/ 1
PTYPE     S  S  S  S  S  R  R  R  R  R  R     R     R     S     Z
POZP      8 10 12  6  0  0  0  0  0  1  3     0     2    24    35
POSN     65 67 70 48 41 14 11 13 15 16 20     9    16    50    42
SNOW          0/    0/    0/1   0/    0/0   0/    0/0   0/    0/0
CIG       4  5  4  4  5  6  7  6  3  2  1     5     6
VIS       3  4  3  5  5  5  5  4  2  2  1     3     4
OBVIS     H  H  H  N  N  N  N  F  F  F  F     H     N
```

Figure 11. The complete NGM-based MOS guidance message (FOUS14) issued on March 6, 1991, for Washington, D.C.



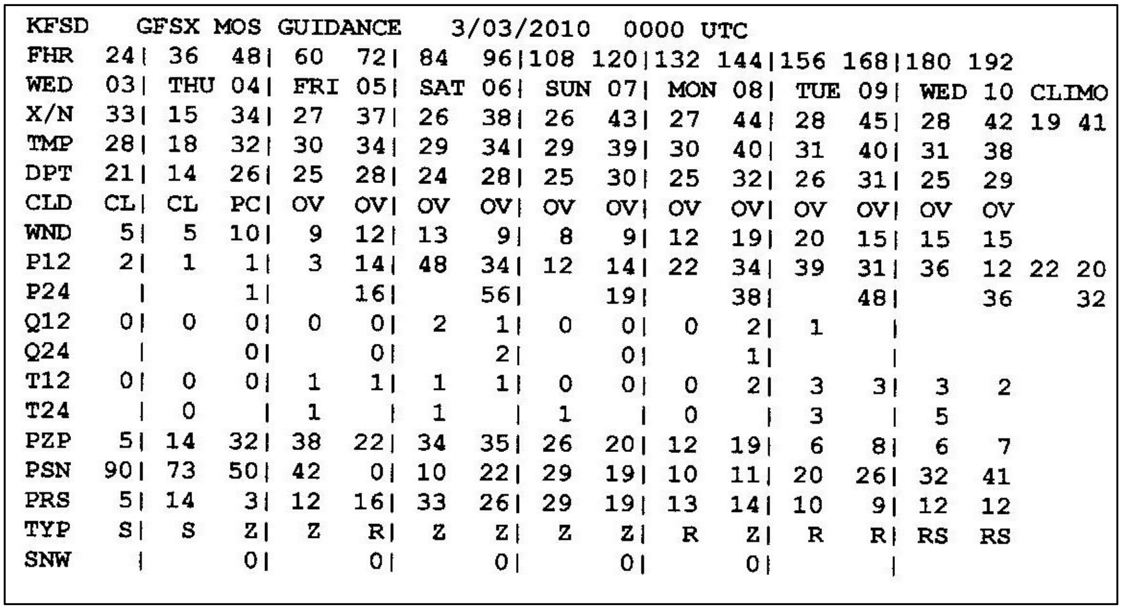
```
NMCFMRALY
FOXE40 KWBC 080000
MRF-BASED OBJECTIVE GUIDANCE  12/08/92  0000 UTC
ALB    DEC 08| DEC 09| DEC 10| DEC 11| DEC 12| DEC 13| DEC 14| DEC 15| CLIMO
MN/MX      49| 34  45| 24  27|  2  18|  5  25| 10  27| 18  38| 29  39| 18  35
POP12      32| 69 100| 67  58| 21   8|  0   3| 12  15| 26  33| 35  42| 26  29
CPOS        0|  2  29| 75  99|100 100|100 100|100  97| 85  71| 63  61| 68  67
CLDS       62| 76  97| 97  88| 52  21| 20  28| 43  55| 62  63| 60  64| 54  58
WIND       12| 15  21| 18  19|  6   8|  2   4|  4   5|  5   7|  7   8|  5   6
POP24        |  100  |   81  |   25  |    3  |   21  |   46  |   55  |   41
```

Figure 12. The MRF-based medium-range guidance message issued for Albany, NY from the 0000 UTC run of the Global spectral model. At this time, the guidance was a combination of both MOS and modified perfect prog approaches.



```
KALB   GFS MOS GUIDANCE    2/02/2004  0000 UTC
DT /FEB   2            /FEB   3                /FEB   4          /
HR   06 09 12 15 18 21 00 03 06 09 12 15 18 21 00 03 06 09 12 18 00
X/N                    30          19          35          28    42
TMP  13 13 14 20 26 29 24 22 23 22 22 27 32 33 34 34 33 32 31 39 32
DPT   7  8 10 14 17 18 18 17 18 19 19 22 26 28 28 28 28 27 25 22 17
CLD  CL CL CL FW SC CL SC SC SC BK OV OV OV OV OV OV OV OV SC BK CL
WDR  33 00 00 01 00 00 00 00 00 00 15 15 15 13 14 17 23 25 26 28 27
WSP  01 00 00 01 00 00 00 00 00 00 01 04 06 07 11 08 08 11 12 14 12
P06         0     0     0     3     1    29    94    85    17  2  0
P12                     0           3          94          87     5
Q06         0     0     0     0     0     1     4     3     0  0  0
Q12                     0           0           4           3     0
T06      0/ 0  0/ 0  1/15  1/ 0  0/ 0  1/ 0  1/11  2/ 3  0/ 0  0/16
T12            0/ 0        1/15        3/ 0        2/11     0/ 0
POZ   5  9  9  5  5  6  7  8  8 13  5 10 10 13 17 17 11 13  8  4 11
POS  95 92 91 95 95 94 93 92 92 32 95 42 48 65 54 44 30 45 57 86 81
TYP   S  S  S  S  S  S  S  S  S  S  S  S  S  S  S  S  R  S  S  S  S
SNW                                 0                       4
CIG   8  8  8  8  8  8  8  8  8  7  4  3  3  3  5  6  7  7  8  8  8
VIS   7  7  7  7  7  7  7  7  7  7  7  7  7  2  4  4  5  7  7  7  7
OBV   N  N  N  N  N  N  N  N  N  N  N  N  N FG BR BR BR  N  N  N  N
```

Figure 13. The GFS-based MOS short-range guidance message issued on February 2, 2004, 0000 UTC cycle for Albany, NY.



```
KFSD   GFSX MOS GUIDANCE   3/03/2010  0000 UTC
FHR  24| 36  48| 60  72| 84  96|108 120|132 144|156 168|180 192
WED  03| THU 04| FRI 05| SAT 06| SUN 07| MON 08| TUE 09| WED 10 CLIMO
X/N  33| 15  34| 27  37| 26  38| 26  43| 27  44| 28  45| 28  42 19 41
TMP  28| 18  32| 30  34| 29  34| 29  39| 30  40| 31  40| 31  38
DPT  21| 14  26| 25  28| 24  28| 25  30| 25  32| 26  31| 25  29
CLD  CL| CL  PC| OV  OV| OV  OV| OV  OV| OV  OV| OV  OV| OV  OV
WND   5|  5  10|  9  12| 13   9|  8   9| 12  19| 20  15| 15  15
P12   2|  1   1|  3  14| 48  34| 12  14| 22  34| 39  31| 36  12 22 20
P24    |      1|     16|     56|     19|     38|     48|     36    32
Q12   0|  0   0|  0   0|  2   1|  0   0|  0   2|  1    |
Q24    |      0|      0|      2|      0|      1|       |
T12   0|  0   0|  1   1|  1   1|  0   0|  0   2|  3   3|  3   2
T24    |  0    |  1    |  1    |  1    |  0    |  3    |  5
PZP   5| 14  32| 38  22| 34  35| 26  20| 12  19|  6   8|  6   7
PSN  90| 73  50| 42   0| 10  22| 29  19| 10  11| 20  26| 32  41
PRS   5| 14   3| 12  16| 33  26| 29  19| 13  14| 10   9| 12  12
TYP   S|  S   Z|  Z   R|  Z   Z|  Z   Z|  R   Z|  R   R| RS  RS
SNW    |      0|      0|      0|      0|      0|       |
```

Figure 14. The GFS-based MOS medium-range guidance message issued on March 3, 2010, 0000 UTC cycle for Sioux Falls, SD.

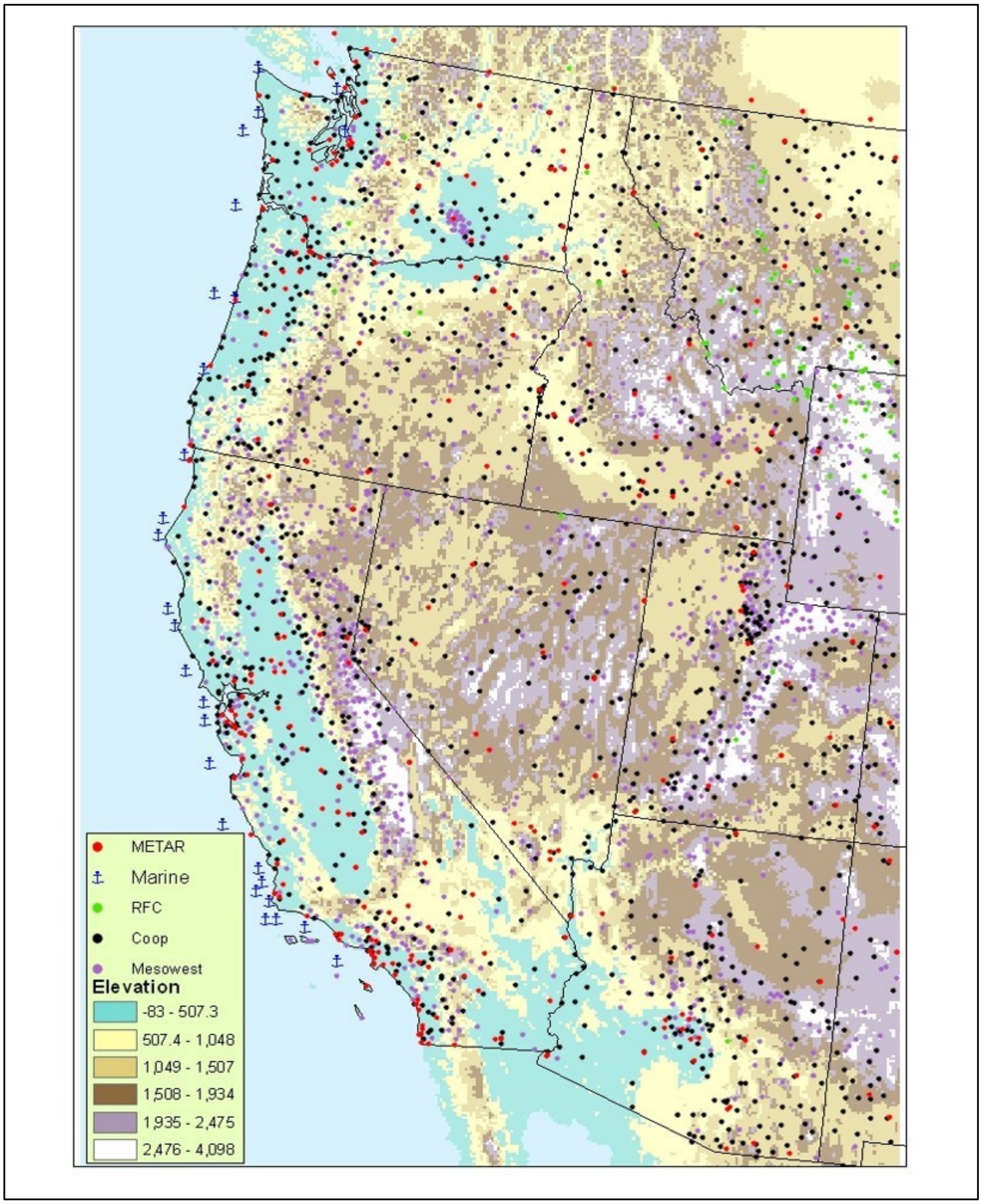
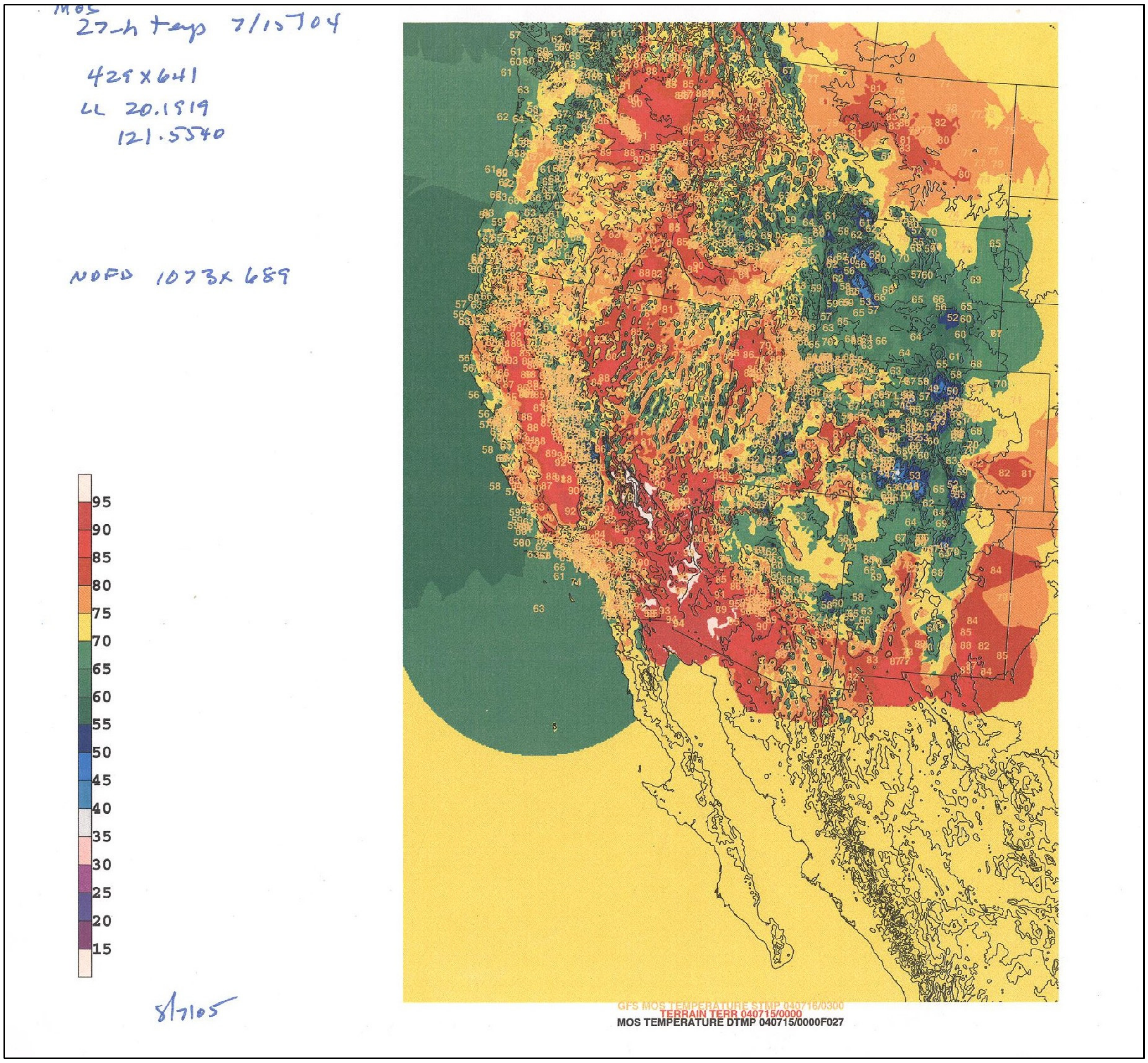


Figure 15. Map of the western CONUS displaying the elevation and locations of the sites for which MOS temperature forecasts are generated. The legend indicates the type of observing site.



MOS
27-h temp 7/15/04

425x641
LL 20.1919
121.5540

NDFD 1073x689

8/7/05

Figure 16. An example of the BCDG analysis used to generate gridded MOS guidance in support of the NDFD. The plotted numbers indicate GFS-based MOS forecast temperatures valid 27 hours after 0000 UTC, July 15, 2004. Colors indicate temperatures according to the color scale shown to the left of the map. Note the density of stations as well as the detail in the temperature field. This analysis was done on the 5-km NDFD grid.