1.2 THE EARLY YEARS – STATISTICAL INTERPRETATION SYSTEMS, VERIFICATION, AND COMPUTER-WORDED FORECASTS

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1. INTRODUCTION

The 1960's and 1970's were a time of great change in meteorology. As knowledge of physical processes affecting the atmosphere increased and as observing systems improved, greater computer power made the possibility of accurate objective weather forecasting a reality. Simple dynamical weather prediction models like the barotropic were replaced by baroclinic models. Within the National Weather Service (the Weather Bureau until 1970), a group of dedicated meteorologists led efforts to make weather forecasting an accurate, reliable service. The National Meteorological Center or NMC (later reorganized as the National Centers for Environmental Prediction or NCEP) was responsible for the development and implementation of the dynamical weather prediction models. Despite the improving models, however, a single model run provided little information about the uncertainty inherent in the forecast. While the model might predict measurable precipitation, the human forecaster did not know how much confidence could be placed in that prediction. The first baroclinic models contained only rudimentary physics or parameterizations describing the processes in the planetary boundary layer. Thus, model forecasts of the surface wind did not account for local topography or surface heating. Predictions of the 2-m air temperature or dew point were not available or were very inaccurate. Human forecasters could subjectively interpret model forecasts, but an objective interpretation of model output seemed essential to the forecast process.

In 1964, the Techniques Development Laboratory or TDL (later reorganized as the Meteorological Development Laboratory or MDL) was created (Glahn 1989). TDL's initial mission was "to insure that basic knowledge in meteorology, hydrology, climatology and allied disciplines is translated into improved operating techniques and procedures." This mission soon became oriented to developing operational techniques and generating from dynamical models objective guidance for the forecasters. Two scientists in TDL were primarily responsible for bringing statistical methods of interpreting model output to the National Weather Service (NWS). Bill Klein was Director of TDL from 1964 until 1976. Bob Glahn, with TDL from its inception, became Director of TDL in 1976 and served in that capacity until retiring in 2012. In a review of TDL's first 25 years, Bob wrote: "*The age of computers freed researchers from depending for development and implementation upon tedious manual calculations …. These methods, which had their heyday in the mid'40's to '50's, made processing of large samples of data almost impossible. With a large mainframe computer at NMC …, researchers could now think not only about multiple regression with many variables and large data samples for development, but also about distributing the results of such research to the field organization on a scheduled basis*."

During his career as researcher, developer, supervisor, and senior executive in the NWS, Bob became synonymous with the development of the Model Output Statistics (MOS) method of interpreting the dynamical model to generate weather element guidance. Bob's contributions to MOS were undeniably significant, yet his vision in proposing computer-worded forecasts, updated short-range guidance, and verification approaches were also critical to the NWS. In this paper, we consider some of the events in the history of Bob Glahn and the development of statistical forecast products. We focus on the early years of Bob's career, ending around 1989 after implementation of a MOS system based on the Nested Grid Model (NGM).

2. EDUCATIONAL BACKGROUND

Bob Glahn obtained dual bachelor of science degrees from Northeast Missouri State Teachers College in 1953, majoring in mathematics and education with an emphasis on mathematics. Following completion of his undergraduate studies, Bob entered the United States Air Force as a commissioned officer. As part of his Air Force training, he took meteorology classes during 1953-54 at Oklahoma A & M College. After 4 years of active duty, Bob returned to civilian life while remaining an officer in the reserves. He eventually retired from the reserves with the rank of Colonel after 30 years of service. In 1957, he started graduate school at Massachusetts Institute of Technology (MIT). MIT awarded him an M.S. in meteorology in 1958. Later that year, Bob began his career with the Weather Bureau. He was assigned to the Short Range Forecast Development Section in Washington, D. C. According to Bob, at that point he had had one introductory course in statistics taken prior to 1953. Moreover, computers were not being used in the section, and no digital archives existed.

The lack of knowledge about statistics and computer programming was remedied by additional

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education. Bob took a FORTRAN programming course and attended night school at American University from 1959 until 1961. By August 1961, he had taken four graduate-level statistics courses. His diligence was awarded when he received a Weather Bureau scholarship for additional training. He entered the Ph.D. program at Penn State University where he studied meteorology and statistics during 1961-62. He was awarded the Ph.D. degree in 1963.

3. INITIAL INVESTIGATIONS

In 1962, Bob Glahn described an experiment (Glahn 1962) to forecast areal coverage of summer rainfall in a small region of the Mississippi Delta. The predictand (the quantity to be forecast) was defined as a weighted sum of the number of sites reporting a trace or more of precipitation during a 24-h period ending at 0700 local time. This experiment was a good example of the "classical" statistical method of weather forecasting, i.e., only observations prior to the start of the predictand period were used as predictors. Many of the possible predictors came from stations outside the region of interest. In other applications, this had been termed a "field" or "network" approach. Bob noted that the classical method was necessitated by the lack of physical and dynamical models that could be used to provide predictive information. The experiment was notable in several ways. First, it was obvious from the small sample size and the type of meteorological observations used that substantial effort was expended to create predictors and predictands. Secondly, both multiple linear regression and empirical orthogonal functions (principal components) were tested as prediction techniques. The empirical orthogonal functions were tried because large correlations among predictors made many predictors redundant. In fact, principal components seemed more stable than screening regression in tests on independent data. Finally, Bob created all the software to derive and evaluate the regression equations and the principal components (personal correspondence 2014). The regression software was capable of screening predictors singly and in pairs, and the user could choose to force certain variables into the regression equations – an option that would later become part of the MOS system. The attempt to forecast the areal extent of convective precipitation from prior observations was not successful. However, Bob did note that advection parameters and input from dynamical models might provide non-linear predictors to the linear regression technique and improve the results.

In his doctoral work, Bob discussed a number of statistical techniques that could be used in objective forecast systems (Glahn 1964a). These techniques included scatter diagrams, linear regression, decision theory, multiple discriminant analysis, contingency tables, canonical correlation, and adaptive logic (later known as artificial intelligence or neural networks). Tested techniques focused on producing a 5-h forecast of ceiling height at Washington National Airport (DCA). The classical method was used, namely, surface observations taken at a network of stations 5 h prior to the verification time were included as predictors.

Important conclusions came from this work, though the problem of forecasting ceiling heights was not solved. Bob advocated the applicability of decision theory to meteorological problems because uncertainty in initial conditions resulted in imperfect forecasts, and, hence, in users making decisions with risk (Glahn 1964b). Probabilities combined with a user's utility matrix would result in optimal choices for that user. The utility matrix denotes the value (perhaps, the economic value or the relative impact) of actions taken by the user for a possible state of nature. In our context, the actions are categorical forecasts and the state of nature is the subsequent observation of the event being forecast. The utility matrix can be used to select predictors when creating a forecast system, to choose a categorical forecast in operations, and to evaluate a series of forecasts. In Bob's opinion, the "best verification statistic of forecasts is their usefulness to the user." Unfortunately, a utility matrix is specific to a user, is often unknown, and may vary widely among users. Nevertheless, the ideas that probabilities were essential to the forecast process and that verification statistics needed to be relevant were firmly established.

In Bob's study, multi-dimensional contingency tables were built and used to predict the probability of specific intervals of ceiling height. Yet, the additional complexity did not seem to increase the utility of the forecasts, and development of contingency tables for the purposes of probability forecasting was cumbersome. Bob mentioned that, perhaps, a parametric technique like multiple discriminant analysis might be more useful in creating an objective forecast system. However, work by Glahn and Allen (1964) on developing a classical method to forecast the probability of precipitation at Salt Lake City via discriminant analysis resulted in a system inferior to a scatter-diagram analysis done by experienced forecasters. Obtaining probabilities from discriminant functions was not easy, and, clearly, scatter diagrams could not form the basis of a nationwide objective forecast system.

Using adaptive logic models to predict ceiling height was also tested (Glahn 1964c). As with multiple discriminant analysis, Bob coded the appropriate software to create the adaptive logic models. Two models were tried, one for a single predictand breakpoint (two categories of ceiling height), and one for multiple categories of ceiling height. Predictors were selected by screening binary variables via multiple discriminant analysis. Both discriminant analysis and the adaptive logic models were able to produce probabilities, and tests were conducted on independent data. Based on the Brier score (Brier 1950), the discriminant analysis probabilities were more accurate than those of the adaptive logic models. A categorical forecast was created from discriminant analysis probabilities by choosing the category which had the highest probability of occurrence. A categorical forecast was the natural result of the adaptive logic models. In terms of percent correct, the discriminant analysis approach was superior to the adaptive logic model. Bob concluded: "for this particular prediction problem discriminant analysis has a distinct advantage over the adaptive logic models that were used." One other significant result came out of this test. In the discriminant analysis system, no categorical forecasts of the lowest ceiling category were made. In both discriminant analysis and multiple linear regression, probabilities for rare events like low ceiling heights are generally low because of the difficulty predicting a rare event. Selecting a categorical forecast on the basis of the highest probability usually eliminates forecasts of the rare categories. Bob noted: "If it is more important to correctly forecast low ceilings than it is to correctly forecast high ceilings, a different utility matrix should be used than the one that equates number correct to utility."

The introduction of canonical correlation analysis in meteorology also resulted from Bob's doctoral work. Bob described canonical correlation as a way of relating two sets of data (predictors and predictands) to one another via canonical functions (Glahn 1968). The canonical relationships for the predictors are uncorrelated to each other, as are the relationships for the predictands. Under certain conditions, canonical correlation is equivalent to either discriminant analysis or multiple linear regression. Essentially, canonical correlation can be considered a technique of using principal components when both predictors and predictands are vector or field quantities. Bob's example of canonical correlation analysis related observed 500-hPa heights at 30 U.S. stations to heights observed at the same sites 24 h earlier. Though canonical correlation was never used at TDL, Wilks (2006) showed how canonical correlation analysis was applied to generate seasonal forecasts.

A thorough summary of statistical techniques that could be used for objective forecasting was presented in Glahn (1965). Bob advanced the notion that objective approaches encompassed both numerical weather prediction models and statistical techniques. He advocated the use of predictors suggested by physical reasoning and conceptual models. Moreover, though all the forecast examples presented in the paper used the classical approach, Bob advocated the use of numerical model forecasts as possible predictors. The paper summarized five techniques: scatter diagrams (graphical analysis), multiple linear regression, multiple discriminant analysis, empirical orthogonal functions (principal components), and adaptive logic. Except for scatter diagrams, the techniques required computers and large data samples.

By this time, Bob had coded software to do all the computer-based statistical techniques. He presented a cogent argument for the use of multiple linear regression, provided the application used physically reasonable predictors and avoided predictors chosen randomly. Linear regression had been introduced into meteorology by Bryan (1944) and into the meteorological literature by Miller (1958). Bob suggested that screening of predictors and avoidance of the F-test (one of the standards for halting the regression process) be standard. The use of REEP (Regression Estimation of Event Probabilities) that had been advanced by Miller (1964) was also advocated for forecasting probabilities. The REEP application had the advantage that, when the predictand categories were mutually exclusive and completely exhaustive, the forecast probabilities added to one. Linear regression also guaranteed that the Brier score (mean square error) was minimized on the dependent data. From a programming perspective, the requirement of REEP that all predictors and predictands be binary (or "dummy") variables had the advantage of speeding up the software application. The disadvantage of REEP was that the probabilities were not constrained between 0 and 1. Multiple discriminant analysis had a serious disadvantage, namely, obtaining probabilities from discriminant functions was not simple. The use of adaptive logic had not proven itself, and screening of predictors was not feasible. Use of principal components showed some promise of stabilizing forecast relationships developed from relatively small data samples. Bob's opinions would be reflected in subsequent development within TDL.

4. CHANGE HAPPENS – THE BEGINNING OF MOS

By 1966, NMC had implemented the hemispheric primitive equation (PE) model (Shuman and Hovermale 1968) to generate forecasts twice daily for projections out to 36 h after 0000 and 1200 UTC (Campana 2004). By May 1967, Bob Glahn (personal notes 1967) had outlined a rationale and structure for a system to provide an objective interpretation of PE output in terms of surface weather variables. Bob stated that the PE model predicted isobaric height values in the troposphere, and had sufficient physics to produce forecasts of mean relative humidity in the troposphere. Algorithms in the model then deduced the occurrence of precipitation. However, forecasters at NMC and in the field had to interpret subjectively the PE model forecasts to infer the probability of precipitation, surface temperature, surface winds, clouds, ceiling heights, the likelihood of frozen precipitation, and so forth. Bob proposed that an archive of PE model output and coincident surface observations be established on magnetic tape. Once the data archive was available, multiple linear regression would be used to relate the predictand to predictors taken from both the latest surface observations (an indication of local effects and persistence) and the PE model forecasts. All model predictors would be interpolated to the station at which the predictand was observed, and the regression would be based on relationships between predictand and predictor at a coincident site. The field or network approach used in many of the earlier statistical experiments would be abandoned in favor of a simpler, more systematic structure.

Two developmental procedures were suggested. In the first, after two months of data were accumulated, the developmental data would be pooled for all stations in a homogeneous region so as to have an adequate sample of cases. Then the forecast equations would be developed and applied operationally. The sums of squares matrices would be saved on magnetic tape, and the forecast equations would be updated weekly with the latest available data. As the sample size increased, the homogeneous regions could be subdivided into smaller groupings, eventually becoming single-station regions.

Many years later, the idea of automatically saving and updating the regression matrices with more current data became known as "updateable" MOS. Though the technique was never implemented in TDL, Bob and the author of this paper considered it once more during development of a modernized MOS system in the late 1990's and early 2000's. We rejected the idea because of its operational complexity. The sheer number of matrices, the accumulation of observations from various sources, the need to quality-control those observations, the aperiodic addition or removal of stations in the developmental sample, and the difficulty of combining matrices from different time periods or different stations in a rational fashion influenced our decision. Updating the equations themselves on a scheduled basis, for example, every 6 months to a year, seemed more practical. Indeed, the initial MOS experiments of the late 1960's and early 1970's used seasonal equations redeveloped before the start of each new season.

In the second proposed method, only a month of data was required for equation derivation. Once the sample of data was accumulated, equations would be developed and implemented. A week later, the oldest 7 days of data would be eliminated, and the most recent 7 days would be added to the sample. Pooling of the data for multiple sites would always be necessary. All equations would be re-developed weekly from the most recent 30 days of data. Later, this approach was termed "short-sample" MOS, and was tested in a rudimentary fashion for temperature forecasting (Dallavalle 1996).

Bob finally suggested that forecasts from both methods be saved and verified on a regular basis. The verifications, if done in near real-time, would permit observations to be related via linear regression to a weighted combination of the forecasts produced by the two methods. This concept was later known as "consensus" MOS and was potentially applicable to MOS guidance generated from multiple weather prediction models.

5. SHORT-RANGE SUB-SYNOPTIC SURFACE WEATHER PREDICTION

Even before the implementation of the PE model, TDL had embarked on a program to improve objective short-range forecasts (Glahn and Lowry 1967). The project focused on predicting surface weather variables 1 to 18 h in advance on a scale of approximately 50 miles. At first, efforts concentrated on prediction of precipitation and clouds, with later work to focus on temperature, winds, relative humidity, ceiling height, and visibility.

For prediction on this time and space scale, accommodation to both operational requirements and computer resources was necessary. During this era, the NWS released the public weather forecasts twice daily, namely, at approximately 0900 to 1000 UTC and 2100 to 2200 UTC. These release times enabled the official forecasts to be available in time for publication in the next issue of the daily newspaper or for use in the morning or evening television news programs. These deadlines meant that a surface observation of 0800 or 2000 UTC was the latest available for a useful short-range forecast scheme. Computer resources were also critical. With the PE model running on the CDC 6600 (the sole computer available for model runs, development of forecast techniques, and implementation of new guidance products), computer time was scarce.

Bob Glahn had said that a classical statistical approach was inadequate and that numerical weather prediction models were essential to a skillful statistical forecast system. Yet, the PE model was running on a polar stereographic grid of 381 km resolution at a latitude of 60° N (later known as a 1-bedient grid). This resolution was not comparable to the density of the surface observation network. When the PE model replaced the barotropic model in 1966, NMC also retired the Reed sea level pressure model (Reed 1963) that had been part of the operational suite. The SLYH precipitation model (Younkin et al. 1965) was another member of the older suite. Part of the Glahn and Lowry plan was to take the Reed and SLYH models, increase their horizontal resolution to 0.25 bedient (95.25 km), and integrate the two models forward in time to cover the desired short-range forecast projections of 1 to 18 h. The eventual configuration of the enhanced Reed and SLYH models became known as the Subsynoptic Advection Model or SAM (Glahn and Lowry 1972a). For the prototype statistical system, public weather elements such as the probability of precipitation and max/min temperature would be predicted for the "today" period, that is, the period from 7 am to 7 pm EST (Fig. 1).

The latest surface observations as well as forecast output from SAM and the PE model were to be used as predictors in the statistical guidance approach. According to the plan, statistical relations between predictand and predictors would "*probably*" be developed by regression techniques.

If daily operational deadlines were to be met by this prototype statistical system, something had to be done to minimize computer usage. At the same time, running the Reed and SLYH models at a 0.25-bedient resolution (the greatest spatial resolution yet used within the NWS) required enhancements and additional computer time. These conflicting priorities were resolved, in part, by reducing the areal extent of the forecast grid to the eastern United States (Fig. 2).

Bob summarized the underlying philosophy behind this initial statistical system (Glahn and Lowry 1972a). As already mentioned, he wanted to develop an objective forecasting system to supplement the NMC system. This system was designed to:

- determine the forecast cycle by the needs of the NWS forecaster rather than the observation time of the upper air soundings;
- use hourly observations routinely available;
- use a model resolution consistent with the spacing of the surface observation stations;
- employ a combination of numerical and statistical models to forecast surface weather variables;
- optimize the available computer time in doing the numerical model computations.

Efforts to make this inaugural sub-synoptic system operational were extensive. For the first time within the NWS, the hourly surface weather observations (also known as SA's) were decoded automatically (Hollenbaugh et al. 1969). Some error-checking was incorporated into the software. The process was complicated because the SA's were collected on the IBM 360/40 computer (the NWS's communications computer) and written to magnetic tape. In turn, the magnetic tape was carried by an operator to be mounted on the CDC 6600. Software on that computer then read the tape and decoded the observations. This process would be simplified in later years when the SA's became available directly in a disk storage area on the computational computer.

At the same time, Bob took the successive approximations analysis method (Bergthorssen and Doos 1955; Cressman 1959) used in the NWS and optimized it for a reduced grid length. He tested his code by reanalyzing 500-hPa heights on a 0.5-bedient grid (Glahn and Hollenbaugh 1969). The analysis was done over the same area shown in Fig. 2. Error-detecting algorithms were written, and wind observations were used to infer geostrophic gradients in the height field. Bob found that the increased resolution on the 0.5-bedient grid resulted in better upper-air analyses than the NMC analysis done on the 1-bedient grid.

Bob then turned to analyzing surface observations on the 0.25-bedient grid for input to SAM. Analyses of sea-level pressure and saturation deficit were needed for the model's initial conditions. The saturation deficit, which was the forecast moisture or "precipitation" variable in SAM, is defined as the difference between the 1000-500 hPa thickness and the saturation thickness. The latter is the 1000-500 hPa thickness required for saturation with a given vertical moisture profile. While surface observations of sea-level pressure, dew point, clouds, temperature, and weather were available on the temporal and spatial resolution of SAM, the vertical moisture profile was only observed every 12 h. To obtain an indication of the moisture profile at the SAM start time, a statistical relationship was developed between the saturation deficit and the hourly surface observations (Lowry and Glahn 1969). This relationship estimated via regression the saturation deficit from surface dew point, sky cover, and precipitation occurrence. Error-detection algorithms were incorporated into this analysis process. Glahn et al. (1969a) provided details about the tuning required to preserve small-scale detail without creating non-meteorological features.

SAM, implemented in June 1968 (Glahn et al. 1969b; Glahn and Lowry 1972a), was the first sub-synoptic model to be fully operational. Running twice daily on the CDC 6600 in less than 3 minutes of computer time, the model generated sea-level pressure and categorical precipitation forecasts for projections of 1 to 17 h after the model start time. For operational reasons, the model start time had been advanced to follow the availability of the 0700 UTC observations. This allowed production of a public weather forecast for "today." The second start time (1900 UTC) allowed for production of a public weather forecast for "tonight." While the SAM forecasts were available approximately 1 hour and 15 minutes after observation time, half of that time was required for collecting observations from the communications circuits. Most of the rest of the time was consumed in loading magnetic tapes, transferring output to paper tape for teletype transmissions, and creating magnetic tapes to generate facsimile graphics on the NMC curve plotters.

Verification of the SAM forecasts (Glahn and Lowry 1972a) indicated that the availability of later surface observations in the model improved the sea-level pressure forecasts relative to those from the PE model. Differences in threat score for precipitation forecasts over a 5-year period indicated that SAM had slightly better threat scores than the PE model. These differences were seasonally dependent and varied with modifications to the PE model. Note, however, that the primary purpose of SAM was to enhance a statistical forecast system blending SAM, the PE model, and the most recent hourly observations (Glahn et al. 1969b).

6. A NEW STATISTICAL APPROACH -- MOS DEFINED AND TESTED

At the first AMS conference on statistical meteorology, Bob presented his new approach to statistical prediction (Glahn and Lowry 1968). He noted that the statistical and dynamical approaches to weather forecasting should be merged, despite a history of growing independently of each other. The lack of complete understanding of atmospheric processes, a shortage of mathematical and computer technology, inadequate observations, and the "random" component of atmospheric motion argued for a statistical-dynamical approach. Statistical approaches had already been tried in predicting variables like ceiling height, visibility, surface winds, and maximum or minimum temperature because the dynamical models were unsuccessful in predicting those quantities. Bob suggested that an approach other than the classical or "perfect prog" methods might be a better answer. Here is Bob's description of what became known as MOS: "*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.*"

6.1 *Probability of Precipitation*

With the MOS concept established, testing commenced. In Glahn and Lowry (1969), the MOS acronym was defined when Bob described the development of probability of precipitation (PoP) forecast equations. Multiple linear regression, specifically forward stepwise regression, was the method of choice. Regression had been successfully used in meteorology before, was relatively simple, and was applicable to both continuous and binary predictands. For a single binary predictand like the occurrence of measurable precipitation, regression provided an estimate of the probability, or the relative frequency, of the event, given a similar set of predictor conditions. Since Bob had built software to do forward stepwise regression as well as REEP, using multiple linear regression was reasonable from both a statistical and a systems viewpoint. Bob again noted that the stopping criterion for the regression process should not be a significance test because many of the assumptions underlying such a test were not applicable in meteorology. He recommended that experience determine the number of variables to use in a prediction equation.

Initial tests began with a short sample (April – October 1967) of SAM and PE model forecasts. Efforts were focused on guidance for the "today" period, and so output from the 0700 UTC SAM and 0000 UTC PE model was used. The predictor and predictand data were pooled because of the small sample size, and a "generalized operator" equation was developed for application to all stations in the sample. Different equations with different predictors were developed for 1200-1800, 1800-0000, and 1200-0000 UTC periods. For "today," these periods corresponded to projections of 12-18, 18-24, and 12-24 h, respectively, after the 0000 UTC PE start time. Developmental data were stratified by season, that is, equations were derived for warm (April-September) and cool (October-March) seasons. Tests on dependent data showed that PE forecasts added to the information provided by SAM; predictors from both models and from surface observations were retained in the MOS system.

Tests on independent data were run from July 1968 through June 1969. For the 1968 warm season, the 1968-69 cool season, and the 1969 warm season, the MOS forecast equations were redeveloped prior to the start of each new season by adding data from the previous season to the developmental sample. In comparison with the local PoP forecasts issued by forecasters at 11 NWS sites, the MOS PoPs were more accurate than the locals in terms of the Brier score. The MOS PoPs were also more reliable. When NMC forecasters began issuing subjective precipitation probabilities for the "today" period in May 1969, the MOS PoPs were more accurate than those forecasts as well.

Early verification results were so promising that the first operational MOS facsimile product, namely, PoPs for the eastern United States, was implemented in February 1969 (Fig. 3). By May 1969, the MOS PoPs were available for 79 stations in alphanumeric format (FOUS) on the Service "C" teletypewriter circuit. In October 1969, PoP guidance became available for the "tonight" period from the 1900 UTC run of SAM and the 1200 UTC run of the PE model.

6.2 *Surface Winds*

Analogous tests were conducted to determine the best method for predicting surface winds (Glahn 1970a). Bob showed that solution of the normal regression equations for the u- (east-west) and v- (north-south) components of the wind vector provides the least squares fit for the total vector. However, the best solution for the u- and v-components does not minimize root mean square errors for either wind direction or wind speed. In fact, wind speed predicted by using the regression-based wind components underestimates the observed wind speed. The problem of estimating the wind direction via regression is complicated by the fact that wind direction is a circular function with a range of 0 to 360 degrees. Bob proposed several models to account for these problems, including modification of predictor winds by turning and stretching the vectors, and predicting the probability of categories of wind direction. In the end, he settled on a relatively simple approach for predicting winds. Single-station equations were developed for each station, forecast projection, forecast cycle, and season. Certain variables were forced to be in the equations. For u- and v-wind components, 1000-hPa geostrophic u- and v-wind components predicted by SAM were required. For wind speed, the SAM-based 1000-hPa geostrophic wind speed was a requisite predictor. Other possible predictor variables included 0700 UTC surface observations and forecasts from the 0000 UTC PE model. The prediction equations were developed simultaneously for the u- and v-wind components so that identical predictors were used in each equation, though the coefficients differed. The MOS wind direction was predicted by the appropriate combination of the u- and v-wind component forecasts. The MOS wind speed forecast resulted from using the prediction equation.

The MOS forecasts were compared over a 2-mo period with the official aviation terminal forecast (FT) winds at 10 stations. Two forecast valid times, namely 1200 and 1800 UTC, were verified. For the MOS system, the valid time represented a forecast of 5 and 11 h, respectively, from the SAM initialization. For the FT's, the valid time represented a forecast of 3 and 8 h, respectively, after the last observation available to the human forecaster making the FT. Although the sample was small, the MOS wind direction forecasts were as good as the FT's. For wind speed, the MOS speeds were more accurate than the FT's. As expected, MOS wind speeds computed from the u- and v-wind components had a negative bias (too slow) compared to the actual wind speeds and to the MOS winds computed from the wind speed equations. MOS wind guidance from these single-station equations replaced SAM geostrophic wind forecasts on the FOUS bulletin in July 1970. As an aside, MOS wind forecasts based on a simple generalized-operator equation had been included with the SAM geostrophic winds on the FOUS bulletin implemented in June 1968. That rudimentary MOS wind guidance was eliminated when the PoP guidance was added to the bulletin in May 1969.

6.3 *Maximum Temperature*

Annett, Glahn, and Lowry (1972) described initial efforts to predict the calendar day maximum temperature ("today's" max) via MOS from output variables of the 0700 UTC SAM and the 0000 UTC PE model start times. Developmental data were again 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 in the regression. Though tests were conducted on a small sample of stations, several important conclusions resulted from the study. First, the optimal number of predictors to use in the forecast equations was tested and 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 the bias. Third, not all of the bias was eliminated; the authors speculated that some bias could have been due to changes made to the PE model over the period that the developmental sample was collected. Lastly, the MOS system was comparable in accuracy to the perfect prog temperature guidance (Klein and Lewis 1970), but was less accurate than the official max temperature forecasts.

6.4 *Ceiling Height and Visibility*

Work on forecasting ceiling height was described by Bocchieri and Glahn (1972). The idea of using only predictors valid at the predictand site had been accepted. In the nascent developmental and operational MOS system, the added complexity of using predictors from a network of stations was not justified by verification results. Multiple linear regression was the statistical technique to be used. Small samples and the rarity of low ceilings meant that developmental data were pooled and that generalized operator equations were derived for each projection. The question as to the type of predictors to use was not settled; experiments were conducted with various combinations of 0700 UTC observations, and forecasts from the 0000 UTC run of the PE model and/or the 0700 UTC SAM run. 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 (Fig. 4). 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 the equations for the binary or continuous predictand, respectively.

Development and testing focused on ceiling height forecasts valid at 1200, 1800, and 0000 UTC, which represented 5-, 11-, and 17-h projections, respectively, after the 0700 UTC observations were taken. In what became a standard model for TDL developers, the verification on independent data was designed to:

- determine the optimal number of predictors;
- decide on the optimal combination of observed and model predictors;
- choose the predictand definition that best fit user needs and produced the best guidance;

- compare the objective forecasts with an appropriate standard, such as persistence, climate, a subjective forecast, or another objective guidance product;
- determine the best approach for transforming the probabilities into categorical guidance.

Extensive tests showed that the MOS approach using all three types of predictors and generating probabilities was better than any of the competing systems. However, the tests also showed that the best approach to choosing a categorical forecast was dependent upon the verification score being used to evaluate the system. The developer needed to select a meaningful score and tune the categorical system accordingly. One of the interesting suggestions for future work was to develop single-station classical REEP equations from a long series of observations, and use the probabilities produced by these equations as a fourth source of potential predictors.

Similar tests were conducted for predicting visibility (Bocchieri et al. 1974). However, an additional set of predictors was tried by developing single-station classical REEP equations from a large sample of observations taken at 0700 UTC and each of the three hours prior to 0700 UTC. The availability of four consecutive hours of observations enabled the creation of complex predictor variables that could indicate trends in ceiling height or visibility, changing weather conditions, etc. These single-station REEP equations produced probability forecasts of each of the visibility categories with characteristics closer to those of each individual station, unlike the guidance produced by generalized operator SAM/PE MOS equations. Verifications indicated that a properly tuned SAM/PE MOS system including single-station probability predictors produced the best guidance of any of the systems tested. In September 1972, that system was approved for implementation on an experimental basis. However, due to delays and the fact that SAM was scheduled to be discontinued a year later, the system was never implemented.

The discussions about generating categorical ceiling height and visibility guidance indicated that a true utility matrix was unlikely to be available for determining categorical guidance. As Bob had pointed out previously, maximizing the percent correct was not beneficial when some categories represented rare events. The bias in the categorical guidance, that is, the number of categorical forecasts of the event relative to the number of observed events, was a concern. Thus, a new utility matrix that would produce biases between 0.98 and 1.02 for ceiling height and visibility guidance was developed. An iterative “trial and error” approach was necessary to obtain this minimum bias utility matrix. The practice of minimizing the bias in categorical guidance products later became widely adopted within TDL.

6.5 *Summary*

The seminal paper on MOS (Glahn and Lowry 1972b) summarized the MOS approach, the use of screening regression, and the development of PoP, wind, and max temperature guidance. At the time the paper was written, development of total cloud amount equations for four stations had been completed and testing had begun. A system to predict the probability of frozen precipitation given that precipitation was occurring (a conditional probability) was briefly described. While the cloud equations were single-station relationships, the equations for the conditional probability of frozen precipitation were developed by using data from nearly 100 stations in a generalized operator approach. In some sense, this paper documented the high-water mark of the SAM/PE MOS system. Fig. 5 shows a portion of the SAM/PE MOS message operational in 1971. Eventually, more extensive MOS guidance in terms of elements and national coverage replaced this rudimentary message, but the effort that went into developing this prototype operational MOS system laid the groundwork for what was to follow.

In building the prototype SAM/PE MOS system, Bob had shown MOS was valuable for predicting surface weather variables, particularly when probabilities were needed. Although the experiments, the number of stations included in the initial development, and the implementation of operational products were restricted by computer resources, Bob had demonstrated that:

- 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 by use of the proper utility matrix;
- 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 PE model changes may have affected the quality of the MOS guidance. The last paragraph of the paper was prescient in Bob’s assessment of the development of objective weather forecasting and future challenges. Here is what he wrote: *“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*.”

7. A VISION – THE COMPUTER WORDED FORECAST

Even before tests of the prototype MOS system were complete, Bob Glahn (Glahn 1970b) published examples of worded forecasts prepared by computer (Fig. 6). At the time, MOS equations had been developed for maximum temperature, surface wind, PoP, cloudiness, and the conditional probability of frozen precipitation. Bob had written software to extract the MOS guidance, use a series of approximately 80 phrases or sentences, rank the forecast elements in order of importance, compose a message from the digital guidance and the plain-language phrases, and add punctuation to the final product. The style imitated the public weather forecast available in many major cities via a telephone call to WE-6-1212. In this prototype system, the computer-worded forecast (CWF) was only available for four U.S. cities and the "today" forecast period. However, Bob mentioned that in approximately 3 years, he thought that forecasts could be available twice daily for stations throughout the United States for the three forecast periods (today, tonight, and tomorrow) from the early morning release time. In routine situations, the forecaster could then use the computer-worded product verbatim. In difficult situations, forecasters could use their time to analyze the weather and then modify the words that had already been prepared. In this scenario, *"the more routine duties can be handled by computer, thereby freeing the meteorologist for the more challenging roles of meteorological consultant and specialist on high-impact weather situations."* This concept was threatening to forecasters who viewed production of the worded forecast as the conclusion to the job of predicting the weather.

8. PERFECT PROG – A COMPETITOR TO MOS?

Bob Glahn's development of MOS during the 1960's and early 1970's was rivaled by another ongoing effort within TDL. Bill Klein, the laboratory's first director, was interested in using statistics in synoptic meteorology. However, Bill was a proponent of the "perfect prog" method (Veigas 1966). In the perfect prog approach, specification equations that related a meteorological variable like maximum (max) or minimum (min) temperature to **observed** or **analyzed** atmospheric conditions like upper-air heights or temperatures were developed. In operations, these equations were applied to **forecast** output from a dynamical model. Presumably, if the dynamical model produced accurate forecasts, then perfect prog equations would generate accurate guidance for the weather element of interest. On the other hand, MOS equations related a meteorological variable like maximum temperature to **predicted** variables from a dynamical model. These equations were applied to **forecast** output from the same or nearly the same dynamical 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 over NWS teletypewriter circuit C for 131 stations in the conterminous U.S. (Klein and Lewis 1970). Unlike the early SAM/PE MOS products, the max/min temperature guidance was valid for periods approximately 24 to 60 h in advance. The perfect prog equations were developed from 18 years of observations, namely, observed calendar day max and min temperatures, as well as 1000-hPa and 700-hPa heights from the 0000 UTC or 1200 UTC analyses of the radiosonde observations. As in MOS development, perfect prog equations were developed by multiple linear regression and from data stratified by season. Because of the lengthy period of record, single-station equations were derived for 2-mo seasons: January-February, March-April, etc. Like many of the classical statistical developments, a field or network approach was used to obtain the predictors. Figure 7 shows the network of stations in this perfect prog system. Computer limitations on the regression software and number of potential predictors meant that equation development was done in stages for four quadrants covering North America. Figure 8 shows the location of possible predictors for stations located in the northeast quadrant of the developmental area. Both max and min temperature equations were developed from observations that lagged the nominal time of occurrence of the max or min.

The 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. Figure 9 shows the system used to prepare the operational perfect prog forecasts. Note that observations were replaced by model forecasts (both the dynamical 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 forecast heights were available from the dynamical model.

The barotropic and Reed sea-level pressure models were used in the initial implementation of the perfect prog temperature system. Because these models lacked forecasts of 700-hPa heights, statistical relationships were necessary to relate the 700-hPa heights and 700-1000 hPa thicknesses to 500-hPa heights and 500-1000 hPa thicknesses. Despite these drawbacks, perfect prog produced max/min temperature forecasts that were comparable, though less accurate, than those generated by NMC forecasters.

Change came quickly to the max/min temperature forecast system. Following implementation of the PE model, the perfect prog system was enhanced to use PE model heights, including those at the 700-hPa level (Klein et al. 1971). Verifications showed improvement in the perfect prog guidance. Tests in February and March 1970 compared the new perfect prog guidance to forecasts generated by NMC forecasters. Only small differences between the objective and subjective forecasts were seen. The NWS decided to replace the subjective forecasts for these 24-60 h projections with perfect prog guidance so as to use available NMC staff in a more efficient manner. In March 1970, the new perfect prog system was implemented. In April 1970, twice-daily transmission of the automated guidance in a four-panel facsimile chart was initiated. As computer resources and the science allowed NMC to increment the forecast projections of the PE model, the perfect prog temperature system was extended to produce guidance for days 3, 4, and 5.

In most respects, the April 1970 implementation marked the zenith of the perfect prog approach. An attempt was made to apply perfect prog to predicting 12-h PoPs for the 12-24, 24-36, 36-48, and 48-60 h projections after 0000 or 1200 UTC (Klein 1971). The availability of PE model output meant that the perfect prog equations could use a variety of additional height and moisture variables. Multiple linear regression was again used to develop single-station equations from a network of predictors. Many tests were run to tune the perfect prog system for PoP. In the end, the system was never implemented.

The competition between MOS and perfect prog within TDL was nearly at an end. 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 forecast equations for the same four projections (approximately 12-24, 24-36, 36-48, and 48-60 h after 0000 or 1200 UTC) that had been available in the perfect prog system. Development of the perfect prog architecture within TDL was over. Bill Klein became an ardent support of the MOS approach.

Operationally, the perfect prog max/min equations were used for many years. The perfect prog system was modified several times to use prognoses from new dynamical models. The resulting forecasts were then compared to MOS forecasts from either the same or an older model. The perfect prog forecasts were also used by NMC forecasters as guidance for extended ranges (3 to 7 days) and were sometimes used in objective forecast products disseminated to the user community if MOS max/min guidance was unavailable for some reason (for instance, a new model had been implemented or additional forecast projections were needed).

9. THE MOS INFRASTRUCTURE

By the early 1970's, the MOS approach that Bob Glahn had pioneered was the NWS method of choice for providing objective guidance from the combination of dynamical and statistical models. As discussed, Bob had chosen multiple linear regression with a number of sophisticated enhancements as the basis for a complete objective interpretation system. Yet, until a formal statistical system was established, the typical approach to statistical analysis had been to collect a small sample of data, punch the data on computer cards, and then write software to analyze the data (Glahn 1989). Clearly, this methodology was inefficient and error-prone. Bob Glahn and 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 had done much of his early programming and testing of statistical concepts on an IBM mainframe computer. However, in 1966, the NWS implemented the PE model on its CDC 6600 computer. This machine hosted the initial TDL model and observational digital databases, MOS developmental programs, and operational processes. Bob led the effort to create the software and archives, writing most of the developmental software himself.

At first, MOS was developed from the SAM and PE model. Later, SAM was replaced by the TDL Atmospheric Trajectory (AT) model, and MOS equations became dependent on the PE and AT models. At this point, Bob recognized that a unified developmental structure with standardized software was necessary to handle different models in the future. He also realized the need for databases, archive processes, software, and developmental procedures to be thoroughly documented. The MOS system on the CDC 6600 is described in Glahn (1973b).

In 1972, the NWS began running the PE and Limited-area Fine Mesh (LFM) models on a new IBM 360/195 mainframe computer. The IBM mainframe had a distinct word architecture and operating system. Facing a phase-out of the CDC machine, Bob and TDL staff converted all programs and archives to run on the IBM computer. These efforts coincided with the recognition within the NWS of the importance of MOS guidance. A revised and enhanced MOS system was established on the IBM 360/195 by 1974 (Glahn 1974). Software, specifically program write-ups for the users, was documented in Glahn et al. (1975). Figure 10 shows the flow and some of the software modules used in MOS. For approximately 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 during that period, the basic architecture remained unchanged.

Bob Glahn, architect of the MOS system, wrote the introduction (Fig. 11) to the document describing the MOS developmental system. The introduction describes what MOS is, why a system was required, and how the documentation was to be maintained. Figure 12 shows a portion of the Contents. Note that Chapter IV lists the models for which grid point archives had been established. Model data were saved on magnetic tape. When NMC implemented new models, TDL established archives to extract subsets of the model grid and the model output variables.

Chapter VI describes surface observation data obtained from the National Climatic Data Center (NCDC) in Asheville, N.C. In the early years of MOS, these observations were the source of nearly all predictand variables. A magnetic tape containing a full month's worth of observations was sent from NCDC to TDL, generally about 6 weeks after the month ended. Hourly observations recorded at 3-h intervals from 0000 UTC to 2100 UTC at approximately 260 sites in the United States were available on these tapes. NCDC had done quality-control on the observations. However, because quality of observations was critical to the success of MOS, TDL did subsequent quality-control via a mix of automation and human judgment.

Chapter X describing the TDL hourly observation archive deserves special mention. This archive was begun in December 1976, and became one of the most essential databases in TDL. Early in the MOS development, Bob Glahn recognized the value of surface observations with hourly resolution. These observations would be needed for all available stations with as much of the meteorological information as could be reasonably extracted. On the IBM 360/195, NMC had established hourly files containing all the surface aviation reports (SA's) that reached NMC. Similarly, files that contained synoptic reports (SM's) were also available. Bob established a project with a dedicated contractor to develop software to access the NMC files and save the data in a format suitable for MOS development. After the archive was established, a team of TDL meteorologists and programmers was assigned the task of creating a thorough quality-control procedure for the hourly data. This effort required significant time and expertise on the team's part. 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 by a station even when rain 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, Bob's foresight was rewarded many times over. As TDL expanded the network of stations in the MOS system, refined predictand definitions, and embarked on new projects to generate guidance valid at hourly resolution, the hourly data archive proved invaluable. Eventually, TDL provided some of its model archives and the hourly observation archive to the National Center for Atmospheric Research (NCAR). Two factors drove this arrangement: the need to have a back-up for TDL datasets in case of a catastrophic event at NMC, and frequent requests from the meteorological community for TDL model and observational data.

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. One last piece was required to complete the infrastructure. In 1979, Bob 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. Bob presented his rationale for the standards with a historical and programming perspective (Fig. 13). His philosophy 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 standards were not, at first, met with unanimous acceptance within TDL. Subsequently, however, MOS developers found them to be essential for the reasons that Bob had stated.

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. Generally, 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 certain that the developmental data were correct. While errors could be and were made during development, they were minimized. Error rates in implementing operational products were low. Cooperative education students came to TDL and assisted senior-level meteorologists in developing new products. In summary, Bob had created an efficient and productive environment in which statistical guidance was developed and implemented. His ability to develop, organize, and lead such a massive undertaking was recognized when he was awarded the Department of Commerce Gold Medal in 1975.

10. CHALLENGES TO MOS IMPLEMENTATION

Like all public servants, Bob was constrained by available resources (both monetary and human), statutory limits, and requirements developed within and sometimes outside the NWS. Particularly during the early years of MOS, computer resources were scarce. Development of a complete product could be slow, implementation of new products faced substantial hurdles, and dissemination of those products often called for innovative solutions. Serious philosophical differences about the direction of weather forecasting existed among dynamical modelers, statistical developers, and forecasters. New statistical guidance products were often greeted with skepticism.

Computer resources in the first 20 years of Bob's career were primitive by modern standards. DiMego et al. (2004) documented the processing speed of NWS computers during these years. When the IBM 704 was bought in 1957, the 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 Kflops 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 in those early years 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 unavailable to developers. 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. Backups of all important data were essential.

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 only small amounts of core 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 to 8 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!

Scarce computer resources for development meant that resources were also limited for running the dynamical prediction models, generating operational forecast products, and disseminating them over NWS communication circuits. Communication bandwidths were small. Operational schedules were sacred. A new product such as a MOS guidance chart or teletype message would not be used by field forecasters unless it reached the field in a timely manner. NMC had the ability to generate many forecast products from the dynamical models. Given conflicting interests, who would act as arbiter to decide what products became operational and when they were transmitted?

In late 1965, the Director of the Systems Development Office (SDO was TDL's parent organization) wrote a memorandum to the Director of NMC that voiced concerns about a mechanism for implementing TDL products (Glahn 1990). An ad hoc committee was formed by early 1966. In July 1969, the committee became permanent, and its name was changed to the Committee on Analysis and Forecast Technique Implementation or CAFTI. According to the terms of reference, CAFTI decisions were to be *"…in the form of a recommended plan for implementation … coordinated with the three offices involved (OMO, NMC, SDO) and forwarded to the director, WB for his approval."* Note that OMO was the Office of Meteorological Operations and WB was the Weather Bureau. By 1974, when TDL began to implement a large number of MOS products, CAFTI membership included members of NMC's Development, Automation, and Forecast Divisions; and representatives from SDO, the Office of Hydrology, OMO, and the Office of Technical Services (the communications office of the NWS). This high-level group performed the role of change management.

With all concerned parties gathered in the same room, decisions were made as to the implementation of all new or modified products. Typically, meetings were held bimonthly. Developers from NMC and/or TDL would present the science behind their latest work, demonstrate the improvement in forecasts by showing verification of the new technique, and suggest specific operational changes. Discussions centered on product quality and mechanisms for implementation. Committee members had the authority and knowledge to recommend implementation. This also meant that schedules on the central computer would accommodate the new products and that products would be transmitted on a facsimile or teletypewriter circuit. Technical Procedures Bulletins were written to inform the forecast community about the products. CAFTI was critical to the implementation of MOS, and facilitated coordination between TDL and NMC.

11. MOS DEVELOPMENT REFINED – THE PE AND TRAJECTORY MODELS

By the early 1970's, with the MOS infrastructure in place and the PE 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 ending approximately 24, 36, 48, and 60 h after 0000 or 1200 UTC.

In 1969, 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 conterminous U.S. The AT fields became another possible source of predictor information for the MOS system, and the PEATMOS acronym was born. Development and implementation of PEATMOS weather guidance peaked during the 1972-1975 period. Because SAM was limited in its geographical coverage and only produced forecasts for the initial public weather forecast period, SAM and its associated MOS products were eliminated in September 1973.

11.1 *The Logit Model - Conditional Probability of Frozen Precipitation*

Bob introduced the logit curve to the MOS system (Glahn and Bocchieri 1975) with the development and implementation of the *conditional* probability of frozen precipitation (PoFP|P). The predictand in this case was defined as the occurrence of either snow or sleet at a specific hour, *conditional* on the occurrence of precipitation. This definition required that all the non-precipitation cases be eliminated from the developmental sample. MOS equations were developed for projections valid 12-, 24-, 36-, and 48-h after both 0000 and 1200 UTC.

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 PE 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, for example, the 850-hPa temperature, 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 PE 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 rain), X was the independent variable (the PE 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 itself also 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 PE data was small, PE model forecasts for projections valid at 0600, 1200, 1800, and 0000 UTC were pooled for the derivation.

The second application of the logit model came in combining predictors to form a prediction equation with multiple variables. The logit program did not have the ability to select predictors by screening. Hence, a set of variables was selected for each projection, differences from the 50% values were computed for the 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. 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.

This system was first implemented in November 1972; a redevelopment of the prediction equations occurred in September 1973. Verifications during the winter of 1972-73 indicated that MOS threat scores were greater than those of the subjective NMC forecasts for the same projections. Bob noted the strength of the MOS approach in removing some of the model errors; he acknowledged that MOS needed an adequate developmental sample as evidenced by the effort to account for the relatively small samples of PE model data. At the same time, Bob noted that "a change in operational prediction models could have a temporary deteriorating effect on the quality of the MOS predictions."

11.2 *Probability of Precipitation*

The first nationwide PEATMOS facsimile chart was implemented in January 1972 for 12-h PoPs ending 24, 36, 48, and 60 h after initial model time (Fig. 14). This product replaced subjective NMC PoPs for these periods. Lowry and Glahn (1976) described the extensive amount of testing that went into developing PoP equations. Like most MOS probability equations, the REEP technique was used. Seasonal stratification of developmental data meant that equations were developed for both warm and cool seasons. Operational equations were redeveloped before the start of each season. As additional seasons were added to the developmental sample, equations were developed for both 0000 and 1200 UTC cycles, instead of combining data from two cycles into one sample. Additional developmental data also meant that a generalized operator equation valid for the entire conterminous U.S. was no longer necessary. Rather, equations were developed for smaller regions that were climatically similar and exhibited similar relationships between observed precipitation and PE relative humidity forecasts. More potential predictors were made available to the screening regression program. Binary predictor limits were modified, and smoothing of the predictor field before interpolation to the predictand station was introduced. More smoothing was applied as the projection of the PE model increased. During testing, Lowry and Glahn discovered an anomalously "dry" year in the PE sample, and the year was excluded from the developmental sample. Later, NMC staff traced the problem to a PE model change; the dry bias was corrected. This evolutionary development of PoP became a prototype for development of other MOS products. The conditional probability of frozen precipitation was added to the PoP charts in November 1972.

11.3 *Maximum/Minimum Temperatures*

As noted earlier, PEATMOS guidance for max/min temperatures was implemented in August 1973 for forecast projections out to approximately 60 h. Unlike PoPs and earlier SAM/PE MOS efforts, MOS max/min temperature equations (Klein and Hammons 1975) included 0600 or 1800 UTC observations (according to the forecast cycle) as potential predictors. These observed predictors reflected the value of persistence in generating MOS max/min temperatures for the first valid period. Changing predictor observations from 7 to 6 h after initial model time responded to the reality of operational schedules and the need to get the guidance to the forecaster community in a timely manner. By August 1975, additional PE data facilitated development of max/min equations for 3-mo seasons (spring, summer, fall, and winter), and resulted in improved guidance (Hammons et al. 1976). As with PoP, extensive testing had led to substantive changes in potential predictors, including the addition of observations as predictors during the second valid period and use of both first and second harmonics of the day of the year to capture seasonal trends in temperature. The max/min guidance was available on a 4-panel facsimile chart and in a teletype message.

11.4 *Winds*

Similar evolution occurred in the wind guidance. MOS equations developed from the PE model were first implemented in May 1973 (Carter 1975) and were only available on the request/reply communications circuit. Guidance was valid for 6-h intervals from 12 through 48 h after 0000 or 1200 UTC. The 0600 or 1800 UTC observations were included as potential predictors for the first projection (12 h). Similar to Bob Glahn's earlier work with surface winds, equations were developed simultaneously for both the u- and v-wind components. In addition, the wind speed was included in the simultaneous derivation so that the predictors in the forecast equations for the three predictands (u, v, and speed) were the same, though the coefficients and constants differed. In this derivation, the PE 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. Ten terms were included in the equations. Early experience showed that the strong winds were being underforecast. In December 1973, a post-processing procedure was implemented to compensate for this bias. As Bob had pointed out earlier, the wind speed computed from the MOS forecasts of the u- and v-wind components tended to have a low bias. The new post-processing procedure looked at two MOS estimates of the wind speed, namely, the speed directly from the MOS equation and the speed as estimated from the u- and v-wind components. The greater of the two speeds was selected as the MOS forecast. This approach helped the underforecasting of the wind speeds.

In July 1975, new wind equations were implemented. The larger developmental sample allowed two more predictors to be included in the equations while forcing of predictors was eliminated. A new post-processing technique was introduced to compensate for the underforecasting of the high wind speeds. The "inflation" technique had been used many years earlier in the perfect prog temperature system. At that time, Bob warned that inflation could have negative consequences by increasing the root mean square error of the inflated forecasts (Glahn and Allen 1966). The positive consequence might be that inflated forecasts would better fit user needs. In the case of winds, inflation resulted in many more strong winds with only minor changes in the overall errors, and so fit Bob's criterion for acceptance.

11.5 *Cloud Amount*

In 1973, Bob published a short paper (Glahn 1973a) describing initial work to develop nationwide MOS guidance for clouds. Single-station multiple regression equations were developed to predict the probabilities of clear, scattered, broken, or overcast at projections of 18 and 30 hours after 0000 and 1200 UTC, respectively. Predictors came from both PE and AT models. As had been emphasized in earlier work, transformation of probabilities into categorical forecasts was dependent upon the verification score assessing the utility of the forecast to the user. In the case of clouds, maximizing the number correct was the goal. In this initial development, however, clear and overcast conditions were overforecast (bias > 1.0) while scattered and broken clouds were underforecast (bias < 1.0). Bob compensated for this undesirable characteristic 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 corresponded to the predictand category with the greatest transformed probability.

Development of MOS cloud guidance seemed particularly vexing. Carter and Glahn (1976) discussed the development of PEATMOS cloud guidance for the 12-, 18, …, and 48-h projections. The predictand was taken from the total sky cover observation roughly divided into categories of clear, scattered, broken, and overcast. Equations were developed simultaneously for four binary predictands corresponding to these categories. In the derivation of the equations, a single-station REEP approach was used; continuous predictors were included. For the 12- and 18-h projection, the latest surface observation (0600 or 1800 UTC) was also screened. The probabilities generated by the MOS equations were then transformed into categorical forecasts with the goal of maximizing the percent correct. The initial transformation simply selected the cloud category with the highest probability as the categorical cloud guidance. Once again the MOS guidance underforecast scattered and broken while overforecasting clear and overcast. This time, a creative solution was designed for the cool season guidance. First, the probability forecasts for each station were inflated. Secondly, the probability forecasts were transformed by a 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. A different approach was taken during the warm season when testing showed that inflation of the probabilities followed by selection of the category with the highest probability produced acceptable categorical biases. Thus, the minimum bias matrix was eliminated during the warm season. The PEATMOS cloud probabilities and categorical guidance were implemented in December 1974.

11.6 *Summary*

A summary of the PEATMOS system was provided by Klein and Glahn (1974). In addition to PoP, conditional probability of freezing precipitation, max/min temperature, wind, and cloud guidance, MOS equations to predict ceiling height, visibility, thunderstorms, the conditional probability of severe thunderstorms, and quantitative precipitation had either been implemented or were being developed. Certain principles for MOS development had been established. Generally, variables from the PE and AT models were used as predictors. Because of the importance of persistence, the latest available observation (for PEATMOS, the observation at 6 h after initial model time) was included as a possible predictor for some short-range projections. With the exception of precipitation amount, bi-quadratic interpolation was used to obtain at the observation site predictor values from model output. Model predictors were space-smoothed before interpolation; the amount of smoothing increased with model projection. Because of timing errors, projections of model predictors often bracketed the time of occurrence of the predictand. Either multiple linear regression or REEP was generally used to develop forecast equations. Sample size dictated that probability equations were most often derived from developmental data pooled by regions. For generalized operator equations, predictors such as elevation that might indicate characteristics of individual stations were desirable. The first harmonics (sine, cosine) of the day of the year were useful for capturing seasonal trends. Post-processing of the MOS guidance before dissemination to the user was often necessary. Details about a particular MOS guidance product differed from element to element, but the approach to development had been established by Bob Glahn during the SAM/PE and early PEATMOS days.

The Klein and Glahn paper revealed that TDL's goal to develop a subsynoptic forecast capability had evolved as NWS priorities changed. The NWS had begun a program called the Automation of Field Operations and Services (AFOS). Certain resources within TDL were redirected toward implementation of AFOS. The desire for additional MOS guidance to support a CWF for AFOS was strong. PEATMOS guidance had a major impact on operational meteorology, yet the PEATMOS package would never be adequately completed for purposes of the CWF.

12. THE NEXT GENERATION — LFM-BASED MOS

The implementation of the Limited-area Fine-Mesh (LFM) model in 1971 (Gerrity 1977) brought more change. The LFM model had a grid resolution of 0.5 bedient, half that of the PE model, and so helped meet the need for sub-synoptic guidance. The LFM model also completed its forecast run about 3 h earlier than the PE. Because schedules could dictate the success or failure of a new product, producing MOS guidance 3 h earlier than with PEATMOS became a priority.

While generating LFM-based MOS guidance was desirable, doing so was not straightforward. At first, the LFM model only made forecasts to 24 h, though the model run was extended to 36 h in 1975 and to 48 h in 1976. Obtaining an adequate developmental sample for MOS was going to take time. Bob Glahn conducted an extensive series of experiments (Glahn and Bocchieri 1976) to determine the best approach for PoP development: testing short samples of data; adding continuous predictors as well as the sine and cosine of the day of the year to the list of potential predictors; adjusting binary limits for certain predictors; and combining output from the PE, LFM, and trajectory models into one sample. Verifications on independent data seemed contradictory, particularly between warm and cool seasons. Two decisions came from the work. First, continuous model predictors and the first harmonics of the day of the year were added to the standard list of PoP predictors. Secondly, the LFM model seemed to have predictive information for PoP. Eventually, PoP guidance for the 6-12, 12-18, 18-24, and

12-24 h forecast periods was developed by using LFM predictors.

Similarly, Carter and Glahn (1976) discussed the development of LFM-based MOS equations for the 6-, 12-, 18-, and 24-h prediction of cloud amount. Unlike the PEATMOS system, the definition of cloud amount was modified in LFM MOS to represent opaque cloud cover, rather than total sky cover. The new predictand definition more closely fit the definition of cloudiness in public weather forecasts. In addition, LFM-based MOS cloud equations for the 6- and 12-h projections used surface observations available 3 h after initial model time as possible predictors. These replaced the later observations used in the PEATMOS equations. The LFM-based MOS guidance for PoF, wind, ceiling, and visibility followed the same approach of using LFM variables and earlier surface observations as possible predictors.

The LFM-based max/min temperature system took yet another path. Various experiments showed only small increases in guidance errors when LFM predictors were substituted for the PE variables in the PEATMOS forecast equations (Dallavalle and Hammons 1976). Thus, the first implementation of LFM MOS for max/min temperature prediction was based on equations developed from the PE model.

The new LFM-based MOS guidance package, now dubbed "early" guidance, was implemented in January 1976. Further development of the LFM MOS system continued throughout the late 1970's. As had happened with the PEATMOS system (by then designated as "final" guidance), each equation derivation brought enhancements to the MOS system. Algorithms for selecting the "best" category from probabilities, grouping of stations for regional equations, and predictand definitions all evolved with each equation derivation. For instance, Carter et al. (1979) discussed development of LFM MOS max/min temperature equations from LFM predictors. For the first time, the max/min temperature equations were developed simultaneously with equations to predict the temperature at specific 3-h intervals. This approach was taken after a suggestion by Bob Glahn and resulted in significant improvement in the usefulness of the LFM MOS temperature guidance. A subsequent effort developed max/min temperature forecast equations simultaneously with equations to predict both the temperature and dew point at 3-h intervals. Post-processing steps were implemented to ensure meteorological consistency among the predicted temperatures and dew points.

By April 1980, the LFM MOS package was essentially completed, though substantive changes would still occur. For instance, a long-standing problem with the max/min temperature system had been the lack of proper observations for daytime max and nighttime min temperatures. Since the days of the perfect prog system, the automated max/min temperature guidance had been valid for a calendar day. By October 1985, algorithms to compute the daytime max and nighttime min from available temperature observations had been written, and new forecast equations had been developed and implemented (Erickson and Dallavalle 1986).

From the early days of MOS in 1968 to the completion of LFM MOS in 1980, a system had been built, and the science of weather forecasting had been altered. Figure 15 shows some of the milestones during this era. The combination of dynamical weather prediction models and statistics that Bob Glahn had envisioned had occurred. The prodigious efforts and vision of Bob in developing and leading the MOS effort were evident. In 1979, Bob and TDL were awarded a NOAA unit citation "… in recognition of outstanding individual and collective achievements in furthering NOAA's mission."

13. THE COMPUTER-WORDED FORECAST REVISITED

In 1976, Bob wrote a paper assessing progress made in automating public weather forecasts (Glahn 1976). Besides reviewing MOS operational guidance, Bob discussed ongoing development of the CWF. Figure 16 is an example of a forecast matrix and CWF designed to support the public weather forecast issued around 0900 UTC. The statistical guidance now covered the needed three forecast periods (today, tonight, and tomorrow), and had sufficient temporal detail in the PoP, conditional probability of frozen precipitation, and cloud amount to indicate whether precipitation might occur in the morning or afternoon. The characteristic of liquid precipitation (showers, drizzle, or steady) was also available. Bob noted that CWF complexity in the wording was user-specified. He also thought that in the AFOS era a local NWS forecaster could modify the matrix of MOS forecasts as necessary and create the CWF locally. The forecaster would then have the option of editing the text or releasing the unedited text directly to the public.

Three years later, Bob provided a detailed description of the algorithms used to construct the automated public weather forecast (Glahn 1979b). Again, he noted the availability of the MOS digital guidance and the inclusion of additional MOS guidance for the CWF (for example, temperature forecasts for 3-h intervals as well as quantitative precipitation forecasts (QPF)). Figure 17 is an example of the MOS matrix and resulting CWF. Even while allowing user flexibility, Bob had adopted certain guidelines in the wording:

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

While the software to construct the CWF had been built and was running on the NMC mainframe computer, Bob envisioned that both digital matrices and CWF's would be transmitted 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 completely disregard.

Ten years later, AFOS had been implemented in the NWS. Not all of the original vision had been realized, however, because of the lack of communications bandwidth and adequate local computer processing power. Despite extensive work on the CWF during the 1980's, Bob (Glahn 1989) acknowledged that "successful implementation had to await systems at field sites capable of providing the input digital forecasts." Twenty years after Bob conceived of automating public weather forecasts, complete implementation of the CWF awaited the next generation field system.

14. THE LOCAL AFOS MOS PROGRAM (LAMP)

As discussed in section 5, the SAM project had several goals, namely, building a prototype MOS guidance system, providing guidance with better temporal and spatial resolution, and improving aviation forecasts. SAM and the SAM-based MOS system were eliminated in the early 1970's because the model only covered the eastern portion of the conterminous U.S., and NMC models had significantly improved, particularly in the prediction of precipitation.

Nevertheless, a capability to provide timely guidance updates for local aviation forecasts was needed. Work by Grayson and Bermowitz (1974) expanded the SAM domain to the western U.S. and added a cloud, ceiling height, and visibility advection component to the model. The Subsynoptic Update Model or SUM was implemented in October 1973. With limited communications bandwidth and computer resources, a timely update system based on SUM could not be implemented at NMC. Instead, with the planned implementation of AFOS, Bob (Glahn 1980) proposed and designed a TDL project to create a MOS update system that would be run at local NWS offices. The effort known as the Local AFOS MOS Program (LAMP) would be based on regression equations derived analogously to the equations used in the LFM MOS system. In LAMP, however, predictor variables would be available from three sources: the most recent MOS guidance, the latest hourly surface observations, and forecasts generated by running SUM from that same set of hourly observations. The numerical integration of SUM and the evaluation of the LAMP regression equations were to be done at local NWS offices. The MOS forecasts produced at NMC were to carry the information from the NMC model to the local site. Then the LAMP process would generate a true local update of the centrally produced guidance from the latest available information. LAMP forecasts would be for most weather elements and would be valid every hour from 1 to approximately 20 h after the latest available surface observation. The LAMP effort required extensive revision of MOS software to handle equation development in a statistically and meteorologically reasonable way. Development of LAMP was somewhat risky since resources at local NWS sites were inadequate at the time to support implementation of LAMP.

Figure 18 shows how the LAMP guidance fit into the operational forecast time lines of the 1980's. The aviation terminal forecasts (FT's) released around 0930 UTC were valid for 24 h beginning 1000 UTC. By that release time, the LFM-based MOS guidance was generated from observations that were at least 7 h old. For many of the aviation elements like ceiling height or visibility, knowledge of current conditions was an essential component of the forecast process. In contrast to central MOS, the LAMP guidance was initiated by the 0800 UTC observation, provided forecasts valid at hourly intervals, and had the advantage of using, by means of advection models, the latest observations from a network of sites.

LAMP was Bob's proposal for improving aviation and short-term forecasts. The LAMP analyses would help the local forecaster analyze current conditions, the LAMP advection models would provide a model view of how conditions might change, and the LAMP MOS guidance would provide a statistical update of forecast conditions. Most importantly, the LAMP system could be run locally at any time on an as-needed basis.

In 1986, a status report on LAMP (Glahn and Unger 1986) included results of an experiment in which LAMP wind prediction equations were developed. Verification results showed the LAMP wind direction and speed guidance to be more skillful than the centrally-based MOS guidance for approximately the first 8 h of the LAMP forecast. The LAMP guidance was also significantly better than persistence at all hours, except the first or second. Development of the LAMP concept and necessary infrastructure would continue. However, lack of resources in TDL and at local NWS sites meant that full development of the LAMP update scheme would be delayed.

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

In many respects, 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. 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 model in most cases, and the user community asked that statistical guidance be generated from the NGM. With all the 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 needed for MOS development, NGM MOS guidance could not be implemented until October 1989 at the earliest.

In lieu of waiting, TDL chose 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. Since similar analyses were unavailable at 0600 and 1800 UTC, 6-h forecasts from the LFM were assumed to approximate observations and were included as possible predictors. After a number of other modifications were made to the traditional perfect prog approach, forecast equations were developed for max/min temperature, PoP, wind speed and direction, and cloud amount at 204 sites in the conterminous U.S. The new NGM-based perfect prog system was implemented in May 1987. This NGM-based guidance was an interim solution, meant to supplement the complete LFM-based MOS guidance (Carter et al. 1989).

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 seasons of data began almost immediately thereafter, and in July 1989, NGM-based MOS equations for max/min temperature, PoP, wind, and cloud amount were implemented (Jacks et al. 1990). This effort represented the first time that the operational NWS model was rerun to increase the size of a MOS developmental sample.

Additional changes were later proposed to the RAFS. Working together, NMC and TDL suspected that some of the changes could 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 near the upper troposphere caused a deterioration in the MOS cloud guidance. To mitigate the effects, TDL re-derived the MOS cloud equations and re-implemented them before the RAFS was operationally modified (Erickson et al. 1991).

Bob was later asked to discuss the perfect prog approach in creating interpretive guidance. His office note (Glahn 1991) was an extensive summary of the history of MOS and perfect prog. As Bob stated in the Introduction, *"this note will find more virtue with MOS than perfect prog. The reader will have to judge whether this is unwarranted bias on the part of the author or well-founded conclusions."* The office note is a summary of Bob's insight and experience over the 30-year period we've just reviewed. To write a synopsis of a summary would not do Bob justice. We suggest the interested reader look at the document.

16. VERIFICATION

The story of the "early" days of Bob Glahn fittingly ends with a comment about forecast verification. From his earliest work in decision theory, Bob thought that forecasts should be verified in a manner fit for the user, that is, *"the best verification statistic of forecasts is their usefulness to the user."* Bob later stated his philosophy in a broader sense (Glahn 1989): *"TDL has endeavored to 'verify' in a way that embodies the characteristics the forecasts of particular elements should have."* Indeed, the MOS system and MOS development followed that credo.

Since 1966, TDL had been responsible for nationwide verification of the local NWS public and aviation weather element forecasts. In Glahn and Jorgensen (1970), Bob discussed the Brier score and the skill of the local PoP forecasts (improvement over the climatological probability). He tried three different models to standardize the local Brier scores relative to either the station's sample or long-term relative frequency of precipitation. The idea of modeling individual station improvements was not pursued, however. In fact, verification was so controversial that TDL provided individual station scores to regional headquarters, but never published those scores. Figure 19 shows nationwide PoP skill scores for the cool season from 1966 through 2003 (Dallavalle and Dagostaro 2004). Several conclusions are clear. First, the skill of the local and objective guidance tends to rise and fall in tandem. Secondly, the skill varies from year to year. Perhaps, Bob's standardization models would have shown less annual variability. Thirdly, the human adds information to the forecast process. Lastly, improvement in the guidance and the local forecasts issued to the public is very much due to MOS and the improvement in the underlying dynamical models driving the MOS guidance.

17. SOME CONCLUDING THOUGHTS

Bob Glahn devoted nearly 6 decades to public service. To consider the breadth of his contributions during the "early" years is to realize the influence he had on the NWS in automating the forecast process. I concentrated on his combination of dynamical and statistical approaches in making an objective forecast. I could have equally well discussed Bob's contribution to the design and development of both AFOS and AWIPS (Advanced Weather Interactive Processing System).

No doubt both systems were improved significantly by Bob's attention to the details of data packing, map projections, system libraries, and so forth.

Bob Glahn was both a visionary and a pragmatist who focused on the ultimate goal of building an operational statistical interpretation system. Bob could have selected a statistical method other than multiple linear regression or he could have selected several methods to demonstrate his intelligence and knowledge. Instead, he realized that multiple linear regression, while relatively simple, could be used in sophisticated ways to produce good results. Perhaps, multiple linear regression was not the best approach in every instance, but it was a productive approach in all instances.

When I mentioned to Bob that "visionary" was applicable to him because of the MOS development, he demurred with the comment that someone else would have realized the need to use model statistics in objective forecasting. Maybe, I guess. I dare say that no one would have developed a system with such foresight, organization, and attention to detail. Bob built a system, not single-purpose programs.

Bob was years ahead of his time in his concept of the CWF and a local update system. In fact, he was so far ahead that many years would pass before these ideas became reality. I can imagine his frustration. I never saw it though. His persistence, discipline, and determination often amazed me, and certainly contributed to his success. His commitment to the NWS mission, his leadership of TDL and his organizational skills were crucial to the laboratory's success. His decisions were based on NWS goals and were consistently the result of careful thought and planning.

When I think of Bob Glahn, three other characteristics immediately come to mind: his loyalty to the NWS, his honesty, and his ability to work harder than any person I have ever known.

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During the 1950's and early 1960's, researchers at Travelers Research Corporation (TRC) introduced the application of a number of statistical techniques to meteorological problems. I would be negligent not to acknowledge the contribution of those long-ago studies at TRC. In his review of TDL's first 25 years, Bob mentioned that the results of TRC's research and development had influenced the statistical system. Perfect prog, REEP, and generalized operator equations were just some of the ideas introduced by TRC. Bob's ability to integrate many of these concepts into MOS was significant.

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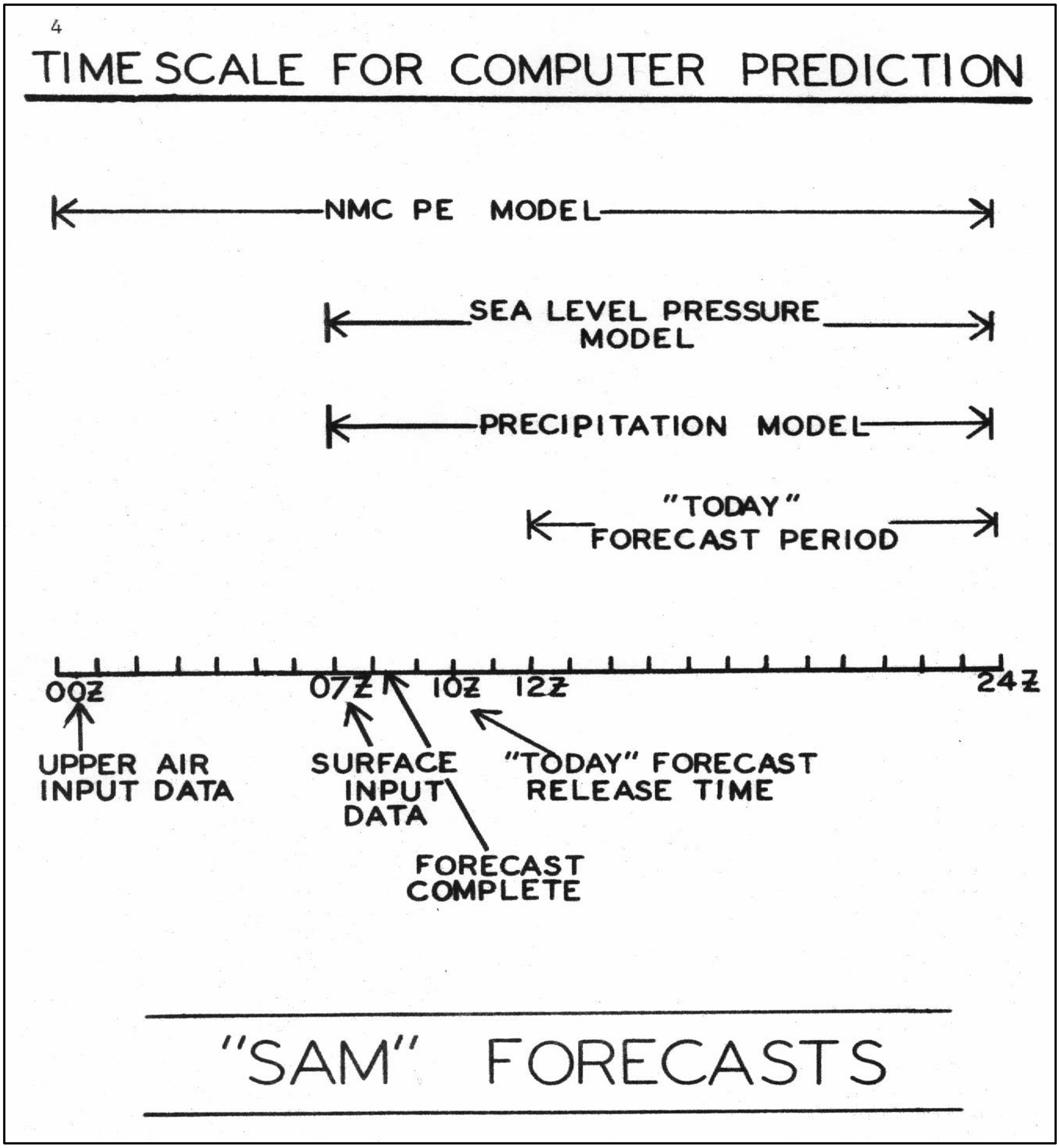


Fig. 1. Temporal relationships among input data, SAM and PE model run times, and the "today" forecast period.

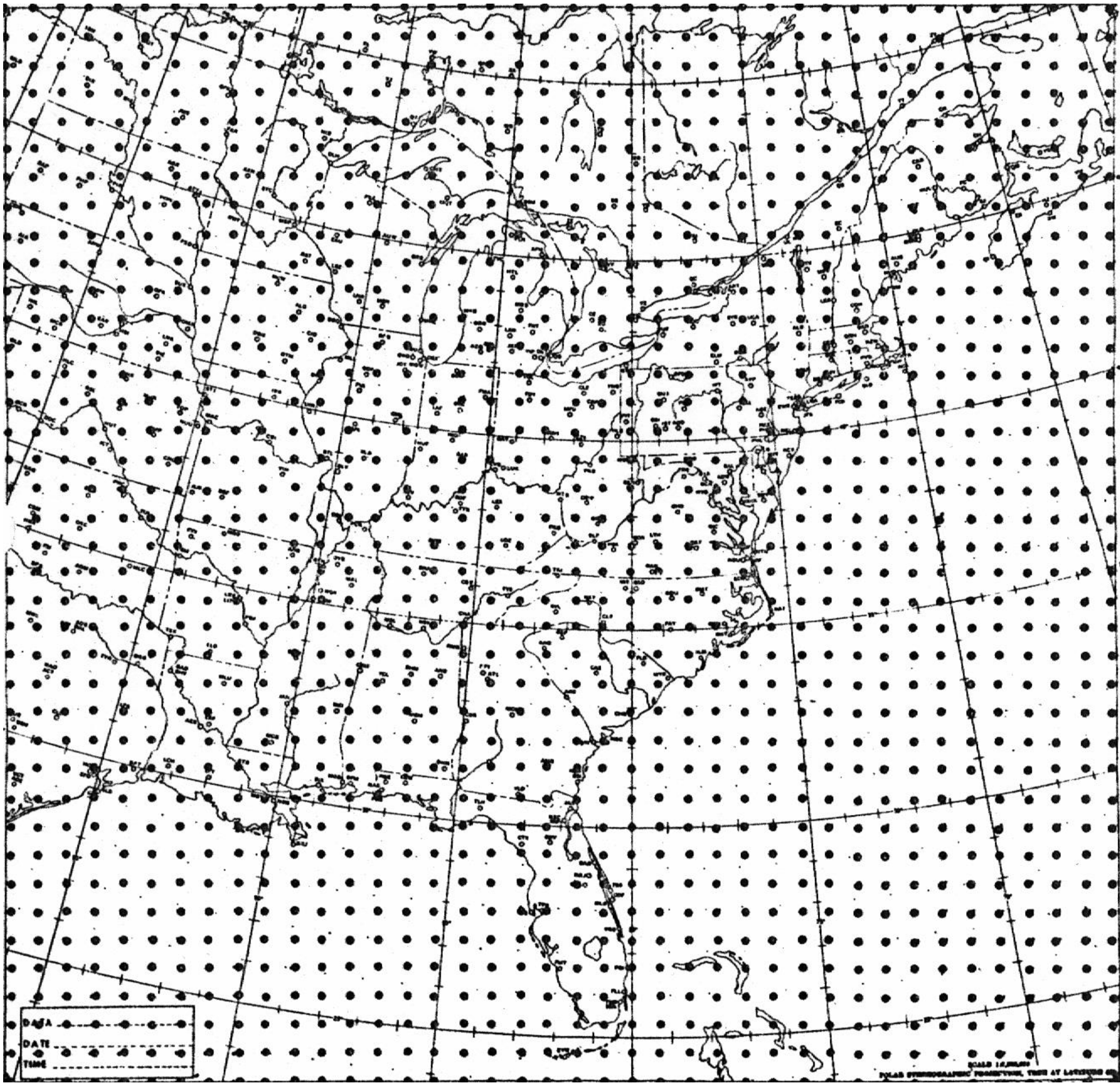


Fig. 2. The SAM 39x40 analysis and forecast grid shown by dots at the grid points.

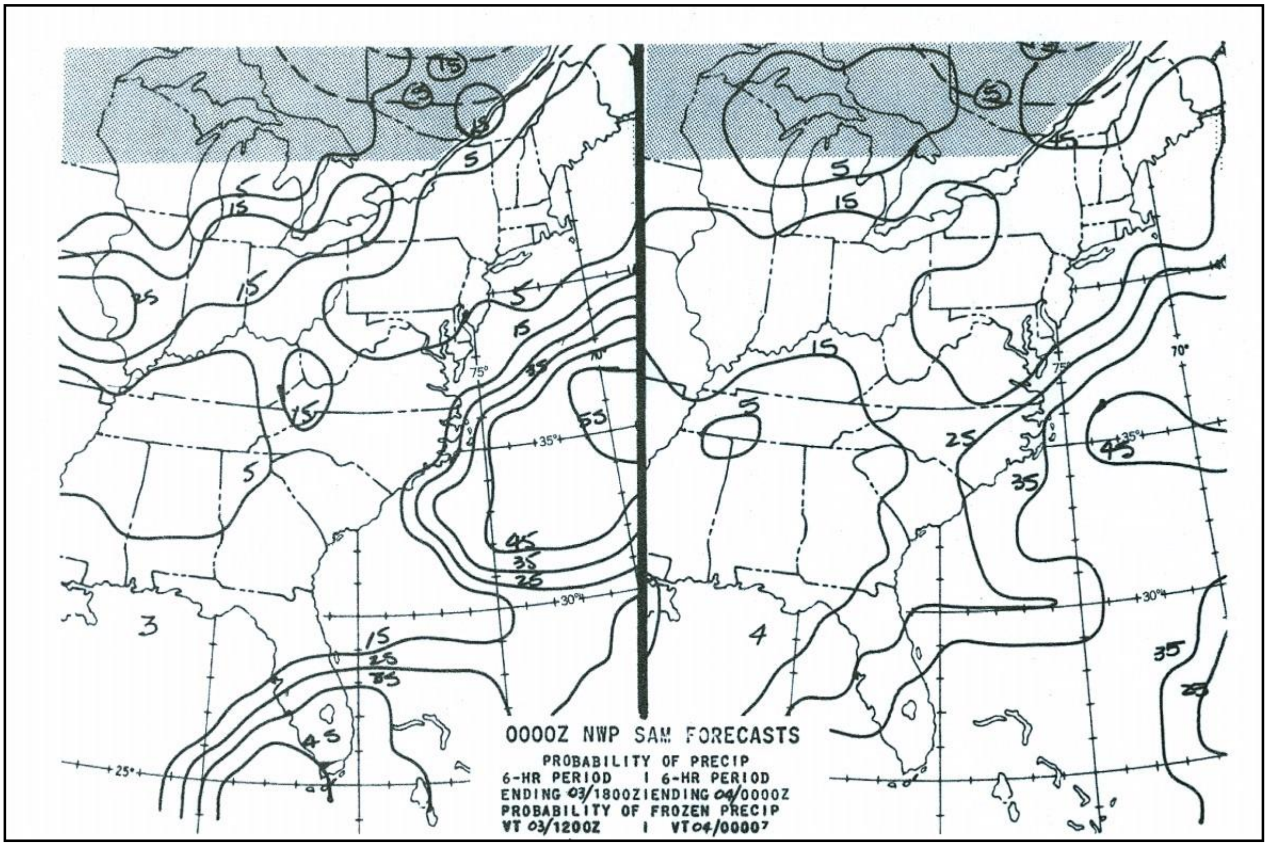


Fig. 3. The lower two panels of a SAM/PE MOS facsimile chart for 0000 UTC, July 3, 1969. The left-hand side shows the 6-h PoP (solid isolines) valid 12-18 h after 0000 UTC. The right-hand panel shows the 6-h PoP for 18-24 h after 0000 UTC. The dashed isolines indicate the conditional probability of frozen precipitation.

Category	Ceiling (ft)
1	≤ 100
2	200 - 400
3	500 - 900
4	1000 – 1900
5	≥ 2000

Fig. 4. The five predictand categories used in development and evaluation of ceiling height probability equations (circa 1970).

```
ZCZC
FOUS4 KWBC 170800
SAM FORECASTS
     12Z      15Z        18Z        21Z        00Z      POP 12 6 6  POFP B E
CAR 2408   176 2110   -12 2112   -32 2012   -42 1809   033 06 33   100 100
BTV 1810   -21 1813   -09 1913   -16 2011   124 2012   068 48 34   100 092
PWM 2205   138 2109   095 2012   -06 2110   -07 2108   025 07 25   094 083
BOS 2513   159 2114   191 2016   250 2316   245 2215   009 02 08   093 063
PVD 2307   179 2211   240 2313   282 2314   279 2210   002 01 02   092 047
BDL 2005   170 2209   258 2412   278 2413   257 2212   010 04 09   091 049
LGA 2512   294 2414   309 2515   326 2415   307 2415   002 01 02   088 037
ALB 1607   166 1912   236 2115   217 2214   201 2111   019 10 11   098 067
BGM 2011   255 2116   250 2215   233 2117   214 2216   023 16 09   097 052
```

Fig. 5. A portion of a SAM alphanumeric message transmitted January 17, 1971. For each station, the MOS forecast of surface wind (ddff: direction and speed) valid at 12Z is given. For each of the four subsequent valid times, the saturation deficit (3 digits) is given followed by the MOS wind forecast. Then the 12-h PoP (3 digits), and two 6-h PoPs (two digits each) valid 12-24 h, 12-18h, and 18-24h, respectively, after January 17, 00Z are listed. Finally, the last two sets of numbers (3 digits each) at the right-hand side of the message are the conditional probability of frozen precipitation valid at 12Z, January 17 (the beginning (B) of the 12-h "today" period) and valid at 00Z, January 18 (the end (E) of the 12-h "today" period).

```
MAR  6, 1970                              TDL EXPERIMENTAL FORECASTS

GOOD MORNING.  THE SYSTEMS DEVELOPMENT OFFICE BRINGS YOU THE LATEST FORECAST
FOR WASHINGTON, D. C. AND VICINITY.  STRONG NORTHERLY WINDS THIS MORNING 20 MPH
WITH GUSTS TO 30 MPH BECOMING NORTHERLY 5 MPH BY EVENING.  COLDER TODAY,
MAXIMUM TEMPERATURE 48 DEGREES.  MOSTLY CLOUDY THIS MORNING WITH DECREASING
CLOUDINESS THIS AFTERNOON.  ONLY 2 PERCENT PROBABILITY OF PRECIPITATION TODAY.

GOOD MORNING.  THE ESSA WEATHER BUREAU BRINGS YOU THE LATEST FORECAST FOR
ATLANTA AND VICINITY.  MOSTLY SUNNY THIS MORNING WITH A FEW MORE CLOUDS THIS
AFTERNOON.  COLDER TODAY, MAXIMUM TEMPERATURE 62 DEGREES.  NORTHERLY WINDS 15
MPH THIS MORNING BECOMING NORTHEASTERLY 5 MPH BY LATE AFTERNOON.  ONLY 2
PERCENT PROBABILITY OF PRECIPITATION TODAY.
```

Fig. 6. Computer-generated forecast from MOS guidance prepared during the 0000 UTC cycle, March 6, 1970.

Fig. 7. The 131 U. S. and 12 Canadian stations available in the perfect prog max/min temperature system.

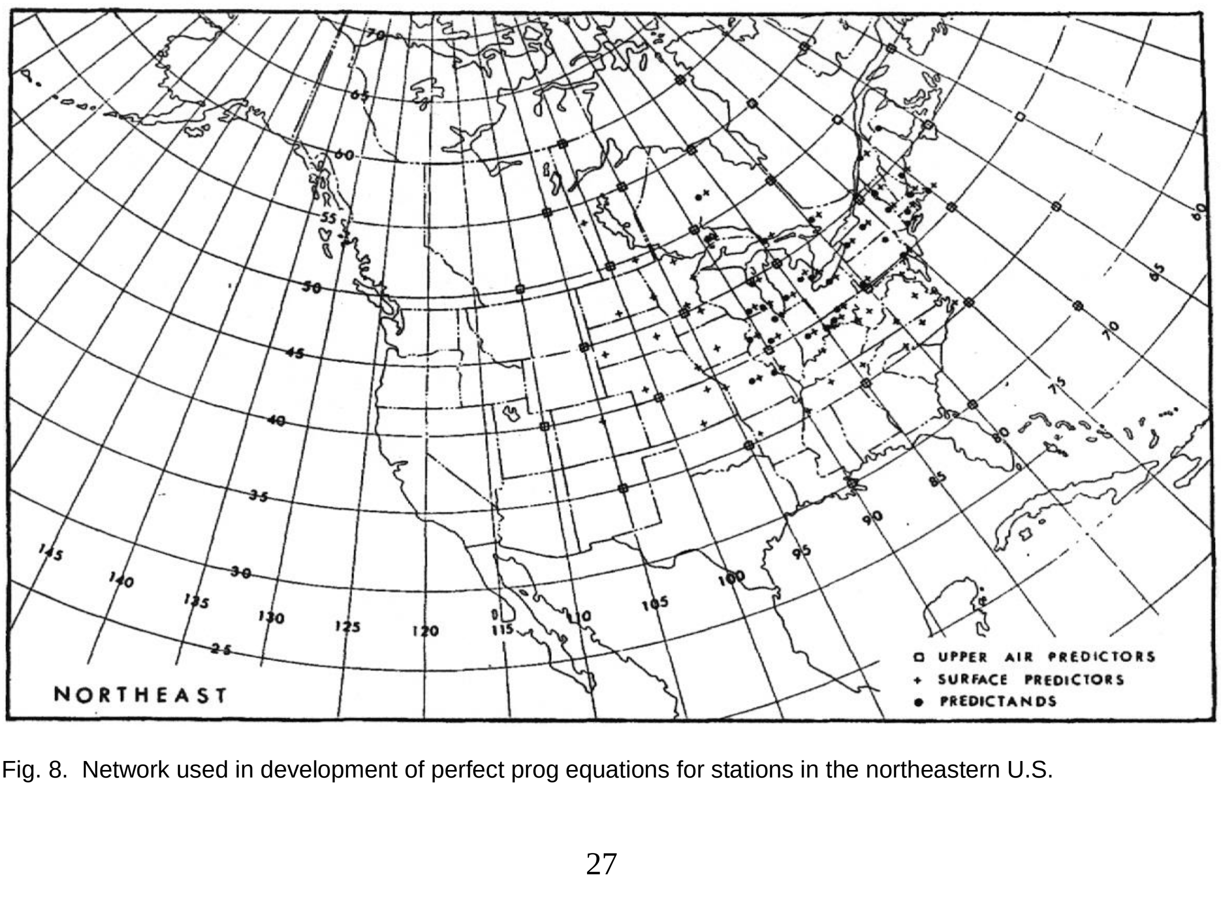


Fig. 8. Network used in development of perfect prog equations for stations in the northeastern U.S.

Forecast	Output	Height and thickness input	Surface temperature input
		From 1200 GMT data	
12 hr	Max	Observed 1200 GMT today	Min observed today, max observed yesterday
24 hr	Min	12-hr numerical progs	Min observed today, 12-hr prog max
36 hr	Max	24-hr numerical progs	24-hr prog min, 12-hr prog max
48 hr	Min	36-hr numerical progs	24-hr prog min, 36-hr prog max
60 hr	Max	48-hr numerical progs	48-hr prog min, 36-hr prog max
		From 0000 GMT data	
12 hr	Min	Observed 0000 GMT today	Max and min observed yesterday
24 hr	Max	12-hr numerical progs	Max observed yesterday, 12-hr prog min
36 hr	Min	24-hr numerical progs	24-hr prog max, 12-hr prog min
48 hr	Max	36-hr numerical progs	24-hr prog max, 36-hr prog min
60 hr	Min	48-hr numerical progs	48-hr prog max, 36-hr prog min

Fig. 9. System for preparation of perfect prog max and min temperature guidance for 12-60 h projections. Note that GMT and UTC abbreviations are equivalent.

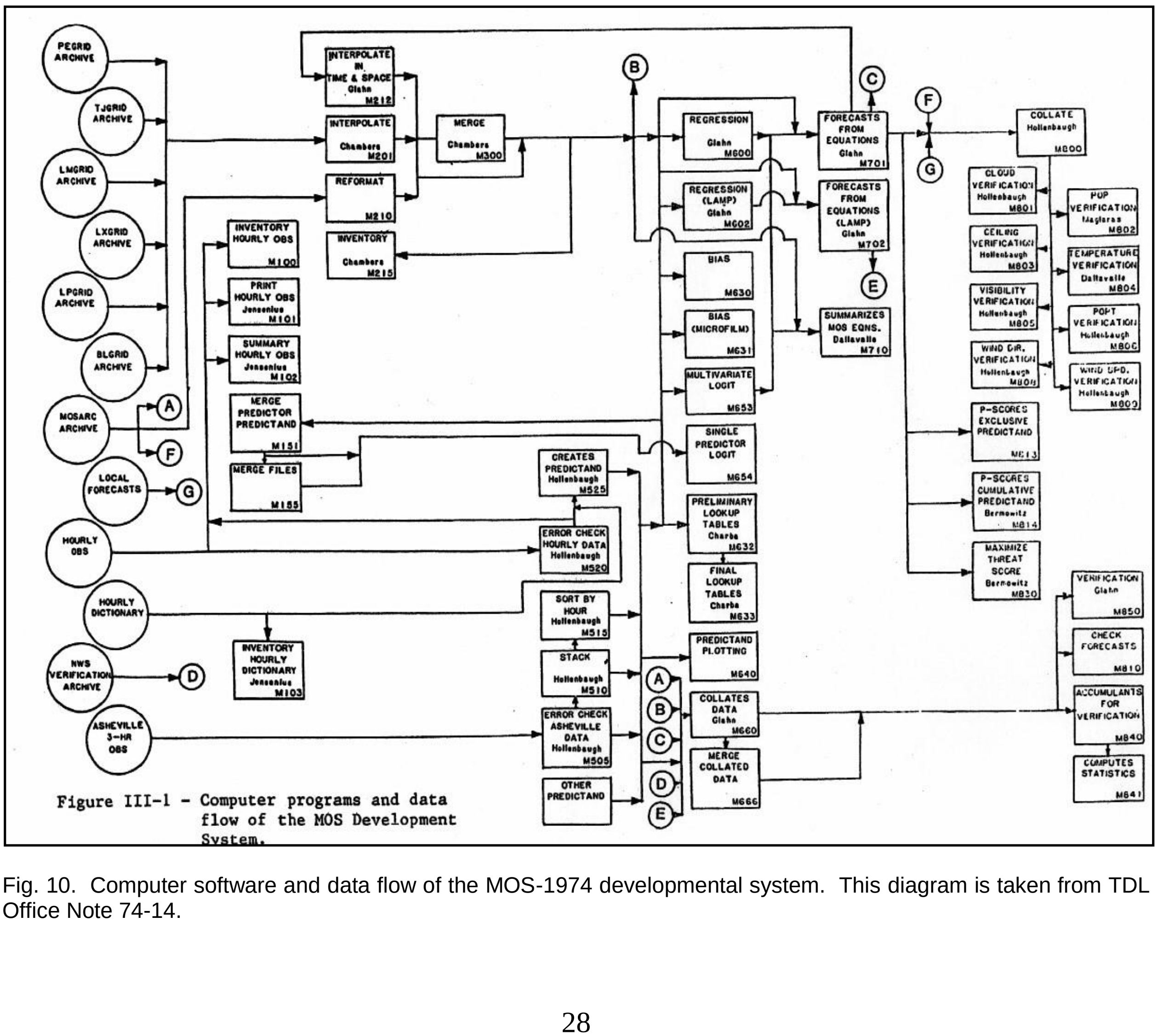


Figure III-1 - Computer programs and data flow of the MOS Development System.

Fig. 10. Computer software and data flow of the MOS-1974 developmental system. This diagram is taken from TDL Office Note 74-14.

THE TDL MOS DEVELOPMENT SYSTEM
IBM 360/195 VERSION

by

Harry R. Glahn

I. INTRODUCTION

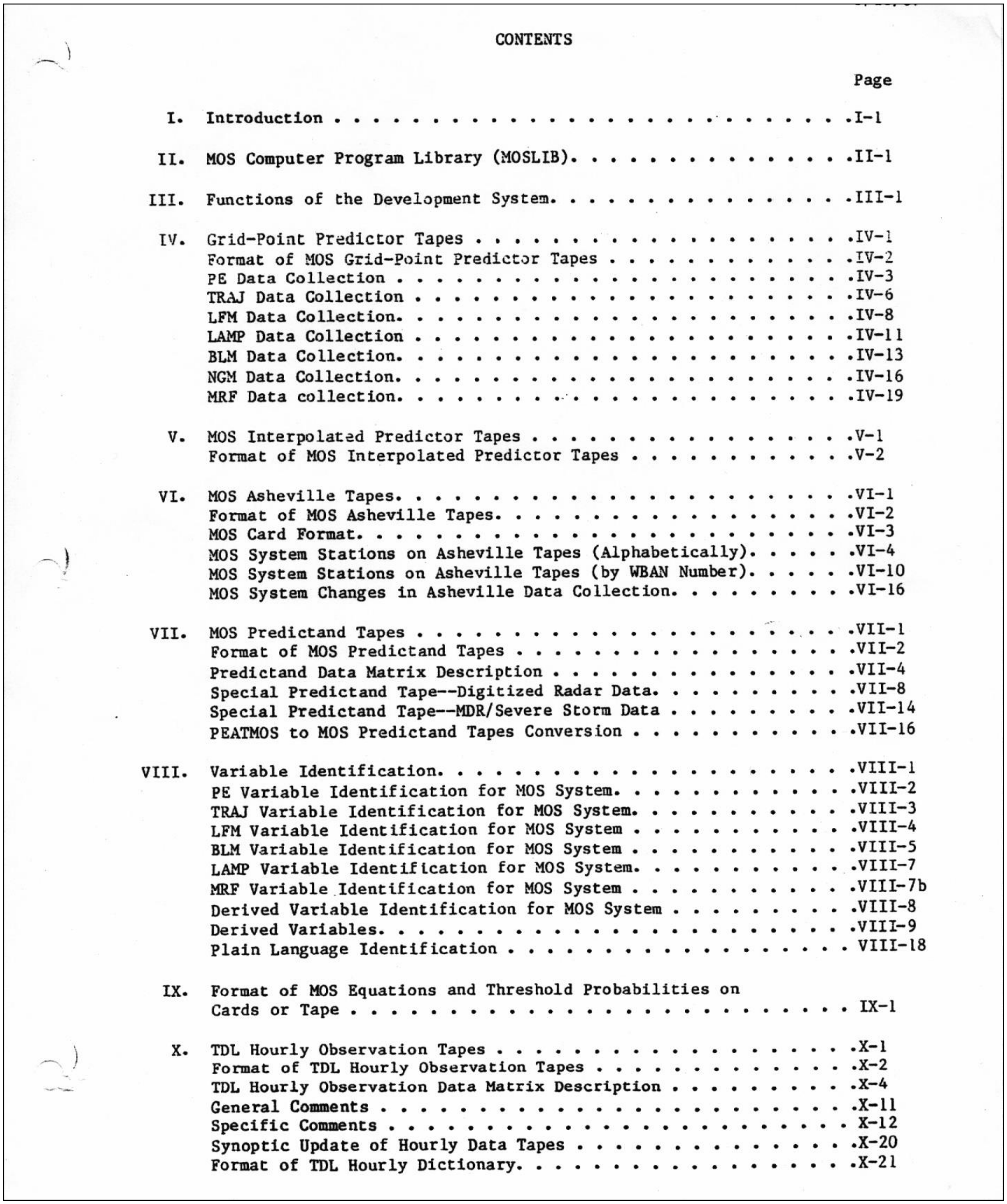
Model Output Statistics (MOS) is a technique in which a predicatand is related statistically to predictors which are themselves forecasts (or output) from numerical models. This technique was conceived and planning began for its use in connection with the development of the Subsynoptic Advection Model (SAM) (Glahn and Lowry, 1972) in 1965. Since that time, and up until 1972, two sets of MOS processing programs have been used, one in connection with SAM and PE (the NMC 6-level Primitive Equation Model, Shuman and Hovermale, 1968) data and the other with PE and Trajectory (the TDL Trajectory model, Reap, 1972) data--the so-called PEATMOS system.

As other models were developed, it became clear that we needed a more general system which would accept data, and allow the merging of data, from several models. It would have to be flexible enough so that output from new models, as they are developed, could be accommodated. Planning for this new system started in March 1972. It went into use in 1973 and was described by Glahn (1973). The so-called PEATMOS data collection ended September 30, 1972 and the new MOS collection started on October 1, 1972. All MOS-related programs up to that time were for the CDC 6600.

In late 1973, NOAA began phasing out its CDC 6600 computers and installing its IBM 360/195 system. This made necessary the conversion of all programs and data tapes. These converted programs and tapes are now ready for use and are described in this Note. Conversion was a joint effort of many people in TDL and several have actively contributed to the programming. In this latter group I want especially to mention Frank Globokar, George Hollenbaugh, Al Forst, Don Foster, and Fred Marshall.

This Office Note is updated and expanded as needed; revisions and additions are issued with the pages dated. Gary Carter has assumed joint responsibility for its upkeep. Significant contributions have been made by several persons other than those mentioned above, including John Jensenius and Paul Dallavalle. MOS related development programs are maintained in a program library and user documentation is provided in TDL Office Note 75-2, edited by Glahn, et al. (1975).

Fig. 11. The introduction to TDL Office Note 74-14 describing the MOS infrastructure later known as MOS-1974.



CONTENTS

Fig. 12. The first page of the table of contents in TDL Office Note 74-14.

TECHNIQUES DEVELOPMENT LABORATORY

SOFTWARE STANDARDS

1. INTRODUCTION

In the early days of TDL, much of the computer work was carried out by individuals with little or no interaction with others. No large projects existed in which software was developed as a group effort. Almost never were programs documented so that others might know of their existence or how to use them. Of course, no software standards existed.

Gradually, larger tasks and projects were formed and these were maintained for longer periods of time. Software documentation began to appear sporadically. Finally in 1972, a TDL library of programs was established and standards for documentation prescribed.

Today, much of the work in TDL is interrelated, the largest common factor being the MOS Development System (Glahn, 1975) and its related implementation programs. A library of about 100 members is maintained for use on the IBM 360/195 and documentation is provided (Glahn, et al., 1975). Its use is expanding, and more people are contributing to the program library. The development system data bases are being increased, both in length and types of data, making expanded use of the system more attractive.

A few weeks ago we took delivery of a dual Eclipse computer system. This equipment will eventually be used at the National Meteorological Center (NMC) to produce automated aviation terminal forecasts (FT's). It will also be available for testing new concepts in producing automated forecasts on AFOS (Automation of Field Operations and Services) equipment at Weather Service Forecast Offices (WSFO's).

I believe it is very important that we establish software standards for use within TDL. Reasons for standards include:

- With more interaction among programmers and more use being made of our MOS system, it is important that certain guidelines be followed so that one person can "read" another person's program.

- Many times it falls to someone other than the originator to modify or maintain a program. Again, if the program has been written and documented according to prescribed rules, revisions and maintenance are much easier.

Fig. 13. The introduction to TDL Office Note 79-13 describing TDL software standards in the MOS-1974 infrastructure.

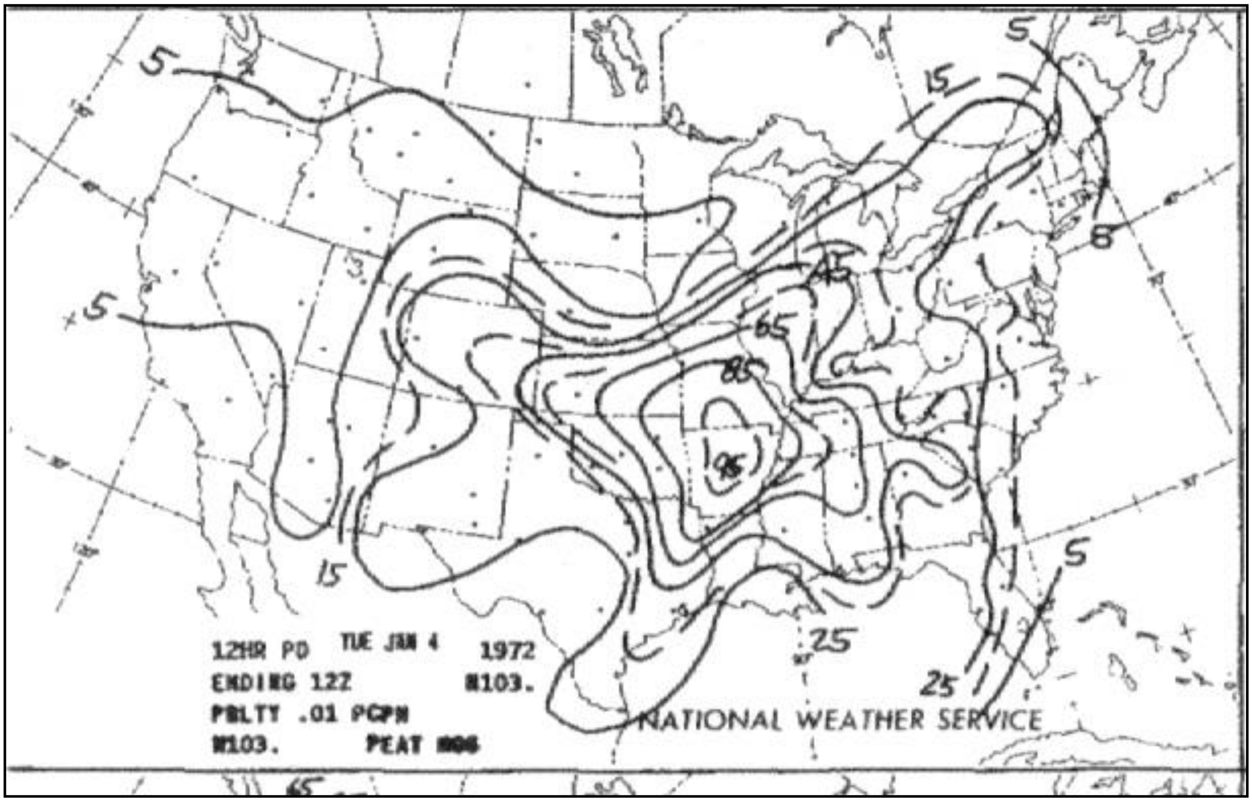


Fig. 14. One of the first PEATMOS National Facsimile (NAFAX) charts for the probability of 0.01 inches or more of liquid precipitation (PoP) in a 12-h period. This chart was issued during the 1200 UTC forecast cycle on January 3, 1972. The PoP guidance was valid for the 12-24 h projection ending at 1200 UTC on January 4, 1972. Note that the isolines and labels were hand-drawn.

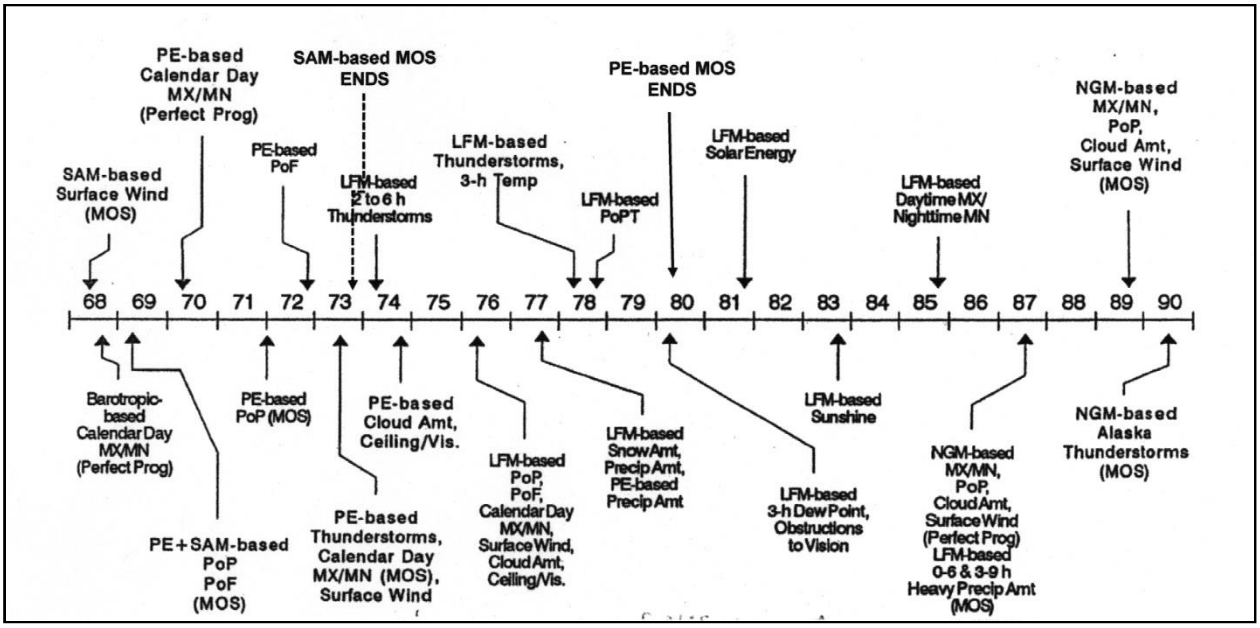


Fig. 15. Significant milestones in statistical development between 1968 and 1990. The following abbreviations are used for the weather variables: PoP: probability of precipitation; PoF: conditional probability of frozen precipitation; PoPT: conditional probability of precipitation type; MX/MN: maximum/minimum 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.

FORECAST MATRIX FOR PITTSBURGH, PA

SUNDAY 14 DEC 1975

ELEMENT	UNITS	FCST MADE DATE MO/DA	TIME Z	12Z	18Z	00Z	06Z	12Z	18Z	00Z
				(---TODAY---	)	(--TONIGHT--	)	(--TOMORROW--	)	
TEMP M/M	DEG F	12/14	00		63		40		51	
POP(12)	PERCENT	12/14	00			35		91		70
POP(6)	PERCENT	12/14	00		0	18	61	84	60	42
POFP(P)	PERCENT	12/14	00	0	0	0	2	4	16	24
R SHR(L)	PERCENT	12/14	00		25		17		18	
DRZL(L)	PERCENT	12/14	00		23		28		16	
RAIN(L)	PERCENT	12/14	00		52		55		67	
TSTM	PERCENT	12/14	00		1		1		2	
CLOUDS	CATEGORY	12/14	00	1	1	4	4	4	4	4
WIND D/S	DEG MPH	12/14	00	1705	2113	2109	2409	2909	3011	3110

FORECAST FOR PITTSBURGH, PA

SUNDAY 14 DEC 1975

CLEAR THIS MORNING, BECOMING CLOUDY WITH CHANCE OF RAIN IN THE AFTERNOON. CONTINUED VERY WARM, HIGH IN THE LOWER 60S. LIGHT SOUTHWESTERLY WINDS. TONIGHT--RAIN, LOW NEAR 40. LIGHT WINDS. MONDAY--RAIN LIKELY. OVERCAST, HIGH IN THE LOWER 50S. PROBABILITY OF PRECIPITATION 40 PERCENT TODAY, 90 PERCENT TONIGHT, AND 70 PERCENT TOMORROW.

Fig. 16. Computer-worded forecast generated from the forecast matrix shown. The forecast matrix was from the 0000 UTC forecast cycle on December 14, 1975.

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.

Fig. 17. Computer-worded forecast generated from LFM MOS guidance (shown) in 1979.

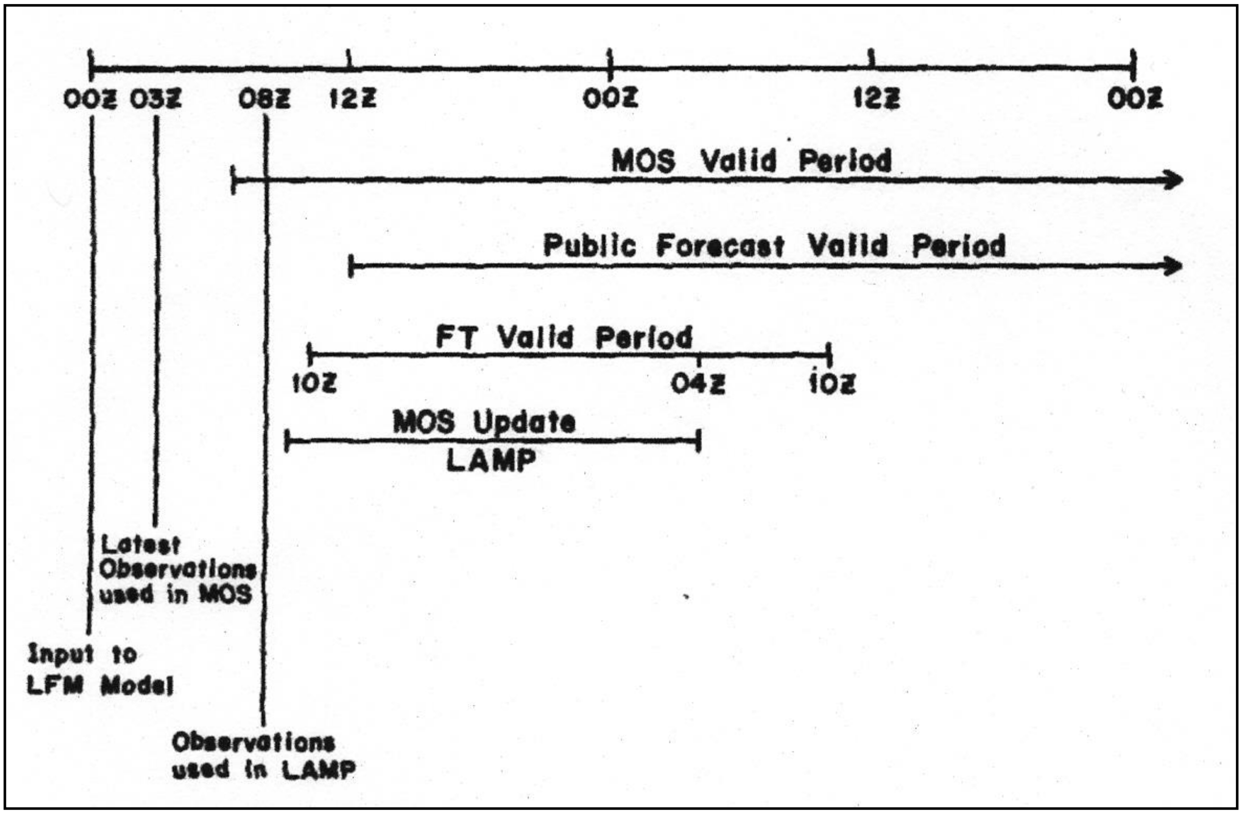


Fig. 18. Relationships among the public and FT (aviation) valid times, the period covered by the LFM-based MOS guidance, and the period for the MOS update system (LAMP). Times are related to the 0000 UTC run of the LFM and the early morning (approximately 0940 UTC) forecast release times existing in 1986.

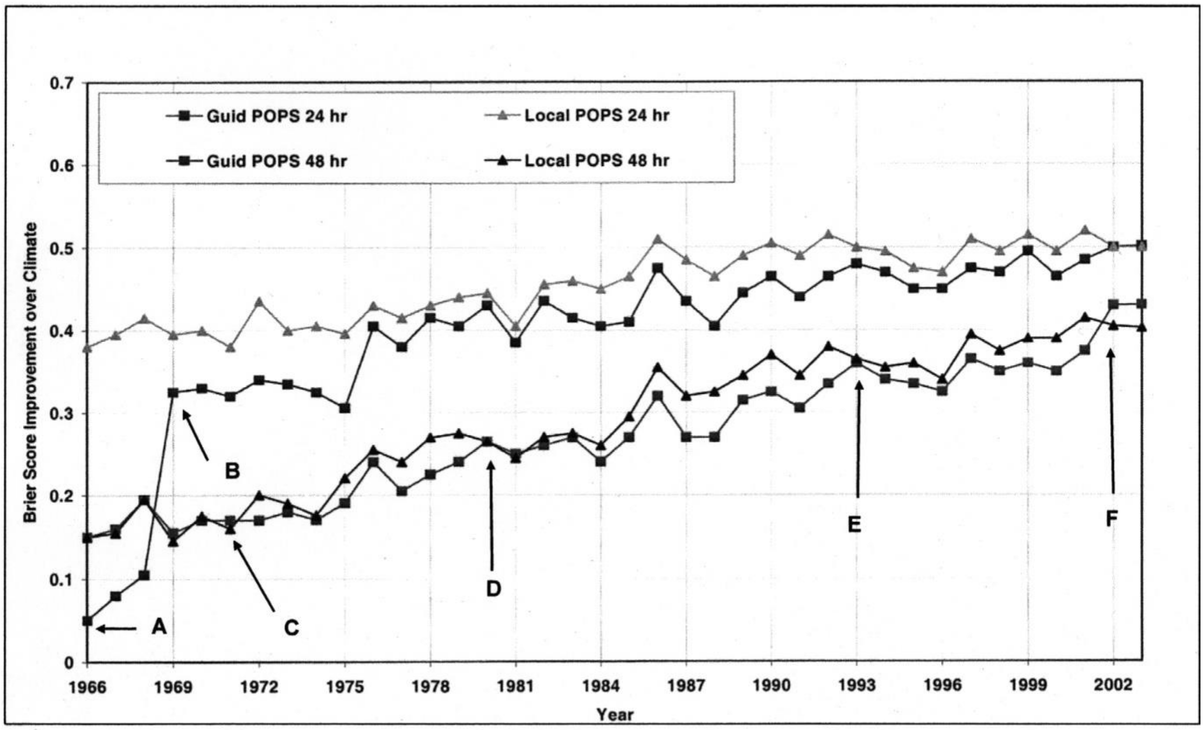


Fig. 19. Brier score improvement over climate (Brier skill score) for cool season (Oct. – March) PoP guidance (Guid POPS) and local PoP forecasts (Local POPS) issued by NWS forecast offices. Scores are shown for the 12-24 h period (today) and 36-48 h period (tomorrow) after 0000 UTC. The time scale on the abscissa indicates the starting year of the cool season; for example, 1972 refers to scores for the 1972-73 cool season. Note that beginning in 1966 (labeled A), the official NWS guidance was provided subjectively by NMC forecasters; the guidance for the 12-24 h period was a categorical (precipitation or no precipitation) statement. Starting in April 1969 (cool season 1969-70, label B), the official guidance for this projection was modified to have a range (0 to 100%) of probabilistic values. In January 1972 (label C), the subjective NMC guidance for both periods was replaced by objective PE-based MOS guidance. In April 1980 (label D), LFM-based MOS became the official NWS guidance. In June 1993 (label E), NGM-based MOS became the official guidance. In the summer of 2002 (label F), MOS PoP guidance based on the Global Forecast System (GFS) became the official standard of comparison for the local PoPs.