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THE USE OF MODEL OUTPUT STATISTICS (MOS) FOR PREDICTING THE PROBABILITY OF HEAVY SNOW

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1. INTRODUCTION

Before issuing a heavy-snow warning to the public, a forecaster must decide if snow will occur and then how much will accumulate. The Model Output Statistics (MOS) conditional probability of frozen precipitation (PoF) (Bocchieri and Glahn, 1976; National Weather Service, 1976a) gives guidance for forecasting precipitation type (snow or rain). We've now developed a new system that gives the probability of heavy snow at stations. We define heavy snow as a fall of $\geq$ 4 inches (10.16 cm) during a 12-hr period at a station. The new system is based on LFM model output and gives both the conditional and approximate unconditional probability of heavy snow, and also a categorical forecast, for the 12-24 hr projection after the 0000 GMT and 1200 GMT cycle times.

The Quantitative Precipitation Branch (QPB) of the National Meteorological Center (NMC) routinely issues heavy snow guidance over the facsimile network (National Weather Service, 1976b). In section 3, we'll show a comparative verification between the QPB and MOS heavy snow forecast systems. The results show some evidence that the MOS system is competitive with the QPB for making point forecasts.

We developed the heavy snow prediction equations with the MOS method (Glahn and Lowry, 1972). In MOS, we determine statistical relationships between the forecast output of numerical prediction models (predictors) and observed occurrences of a particular weather element (predictand).

2. DEVELOPMENT

a. The Predictand

We first developed a conditional probability of heavy snow [PoSH(S)] system. For this system, we included only "pure snow" events in our developmental sample. A pure snow event was defined as the occurrence at a station of $\geq$ .1 inches (.254 cm) of snow and/or sleet, and no other type of precipitation, during a 12-hr period. The heavy snow events were then a subset of the pure snow events. In the statistical development, the predictand equaled one if heavy snow occurred and zero otherwise. Therefore, the PoSH(S) system produces probability forecasts of the heavy snow event at the forecast site given that a pure snow event occurs. We developed PoSH(S) forecast equations for the 12-24 hr projection for both the 0000 and 1200 GMT LFM cycle times.

Actually, we could isolate only quasi-pure snow events in our developmental sample. Our basic data were 6-hr snowfall amounts at 195 stations in the conterminous United States. These data are obtained routinely by TDL from the National Climatic Center. To obtain 12-hr snow amounts, we added two 6-hr reports. We also examined the "weather" observations to determine the type of precipitation falling within the 12-hr period. We needed to do this to isolate the pure snow events. However, weather observations were available only every third hour. Therefore, we couldn't be completely certain that only snow or sleet fell within the 12-hr period; so a number of our pure snow events may have been only quasi-pure. We followed the above procedure to assemble the developmental sample for our 195 stations for September through May, 1972-73 through 1975-76.

b. The Predictors

Our potential predictors, listed in Table 1, consisted of LFM model output plus station elevation. We used linear screening regression to develop 12-term prediction equations. All model output predictors were space smoothed by 5 points to eliminate small scale noise. The predictor list contains basic predictors plus derived predictors such as moisture convergence, wind divergence, vorticity, and vorticity advection. The derived predictors were computed from LFM grid-point forecasts of basic moisture and wind variables at various levels. U-winds represent the east-west wind component where west winds are positive, and V-winds represent north-south winds where south winds are positive. Boundary-layer relative humidity covers the lowest 50-mb (5-kPa) layer in the LFM model. Precipitation amount is valid for the 6- or 12-hr period ending at the time shown.

We decided a priori to develop a regionalized system because of the nature of the predictand. To determine the regions, we computed the relative frequency of heavy snow at each station for all cases when the LFM 12-hr precipitation amount was ≥ .1 inches (.254 cm) for the developmental data sample. The relative frequencies were spatially erratic but generally showed higher values for the more northern, interior, and higher stations. We also considered climatologies of general snowfall amount and snow-to-liquid equivalent ratio in deciding on the regions. The regions are shown in Fig. 1. We realize that the regions are large (with one exception); they had to be large because we were dealing with a rare event and had only four seasons of developmental data. We can, in the future, increase the number of regions as we accumulate more data.

We then developed a generalized operator prediction equation for each region and LFM cycle time. The first six predictors picked in the screening process for each region are shown in Table 2 for the 0000 GMT LFM cycle time. Similar predictors were picked for the 1200 GMT cycle time. The reduction of variance ranged from a low of 11% for region 1 to a high of 25% for region 3. The relative frequency of heavy snow for the pure snow event sample ranged from about 3% in region 1 to about 14% in region 2. Generally, the most important predictor was the LFM precipitation amount forecasts. Other predictors picked early in the screening process included moisture and wind divergence, vorticity and vorticity advection, vertical velocity, and upper-level wind components. These predictors are associated with the physical processes that are important in producing large amounts of snow from synoptic-scale systems.

c. The Unconditional System

As explained above, the PoSH(S) system gives the conditional probability of heavy snow; the condition is that pure snow occurs. We then developed a method to compute the approximate unconditional probability of heavy snow (PoSH). For each case in our developmental sample, we computed the probability of precipitation (PoP) and PoF forecasts for the 12-hr valid period. We used the PoP (National Weather Service, 1976c) and PoF equations (National Weather Service, 1976a) that were operational during the 1976-77 winter season. Since the PoF forecasts are valid at specific times, we computed an average of the 12-, 18-, and 24-hr PoF forecasts to obtain a value for the 12-hr period. In the averaging, the 18-hr PoF forecast was weighted twice as much as the 12- and 24-hr forecasts. The PoSH was then computed by

$$\text{PoSH} = \text{PoSH(S)} \times \text{PoP} \times \text{PoF(avg)}. \quad (1)$$

To obtain a categorical heavy snow forecast from the PoSH forecast, we developed a best threshold probability for each region and each LFM cycle time. A categorical forecast of heavy snow results if the PoSH forecasts exceeds the best threshold probability. We determined the best threshold probability in the following manner. For the developmental data sample, we made categorical heavy snow forecasts using a number of different threshold probabilities. We tried threshold probabilities ranging from about 2 to 25% at 1% intervals. We did this for each region and forecast cycle. Then, we computed the threat score and bias[1] of the categorical forecasts for each threshold probability. The best threshold probability was that value which gave the best threat score within the bias range 1.00 to 1.50. Table 3 shows the best threshold probabilities for each region and LFM cycle time.

3. VERIFICATION

We wanted to compare the PoSH forecasts with some standard. The only heavy snow guidance presently operational is that issued by the QPB at NMC. The QPB forecasters use numerical guidance, objective forecast aids, and subjective reasoning to outline expected areas of heavy snow occurrence (National Weather Service, 1976b). QPB's heavy snow forecast maps are routinely issued over the facsimile network. Sadowski and Cobb (1974) have shown that the QPB heavy snow forecasts were more skillful than those issued at NWS forecast offices for the period 1962 to 1972.

We compared the PoSH forecasts with the QPB forecasts for the independent data period October 1976 through March 1977 at 195 MOS stations. We did

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[1] The bias is the number of heavy snow forecasts divided by the number of observed heavy snow events.

the verification for the 12-24 hr projection after both the 0000 GMT and 1200 GMT LFM cycle times. In their operational product, the QPB outlines areas where heavy snow is expected to occur. To get the QPB forecasts for our MOS stations, we subjectively determined which stations were included within the forecasted areas. To get the MOS heavy snow forecasts for the MOS stations, we transformed the PoSH forecasts into categorical forecasts by using the threshold probabilities discussed above. We emphasize that the scores we obtained for the QPB product will not agree with the scores the QPB obtained for their product for the same data period for at least the following reasons:

a. The QPB verifies their product by the area method; we did our comparative verification at points (MOS stations).

b. The QPB does not include locally heavy snow events, such as lake-effect events and isolated events in mountainous areas, in its verification. We did not remove locally heavy snow events from the sample for the comparative verification.

Also, we recognize that the comparative verification was not carried out under optimal conditions because the QPB forecasters did not know that their forecasts would be compared to the PoSH forecasts. If they had been aware of the verification and knew the ground rules, they may have been able to obtain better scores than we show below. Also, the QPB forecasters did not have the PoSH forecasts as guidance, but they did have later data to consider.

The results of the comparative verification, shown in Table 4, indicate that the PoSH forecasts (in terms of categorical forecasts) were less biased (closer to 1.00) and had a better post-agreement than the QPB forecasts. For threat score and prefigurance, the QPB forecasts were better for the 0000 GMT data time and worse for the 1200 GMT data time. For both data times combined, the PoSH forecasts were better for all scores except pre-figurance. These results give some evidence that PoSH is competitive with the QPB for <u>station forecasts</u> of heavy snow. However, considering the conditions under which the comparison was made, the results should be interpreted with caution.

The scores for the PoSH in Table 4 also indicate the following:

a. The bias shows that the PoSH system slightly overforecasted the heavy snow event.

b. The post-agreement shows that, when PoSH forecasted heavy snow, it was correct about 28% of the time.

c. The pre-figurance shows that, when heavy snow was observed, it was correctly forecasted about 32% of the time.

Note that these are average characteristics of the system; there is significant variation from station to station. Also, there is no guarantee that the scores would remain the same for another data sample.

Figs. 2 through 9 show sample PoSH forecasts for two independent data cases during the 1976-77 winter. Figs. 2 through 6 (7 through 9) apply to the storm of January 9 through 11 (March 22 and 23), 1977. For each storm, PoSH forecasts are shown for successive 12-24 hr projections from either the 0000 GMT or 1200 GMT LFM cycle time. The observed heavy snow areas are also shown in the figures. These areas were defined from snow amount reports at MOS stations and are only approximate since the MOS stations are rather widely spaced. In both cases, a low-pressure system (low) moved into the Ohio Valley from the southwest. A new low developed near New Jersey and intensified as it moved northeastward near the New England coast.

Figs. 2, 3, and 7 show that the PoSH forecasts were quite low in the earlier stages of development for both cases. We considered these to be bad forecasts, because we'd like to see higher probabilities in observed heavy snow areas. The lows became better organized as they tracked northeastward, and the PoSH forecasts became higher, even 90% (see Figs. 4, 5, 6, 8, 9). This behavior of the PoSH forecasts will probably prove to be rather typical since the LFM model usually behaves better for well-organized, synoptic-scale systems. We'd have to compute the reliability and resolution of the PoSH forecasts for an adequate data sample to better assess their value.

4. MESSAGES AND SCHEDULES

The 12-24 hr MOS heavy snow forecast is included in the early FOUS12 bulletin, which is available on request/reply. For the 0000 (1200) GMT LFM cycle, the early FOUS12 bulletin is available at approximately 0330 (1530) GMT. The heavy snow forecasts are given for the same stations that receive PoF forecasts except for those listed in Table 5; heavy snow is very unlikely to occur at the stations in Table 5.

An example of the early FOUS12 bulletin with an explanation of the new heavy snow message is shown in Fig. 10. The heavy snow forecast (called POSH in the bulletin) is given below PoF and, in the example shown in Fig. 10, is valid for the 12-hr period ending 1200 GMT, 21 December 1976. The first probability, 20%, is the conditional probability of heavy snow [PoSH(S)] (see section 2a). This probability will be assigned a 99 value if the product of PoP12 and the weighted average of PoF for the period (the product being the chance of snow) is less than 1%. The second probability, 5%, is the unconditional probability of heavy snow (PoSH) (see section 2c). This probability will be assigned a 99 value if the PoSH(S) is assigned a 99. Both probabilities are given to the nearest percent with a maximum probability value of 98. After the slash, the categorical forecast is given (see section 2c), 0 indicating a non-heavy snow event.

V. OPERATIONAL USE

Although we used only pure snow cases to develop the PoSH(S) equations, the PoSH forecasts, as computed by equation (1), should be applicable to cases in which heavy snow occurs in association with rain for the following reasons. Assume for a particular case that the PoSH(S) forecast is 100%. This indicates that enough precipitation will likely fall to produce heavy snow, if precipitation occurs and if the precipitation is pure snow. Assume that the chance for precipitation, given by PoP12, is 100%. The PoSH then depends on the form of the precipitation during the 12-hr period. It's true that the precipitation doesn't have to be pure snow for heavy snow to occur. However, the chance of heavy snow surely increases as the proportion of the precipitation that's in the form of snow increases. In our system, we compute a weighted average of the 3 PoF values valid within the period [PoF(avg)] to obtain a measure of the form of precipitation (see section 2c). If the PoF(avg) is very high, 80% for instance, then the PoSH (as we compute it) would be 80% in this example and a heavy snow forecast is justifiable. The important point here is that the PoF(avg) value of 80% implies that most, if not all, of the precipitation event should be in the form of snow. That is, the event does not have to be a pure snow event to apply our system. In fact, the proportion of the precipitation event that's in the form of snow should be well related to PoF(avg). If, in our example, the PoF(avg) was 10%, then most of the precipitation would probably be rain, and the PoSH would be low, 10%. Also, we transform the PoSH forecasts into categorical forecasts by using a threshold probability. This threshold probability was determined for each region on the developmental sample by computing the threat score and bias (see section 2c). To compute those scores we used observed 12-hr snow amounts, not necessarily pure snow amounts. So the heavy snow cases that occured in association with rain were incorporated into the system in determining the threshold probabilities.

The MOS heavy snow system depends on model output from the LFM, a synoptic-scale model, and will not forecast heavy snows associated with lake-effects and local topography. Also, the MOS heavy snow forecasts associated with intense, well-organized synoptic systems will be more accurate than those associated with weak, ill-defined systems.

The PoSH forecasts will be quite low most of the time because heavy snow is a rare event. The threshold probabilities listed in Table 3 provide a guide as to how high a PoSH forecast should be to consider issuing watches or warnings.

By including the PoSH(S) in the early FOUS12 bulletin (see Fig. 10), we've given the forecaster the opportunity to compute his own PoSH forecast. That is, if the forecaster wants to modify the PoP12 or PoF values, he can do so and plug the modified values into equation (1) in section 2c to compute an adjusted PoSH forecast. Remember, the PoF value in the equation is an average value for the period. In our development, we chose to weight the 18-hr PoF forecast twice as much as the 12- and 24-hr PoF forecasts. The weighting scheme can be changed depending on when the forecaster thinks most of the precipitation is expected to fall during the 12-hr period.

VI. REFERENCES

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Table 1. LFM output used as potential predictors for the 12-24 hr projection in PoSH(S). All predictors except station elevation have been space smoothed by 5 points to eliminate small scale noise. The time is the number of hours after 0000 GMT or 1200 GMT cycle times.

Field	Time	Form[1]
Station elevation	-	C
Boundary-layer moisture convergence	12,24	B,C
Boundary-layer relative vorticity	18	B
Boundary-layer relative humidity	18	C
850-mb wind divergence	18	B,C
850-mb moisture convergence	12,24	B
700-mb U wind component	12,24	B,C
700-mb V wind component	24	B,C
700-mb wind divergence	12,24	B,C
700-mb moisture convergence	12,24	B,C
700-mb vertical velocity	18,24	B,C
500-mb U wind	24	B,C
500-mb geostrophic vorticity	18,24	B
500-mb vorticity advection	12,18,24	B,C
12-hr precipitation amount	12,24	B,C
6-hr precipitation amount	24	B,C
Precipitable water	12,24	B,C

[1] B = binary form, C = continuous form.

Table 2. The first six predictors picked for the PoSH(S) system for the four regions shown in Fig. 1 for the 12-24 hr projection after the 0000 GMT LFM cycle time. R.V. = reduction of variance. Total R.V. is for the 12-predictor equation. The number of cases is the total amount of developmental data when all stations within a region are grouped together. All predictors are 5-point smoothed.

Predictor	Projection	Binary	Additional R.V.
Region 1			
1255 pure snow cases	Rel. freq. of heavy snow = .031		Total R.V. = .108
850-mb wind divergence	18	Continuous	.024
500-mb vorticity advection	12	$\le$ 25 $sec^{-2} \times 10^{-10}$	.019
12-hr Precip. amt.	24	$\le$ .0051 m	.011
700-mb U wind component	24	Continuous	.009
850-mb moisture convergence	24	$\le$ -8 $sec^{-1} \times 10^{-8}$	.010
500-mb geostrophic vorticity	18	$\le$ 7 $sec^{-1} \times 10^{-5}$	.006
Region 2			
428 pure snow cases	Rel. freq. of heavy snow = .136		Total R.V. = .206
12-hr Precip. amt.	24	Continuous	.066
700-mb U wind component	24	Continuous	.022
700-mb vertical velocity	24	$\le$ 0 mb/sec	.026
12-hr Precip. amt.	24	$\le$ .0102 m	.009
12-hr Precip. amt.	24	$\le$ .0051 m	.008
00-mb U wind component	12	Continuous	.009
Region 3			
2457 pure snow cases	Rel. freq. of heavy snow = .057		Total R.V. = .254
12-hr Precip. amt.	24	Continuous	.196
12-hr Precip. amt.	24	$\le$ .0102 m	.015
700-mb moisture convergence	12	$\le$ -8 $sec^{-1} \times 10^{-8}$	.012
Boundary-layer moisture convergence	12	Continuous	.009
700-mb moisture convergence	24	$\le$ -2 $sec^{-1} \times 10^{-8}$	.005
Boundary-layer rel. vorticity	18	$\le$ 5 $sec^{-1} \times 10^{-5}$	.003
Region 4			
1981 pure snow cases	Rel. freq. of heavy snow = .050		Total R.V. = .156
6-hr Precip. amt.	24	Continuous	.104
Boundary-layer rel. vorticity	18	$\le$ 4 $sec^{-1} \times 10^{-5}$	.007
500-mb vorticity advection	18	$\le$ 15 $sec^{-2} \times 10^{-10}$	.006
500-mb U wind component	24	$\le$ 4 m/sec	.006
6-hr Precip. amt.	24	$\le$ .0076 m	.004
Boundary-layer rel. humidity	18	Continuous	.003

Table 3. The best threshold probabilities to convert PoSH forecasts to categorical heavy snow forecasts for the 12-24 hr projection after the 0000 GMT and 1200 GMT LFM cycle times.

Region	Threshold Probability (percent)	
	0000 GMT Cycle	1200 GMT Cycle
1	9	9
2	18	19
3	23	21
4	13	14

Table 4. Comparative verification between MOS PoSH and QPB at MOS stations for heavy snow forecasting. Heavy snow is defined as the occurrence of $\geq$ 4 inches in the 12-24 hr period after each LFM initial data time. Independent data combined for 195 stations from the 1976-77 winter season (October through March).

INITIAL DATA TIME(GMT)	SYSTEM	BIAS	THREAT SCORE	POST-AGREEMENT	PRE-FIGURANCE	NO. OF HEAVY SNOW CASES OBSERVED
0000	PoSH QPB	1.00 1.70	.16 .18	.28 .25	.28 .42	102
1200	PoSH QPB	1.24 1.77	.19 .11	.29 .15	.36 .27	100
0000 and 1200	PoSH QPB	1.12 1.73	.18 .14	.28 .20	.32 .35	202

Table 5. MOS stations for which PoSH forecasts will not be given in the early FOUS12 bulletin.

Daytona Beach, Fla.	Yuma, Ariz.
Orlando, Fla.	San Diego, Calif.
Tampa, Fla.	Daggett, Calif.
Fort Meyers, Fla.	Long Beach, Calif.
West Palm Beach, Fla.	Los Angeles, Calif.
Miami, Fla.	Santa Maria, Calif.
Key West, Fla.	Bakersfield, Calif.
Victoria, Texas	Fresno, Calif.
Corpus Christi, Texas	Stockton, Calif.
Brownsville, Texas	Oakland, Calif.
San Francisco, Calif.	Sacramento, Calif.

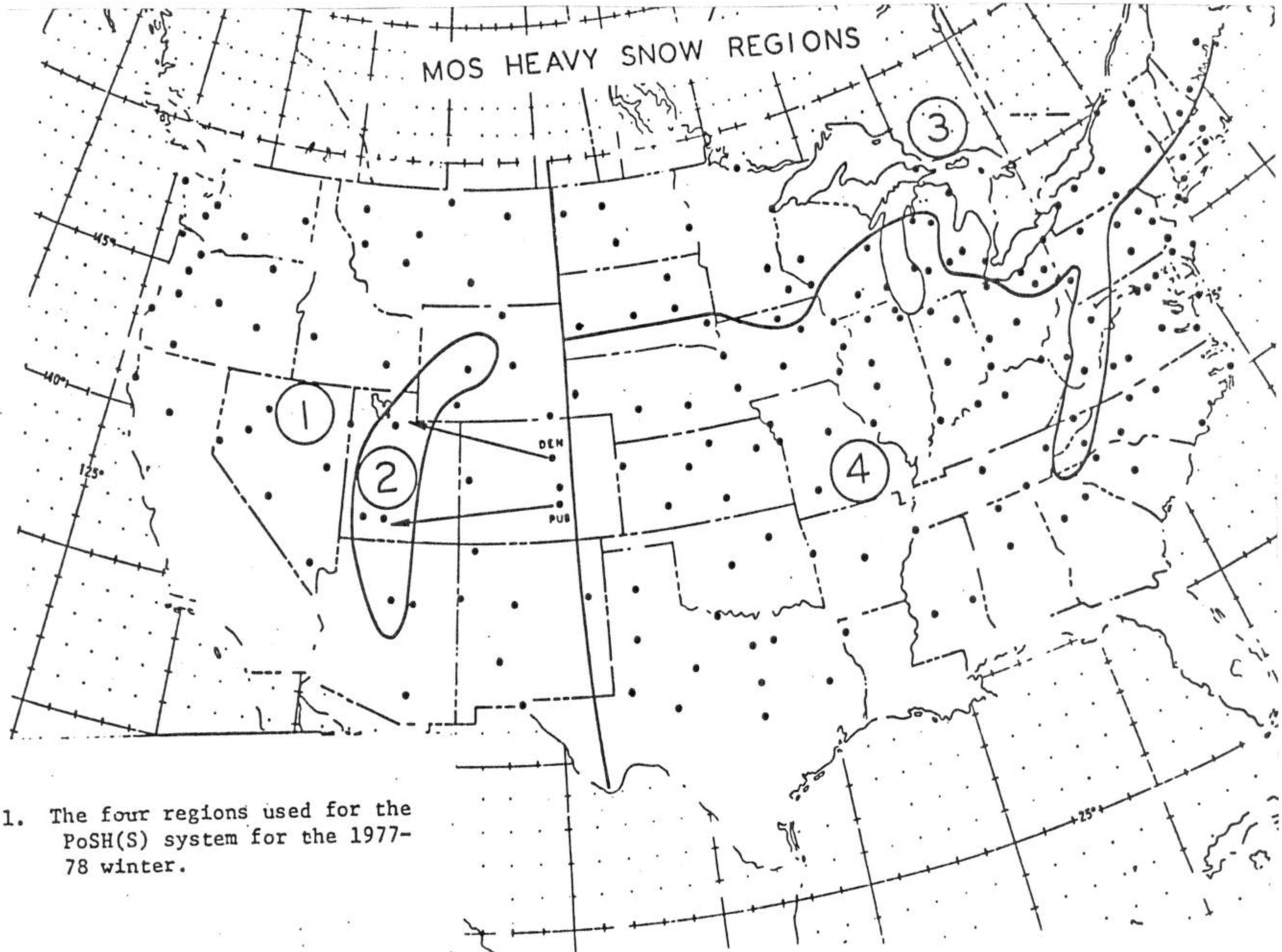


Fig. 1. The four regions used for the PoSH(S) system for the 1977-78 winter.

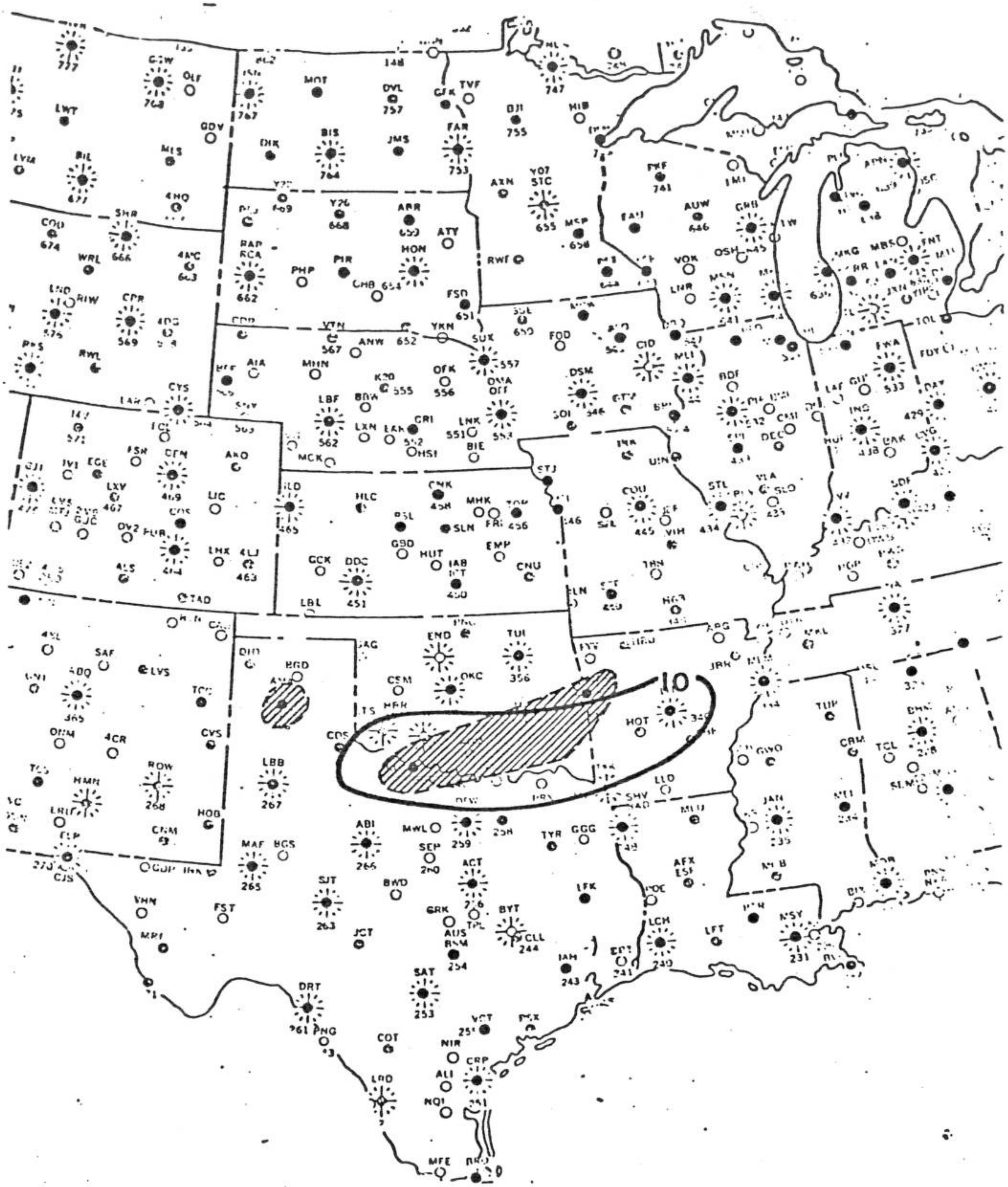


Figure 2. Sample 12-24 hr PoSH forecasts in percent (solid lines) and observed heavy snow (area within dashed line) for 12-hr period ending 1200 GMT 9 January 1977. Heavy snow is defined as the occurrence of $\geq$ 4 inches during the 12-hr period.

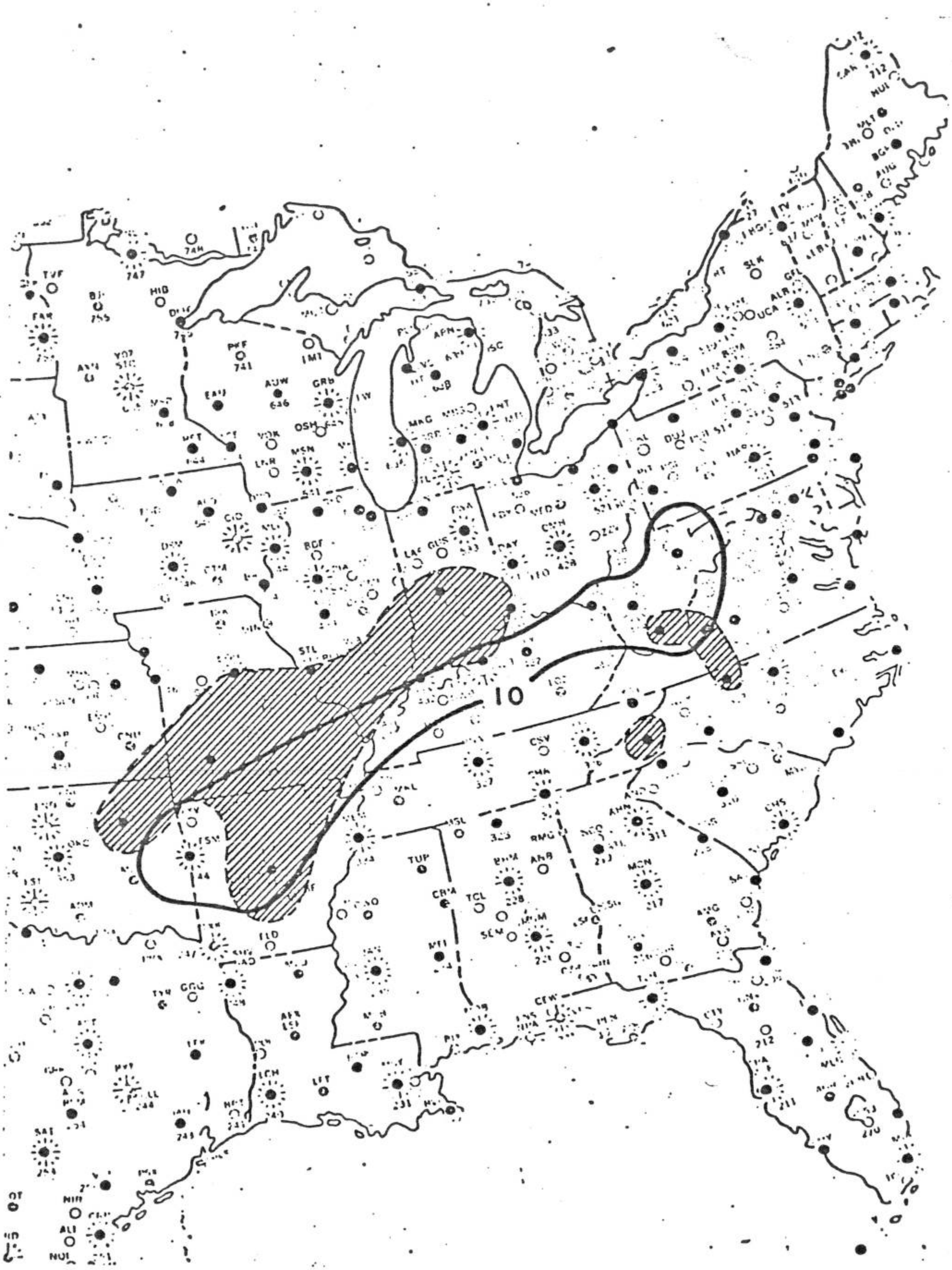
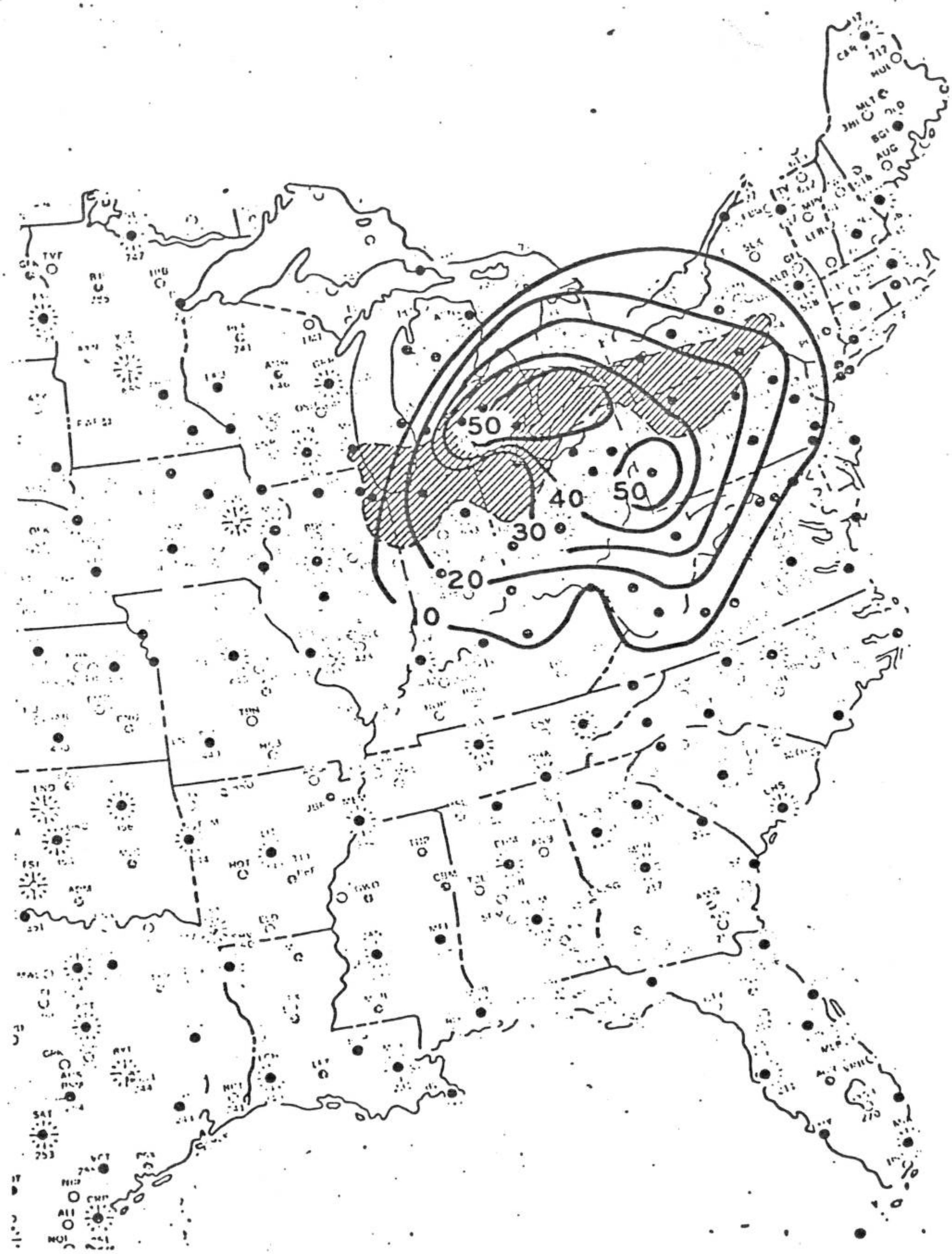


Figure 3. Same as Figure 2 except for 12-hr period ending 0000 GMT 10 January 1977.



gure 4. Same as Figure 2 except for 12-hr period ending 1200 GMT 10 January 1977.

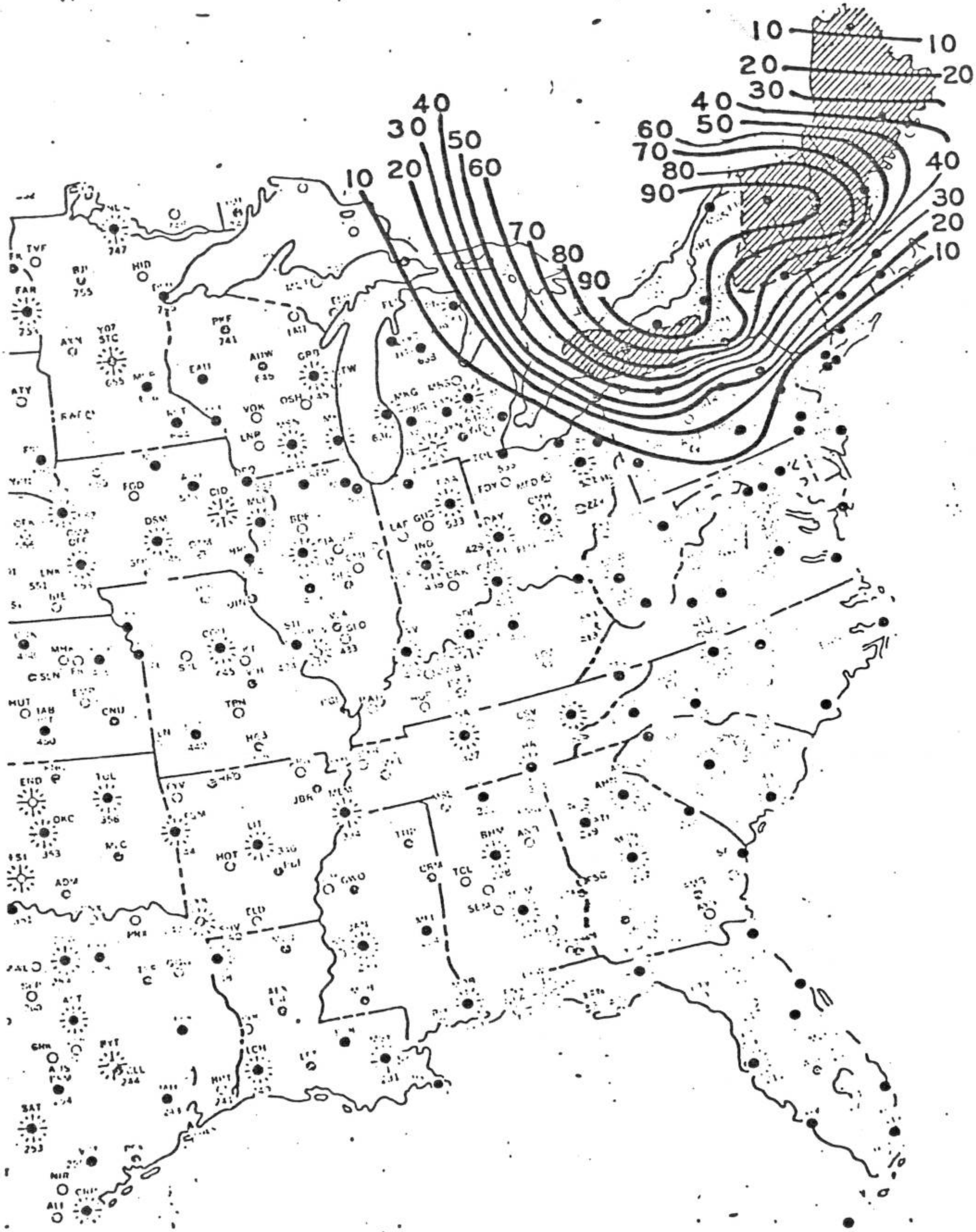


Figure 5. Same as Figure 2 except for 12-hr period ending 0000 GMT 11 January 1977.

'igure 6. Same as Figure 2 except for 12-hr period ending 1200 GMT 11 January 1977.

Figure 7. Same as Figure 2 except for 12-hr period ending 1200 GMT 22 March 1977.

Figure 8. Same as Figure 2 except for 12-hr period ending 0000 GMT 23 March 1977.

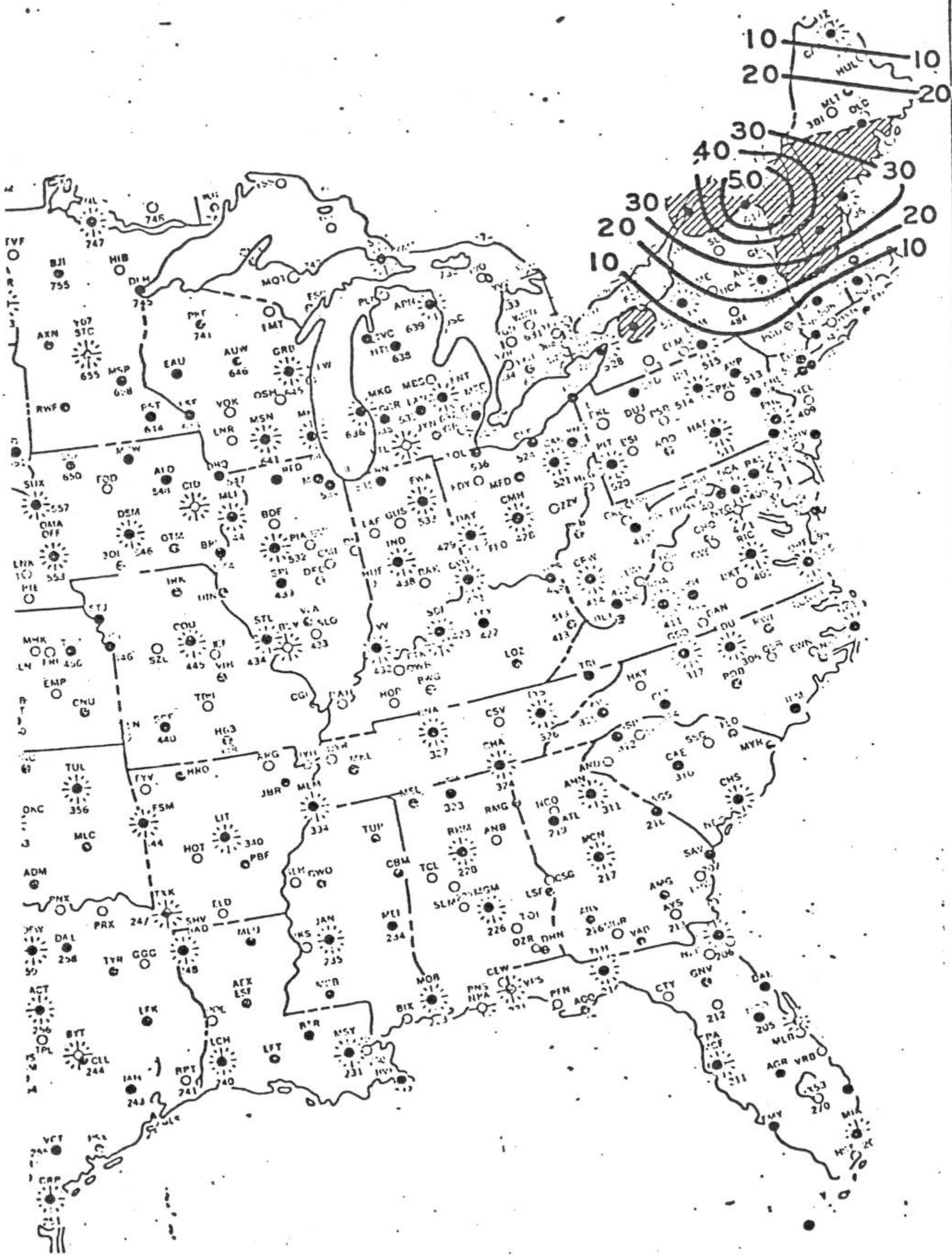


Figure 9. Same as Figure 2 except for 12-hr period ending 1200 GMT 23 March 1977.

HDNG MOS FCSTS EARLY GUIDANCE 12/20/76 1200 GMT

DATE/GMT	20/18	21/00	21/06	21/12	12/18	22/00
DCA POP06		80	30	10	20	
POP12				40		30
POF	0	0	71	100		
POSH				20 5/0		
:						
CLDS	0019/4	1018/4	2215/4	4221/2		
CIG	001270	001171	000131	000019		
VIS	001153	001144	000019	000009		
C/V	5/5	5/5	5/6	5/6		
WIND	2114	2915	2915	2917		

EXPLANATION OF POSH MESSAGE:

POSH 20 5/0

CONDITIONAL PROBABILITY [PoSH(S)]

1. GIVES PROBABILITY OF HEAVY SNOW IN 12-HR PERIOD IF SNOW OCCURS.

2. WILL BE ASSIGNED 99 IF PoP12 TIMES AVERAGE PoF FOR PERIOD IS LESS THAN 1%.

UNCONDITIONAL PROBABILITY (PoSH)

1. PRODUCT OF:
   POP12 (1st PD),
   POF (AVG FOR 12-HR PD),
   AND PoSH(S).

2. WILL BE ASSIGNED 99 IF PoSH(S) IS ASSIGNED 99.

CATEGORICAL FCST

4 = HEAVY SNOW ($\geq$ 4 INCHES)
0 = < 4 INCHES

DEPENDS ON THRESHOLD PROBABILITY VALUE FOR STATION.

Fig. 10. Example of Early FOUS12 bulletin with new POSH message.