6.3 PRODUCING MOS SNOWFALL AMOUNT FORECASTS FROM COOPERATIVE OBSERVER REPORTS

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1. INTRODUCTION

Correctly forecasting the occurrence and amount of snowfall has important economic and safety consequences for the entire nation. The ability to prepare in advance for a snowfall event can mean the difference between a manageable snowfall and a city shut down by impassable road conditions.

The forecasters of the National Weather Service (NWS) are tasked to provide snowfall amount forecasts for 12 to 36 hours (NWS 2002a), and outlooks for 3 to 5 days (NWS 2002b) in advance. To help in this effort, the Meteorological Development Laboratory (MDL) has produced Model Output Statistics (MOS) guidance based on the Global Forecast System (GFS) for snowfall amount. The GFS MOS snowfall guidance consists of the probabilities of snowfall exceeding a trace, 2 inches, 4 inches, 6 inches, or 8 inches in a 24-h period, and a categorical forecast of the amount.

The MOS technique (Glahn and Lowry 1972) statistically relates observed predictand data to predictor data such as forecasts from dynamical models and surface observations. While the statistical techniques used in a MOS development are relatively straightforward, the success of any development depends largely on the existence and use of a high-quality observational dataset. The National Climatic Data Center's (NCDC's) Cooperative Summary of the Day reports were used in the snowfall development. This dataset presented many challenges, including data formatting, quality control, varying reporting times, and station changes throughout the sample. The design of the MOS snowfall system had to account for characteristics of the data and requirements of the forecasters. In this paper, we discuss the snowfall guidance development, focusing on the observational dataset and the system design. We also describe the snowfall guidance products and a verification of the equations on independent data.

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2. DATA COLLECTION AND MANIPULATION

Measuring snowfall could be considered a matter of personal style. The amount is influenced by the surface on which the measurement is taken, as well as how often the measurement is taken (Doesken and Leffler 2000). Without strict standards, a group of observers in the exact same location could report a wide range of amounts, depending on their measurement technique. If one looks for an extensive dataset containing accurate snowfall amount observations for the last 5 to 7 years, there are very few options. With the advent of the Automated Surface Observing System (ASOS) in the 1990's and the conversion in the United States to METAR standards, most observing sites stopped reporting snowfall amount, with the exception being some sites with human observers. Over the last few years, many of those manual sites were replaced with ASOS equipment. The result is that snowfall amount is no longer available in the hourly observational record, our primary source of observational data for MOS development. Six-hourly snowfall amounts are available in the Supplementary Climatic Data (SCD) reports, but these reports are only available for about 120 NWS Forecast Offices across the country.

2.1 NCDC Co-op Data

For the GFS MOS snowfall development, NCDC Cooperative Summary of the Day (hereafter, referred to as "co-op" data) precipitation and snowfall reports were used since this dataset provided sufficient spatial coverage for an extended period of time. The co-op data reports are taken daily by volunteers at their residence or place of work and sent to NCDC which collects and processes the data. Data such as precipitation amount, snowfall, maximum and minimum temperature, and snow depth are reported once per 24-h period. Observations are available for approximately 8000 active sites in the contiguous United States and Alaska. The data used for this particular development were from September 1997 through May 2002.

Transforming the data from NCDC's format to MDL's binary format proved quite difficult. During the developmental period, the co-op data were saved in two different formats. In addition, NCDC organizes the data by grouping one element for a station for an entire month in each record. Each record has 31 separate values, one for each day of the month. After a record for one month, one element, and one station is complete, the next record is then for the same station but for a different element. In cases where a month has less than 31 days, those extra days are filled with missing values. The MDL system is organized by date with each record containing all the sites for one element for one date. As a first step, we converted the NCDC data into monthly alphanumeric tables sorted by hour, site identification number, and element. The alphanumeric table allowed us to view the data in a tabular output that was user-friendly, and enabled us to check on observations if questions arose at any time in regard to data reliability.

2.2 Quality Control

The quality of the observational data is critical to creating reliable statistical guidance (Allen 2001). NCDC has done considerable quality control of the co-op data, although the methods have changed over time. Before the alphanumeric tables were put into MDL's binary format, the quality control documentation was examined to understand what checks were made. NCDC makes 36 different checks of the data for consistency and quality (NCDC 2000). In some cases where NCDC kept the data, we questioned the reason. If we did not understand why the data were kept, or we still did not feel the data were reliable, we eliminated the observations. For example, one of the quality control messages stated "accumulated amount since last measurement." Since we did not know the last time snow was reported at that site, we couldn't tell if the data were valid. Another vague quality control message was "subjectively derived value." In other cases, snowfall was reported, but precipitation was not. For all of these instances, we deemed the snowfall reports unreliable and they were eliminated.

2.3 Reporting Time of Stations

The issue of time was the most complex facet of the development. Since MOS guidance is produced for the entire nation, UTC reference times are generally used. Raw NCDC data are saved with the local (based on a 24-h clock) hour of the reporting site. The time is often chosen by the observer, so reporting hours vary among sites. Therefore, the co-op reports needed to be converted to UTC time from local time, and this conversion was site-specific.

In order to assign a reporting time for each site, we had to determine the validity of the reporting times contained in the individual observations. Some stations reported their observation time with an hour greater than 24. If the reporting hour was not between 1 and 24, the observations were eliminated from development.

We assumed that all elements of co-op data were reported at the same hour for a particular site. One exception to this was that some sites labeled precipitation reports at different hours than the other elements, presumably to correspond to the 7 a.m. to 7 a.m. hydrological day. In cases like this, data were stored at the appropriate hour for each particular element.

In some instances, a station reported at different hours throughout the sample. This was possibly due to changes from daylight savings time to standard time and vice-versa. We examined the reporting time of all snow observations in the sample to determine when a station reported. If a station reported at more than two hours, the station's reports were not used unless the two hours were consecutive, or if the number of reports at the "off" hour was less than 10% of the total number of reports. For example, a site that reported at 6 and 7 a.m. local time was retained while a site reporting at 6 and 9 a.m. local time was not included in the sample, unless there were only a small number of reports at one of the two hours. If there was any question at all about a reporting time at a site, the non-precipitation reports were assigned the hour of the snowfall reports.

2.4 Choosing Developmental Sites

NCDC lists over 12,000 co-op sites that were active at some time in the last 10 years. In order to have a reliable and consistent station list for development, certain criteria were used. First, a minimum of 200 reports of precipitation and snow amount (0 is a legitimate report) were required for the years 1997-2001. Secondly, any station that stopped observing before the year 2000 was dropped. Thirdly, changes in station location and elevation were examined. Any station that is relocated more than 5 miles from its original location is assigned a new identifier and is then treated as two unique sites, before and after relocation. Any elevation change of 50 ft or greater resulted in the site being discarded from the development sample. Lastly, due to their lack of snowfall, stations in southern California, south Florida, Hawaii, Puerto Rico, and the Pacific and Virgin Islands were not used (Fig. 1).

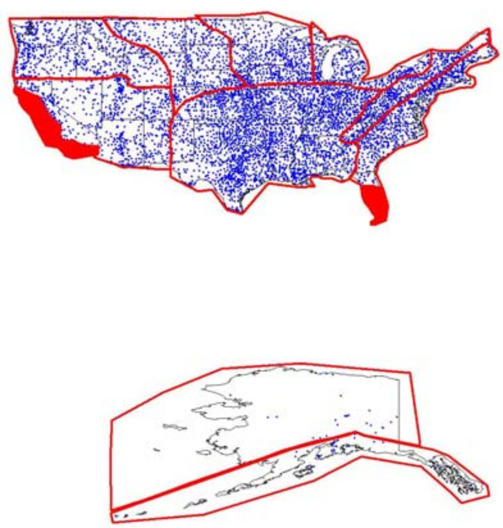

Figure 1. Regions used in the GFS snowfall development for the contiguous U.S. and Alaska. Snowfall forecasts are not produced for stations in the red shaded areas.

Since the co-op observations are valid for a 24-h day, and their ending hour varies, an "hour window" was used to gather the maximum number of stations for development. GIS software was used to view the spatial distribution of stations. A histogram that plotted the number of sites reporting at each hour allowed us to see the temporal distribution (Fig. 2). Originally, we planned to have one "hour window" ending approximately around sunrise (1200 UTC), but after examining the histogram along with the spatial and temporal coverage of the station reports, we decided that two windows would maximize the number of developmental sites and the usefulness of the snowfall guidance: 1100-1700 UTC (4792 sites) and 2100-0300 UTC (1202 sites). The former window was defined as the 24-h period ending nominally at 1200 UTC since the majority of observations in the window were reported at 1100, 1200, or 1300 UTC. The latter window was defined as the 24-h period ending nominally at 0000 UTC since many of the reports in the window were reported at 2200, 2300, or 0000 UTC. Any sites reporting outside of these two developmental windows were not used in development. Therefore, the total number of sites used for development was 5994.

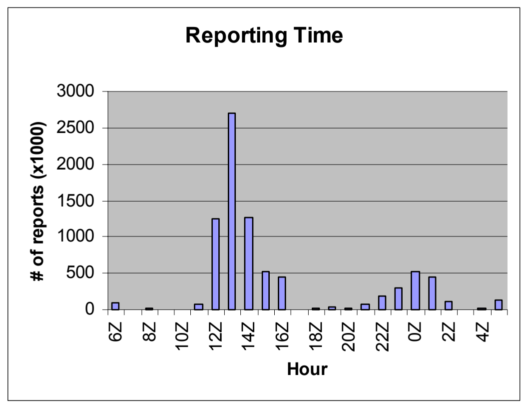

Figure 2. Histogram showing frequency of reporting hour for co-op sites. Data evaluated from September 1997 to April 2001.

3. SNOWFALL SYSTEM DESIGN

3.1 Predictand Design

Development of MOS equations must strike a balance between the information needed by the users and the available observations. In the case of snowfall, the forecasters need to know the amount of snow that will fall over a specific period of time, for example, 6, 12, or 24 hours. Given that the co-op observations are taken once per 24-h period, the snowfall predictand was structured as snowfall occurring in a 24-h period. Categorical amounts of greater than a trace, 2, 4, 6, and 8 inches were chosen as predictands, in part, because the amount of snow required to issue Winter Weather Warnings varies across the country. While one office may need to issue a warning when the amount exceeds

8 inches, another may need to warn for an excess of 4 inches.

For each 24-h period, a snowfall amount and precipitation amount observation was available in the co-op observations. While we could have developed the snowfall probabilities directly from the snowfall amount observation, this would mean that precipitation cases are mixed with non-precipitation cases, and that snow cases are mixed with rain cases. By using the precipitation amount observation, we could develop separate equations to predict the probability of precipitation (PoP), the probability of snow conditional on precipitation occurring (CPOS), and the probability of snowfall exceeding a certain amount, conditional on snow occurring (CSNOW). This allows each equation to be tuned to the precipitation/no precipitation, snow/rain, and snowfall amounts, respectively.

Thus, the snowfall system consists of three predictands, defined as follows:

PoP: precipitation occurs;
defined as $\geq$ 0.01 inches of liquid-equivalent precipitation in a 24-h period

CPOS: snow occurs;
defined as precipitation occurs, and $\geq$ 0.1 inch of snow in a 24-h period occurs

CSNOW: snowfall occurs for a specific amount;
defined as snowfall occurs and exceeds a given categorical amount in a 24-h period

The CSNOW predictand is actually broken into 4 predictands, namely, amounts of $\geq$ 2, $\geq$ 4, $\geq$ 6, and $\geq$ 8 inches. Trace amounts of precipitation and snowfall were considered non-events to enhance the tuning of the equations to significant precipitation events.

3.2 Equation Development

The equations for POP, CPOS, and CSNOW were developed by using multiple linear regression. Model predictors offered were valid over the period of time that the event could occur. The model predictors chosen most often included precipitation and relative humidity for POP; 2-m temperature, wetbulb temperature, and estimated 24-h snowfall amount for CPOS; and temperatures, vertical velocity, precipitation, and estimated 24-h snowfall amount for CSNOW. The estimated 24-h snowfall amount was a derived predictor based on the liquid precipitation amount forecast by the model, as well as the average surface temperature during the 24-h period. The NWS Snowfall to Estimated Meltwater Conversion Table (NWS 1996) was used to convert the liquid precipitation amount to snowfall depending on the average surface temperature. In addition to these model predictors, the elevation at the site was frequently chosen, especially for CPOS and CSNOW.

The equations were developed for both the 0000 and 1200 UTC windows by using observational and model data for the appropriate developmental sites from the cool seasons (September 1 - May 31) of 1997-98 through 2001-02. Ten geographic regions (Fig. 1) in the contiguous U. S. and Alaska were used for equation development. These regions are based primarily on climatology and geographical similarity. Combining stations into geographical regions helps to develop more stable forecast relationships, especially for rare events like heavy snowfall. Regional equations also allow MDL to produce guidance for sites that did not have data available for the development. Although the forecast equations were developed by using data from the co-op sites, the traditional MOS sites were placed in the appropriate regions in the final equations so snowfall guidance could be produced for them as well. Equations were developed for all four cycles of the GFS out to approximately 84 hours, with extended-range forecasts out to 132 hours for the 0000 UTC cycle only.

3.3 Operational Guidance

When the forecast equations are evaluated, the POP, CPOS and CSNOW probabilities are combined statistically to create the final unconditional snowfall probabilities. First, the POP and CSNOW are multiplied together to produce the unconditional probability of snow occurring. This probability is then multiplied by each of the CSNOW probabilities to give the unconditional probability of exceeding that amount of snow. During this process, checks are performed to ensure consistency among the probabilities. A categorical forecast of snow amount is then produced by comparing each of the unconditional snow probabilities to a set of pre-determined thresholds. These thresholds were obtained from the dependent data by a numerical algorithm that maximized the threat score of MOS forecasts made on the sample while maintaining a forecast bias between 0.9 and 1.1.

4. VERIFICATION

After the equations were developed, additional observations were obtained from NCDC. We then generated and verified guidance for the period of September 2002 through February 2003. Snowfall forecasts were produced from the 0000 UTC cycle and categorical guidance was verified for the following categories:

- > a trace to < 2 inches;
- 2 to < 4 inches;
- ≥ 4 to < 6 inches;
- ≥ 6 to < 8 inches;
- 8 inches or more

Figure 3 shows the Heidke skill score (HSS) for the forecasts at the appropriate developmental sites. Scores are presented for both the 0000 and 1200 UTC valid times. Note that guidance valid at 0000 UTC has a lower skill score. This is most likely because those equations were developed by using data from mainly western U.S. sites. The complex terrain in this region makes forecasting snowfall more difficult. To put these numbers in some perspective, the HSS for the NGM MOS snowfall forecasts for the 12-24 h period from the 1993-94 cool season was 0.384 (Dagostaro et al 1995). The GFS MOS snowfall skill score for the 6-30 h and 18-42 h periods is at a comparable level.

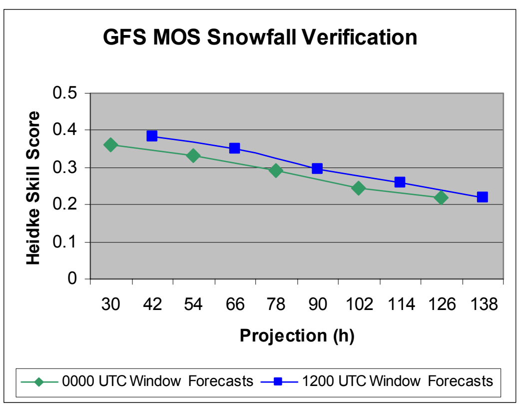

Figure 3. Heidke skill scores for 0000 UTC GFS snowfall forecasts.

5. PRODUCT DESCRIPTION

The snowfall amount guidance will be available from September 1 through May 31 in text and graphical formats. Categorical snowfall amounts for the traditional MOS sites will be included in alphanumeric text bulletins (Dallavalle and Erickson 2000, Erickson and Dallavalle 2000). We will also analyze the probabilistic and categorical forecasts for almost 6000 cooperative observer sites and create GRIB products (GRIdded Binary). These GRIB files will be converted to graphical depictions on our webpage,
http://www.nws.noaa.gov/mdl/synop .

6. CONCLUSIONS AND FUTURE WORK

In the future, we will develop algorithms to estimate 6- and 12-h snowfall amount from the 24-h snowfall guidance. While the co-op data do not support 6- and 12-h predictands, we plan to use other MOS guidance, including precipitation type and probability of precipitation, to develop a post-processing technique that estimates the amounts for shorter periods. During the 2003-04 winter, we will develop equations to predict snowfall based on the Eta model. MDL is also embarking on a project to produce MOS guidance on high-resolution grids. The increased resolution of the co-op snowfall guidance will figure prominently in this task.

NCDC's dataset was vital to the creation of MOS snowfall amount guidance. Using this dataset allows us to produce forecasts for four times as many sites as the traditional MOS system. While the dataset provided a wealth of information, the use of the data required extensive time and effort. At a time when the NWS is modernizing the cooperative observer network, we felt it was important to outline the issues that arose in trying to use these data. If the reporting time could be standardized, and the data format could be simplified, this dataset would be much easier to use, and many more groups could take advantage of this valuable resource.

6. ACKNOWLEDGMENTS

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