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A Test of Finer Resolution

Norman A. Phillips
Development Division

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A TEST OF FINER RESOLUTION

Abstract

Tests with differing resolution in the 7 level and Nested Grid models were made on two winter cases. Significant improvements were obtained over current operational models. However, the main difference in these two cases was a model difference, and not a resolution difference. Horizontal resolution smaller than about 150 km did not improve the flow pattern forecasts significantly in either model, but did improve precipitation forecasts.

Contents

1. Background

Forecasts of atmospheric flow patterns by the National Meteorological Center (NMC) have improved since the Shuman-Hovermale 6 level primitive equation hemispheric model was introduced 10 years ago. This model had a horizontal resolution of 349 km at 45° latitude. Much of this improvement has been due to introduction of finer horizontal resolution into the original model. Two operational milestones are:

a. The LFM regional (limited fine mesh) with horizontal resolution of 174 km at 45° latitude was introduced in 1971. This greatly improved sea-level and 500-mb flow pattern forecasts.

b. The 6 level hemispheric model was replaced with a 7 level version with 174 km at 45° latitude in January 1978. Preimplementation tests demonstrated a consistent improvement over its coarser parent. Little or no improvement in precipitation forecasting over the 6 level model was achieved in these changes, however, except perhaps in those cases when the precipitation occurred on a large-scale and major improvement had been achieved in the forecast position of surface low pressure centers.

Improvements in precipitation forecasts were achieved, however, by the experimental Movable Fine Mesh (MFM) model developed by J. Hovermale, typically operating with a horizontal resolution of 100 km in a 5000 x 5000 km area.[1] The parameterization of convective precipitation in the

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[1] See Hovermale, J., D. Marks and S. Scolnik, 1977. Operational analysis and prediction with a moveable fine-mesh system at the National Meteorological Center. Proc. 7th Tech. Exch. Conf., El Paso. Atm. Sci. Lab., White Sands.

MFM was based on the Kuo method, whereas the 6 level, LFM and 7 level models referred to earlier have only a very rudimentary parameterization of this process. Nonetheless, tests suggested that much of the MFM's better precipitation forecasting was dependent on the finer horizontal resolution features of the MFM.

Operational exploitation of these possibilities of improved weather forecasts is dependent on the availability of faster computers, since the current operational LFM and 7 level models are at the limit of what is possible in operational deadlines with an IBM 360/195 in the NOAA computer system.

The Development Division of NMC was therefore asked to explore the extent to which better weather forecasts could be made with experimental models which took too long to meet operational deadlines. This effort got underway in the early fall of 1977 and initially involved three forecast models.

a. The 7 level model (J. Stackpole, A. Desmarais)

b. The Nested Grid Model (NGM) (N. Phillips, K. Campana, and M. Mathur)

c. The MFM model (J. Hovermale)

The basic features of these models are summarized in the Appendix. This is a report of the tests done to date. Conclusions are those by the writer, however.

2. Selection of cases and initial analyses

Forecast error sources can be divided into questions of

a. Initial data and analysis

b. Computational compromises (or ignorance) in formulating "physical" processes such as convection, radiation, turbulent exchange, friction, etc.

c. Choice of numerical methods and the spatial resolution of the model variables.

The thrust of the demonstration was primarily directed toward the last of these questions. None of the participants were ready to attack question b. from the viewpoint of how much more computer power was needed for more accurate physical formulation, and it was felt that additional computer power would not by itself solve much of question a.

The problem of initial data and analysis is of course a major one, not only in operational prediction (when the western half of the United States is often subject to uncertainties in the Pacific), but also in tests such as these, where poor initial analysis can confuse attempts to make use of better physical formulation and computational methods. Two test cases are reported on here.

Case I. 1200Z 9 January 1975

This was selected because it was a typical "locked-in-error" case, in which the LFM and 6 level models produced a large error. The adequacy of the initial analysis was deemed to be satisfactory since the 174 km 7 level model had shown some improvement over the 344 km 6 level model in its forecasts over the eastern United States.

More detailed examination showed some weak points in the (Flattery) analysis of this case, however.

a. Although the speed of the northwesterly jet at 300 mb over the plateau area was correctly analyzed, the center seemed to be placed about 150 km too far west. This could be a result of the smoothing inherent in the wave number 24 truncation of the Flattery system.

b. The Flattery analysis was too wet in the Gulf of Mexico and surrounding region.

A regional analysis program operating on the LFM area was in process of development by R. Jones. It achieved better fit of $\vec{v}$ and z to radiosonde values than did the Flattery analysis. However, the height fields obtained from inserting its (non-divergent) wind field into the (non-linear) balance equation produced height changes that ranged from an average of about -96 meters to about +115 meters at each standard level.[2] This was deemed unacceptable and Jones' fields of $\vec{v}$ and z were therefore used only in some exploratory computation that are not reported on here.

The humidity field analyzed by Jones did fit the radiosondes better than did the Flattery analysis. At 19 radiosondes surrounding the Gulf of Mexico, a comparison was made of precipitable water from ground to

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[2]This analysis, although performed on potential temperature surfaces, does not use the Montgomery potential $\psi = c_p T + g z$, but analyses (T, z) and $\vec{v}$ separately. This feature may contribute to the large differences between the original and balanced height fields.

700 mb at 12Z 9 January 1975. Values at the stations ranged from 4 mm (a Mexican plateau station) to 24 mm at Tampa. If x denotes the deviation of the analyzed value from the radiosonde value, Flattery had a mean x of +4.4 mm and a mean x^2 of 32.5 mm^2. The Jones analysis had a mean x of -1.2 mm and a mean x^2 of 17 mm^2.

The initial moisture in the Gulf area was critical for the ensuing weather (see Figures 1 and 2). The coastal radiosondes such as Brownsville showed very dry air above 850 mb, whereas the Flattery analysis had relative humidities of 50-60 per cent at 700 mb.[3] This air had considerable convective instability. The first forecasts with the MFM and NGM used the Flattery humidity analysis. By 30 hours an unrealistic large-scale cloud was produced in the Ohio Valley by both models. This cloud was accompanied by pronounced vorticity changes in the lower and middle troposphere and excess precipitation. It seemed clear that the Kuo convective mechanism could not stabilize this unreasonably unstable moisture distribution. Use of the more accurate Jones' humidity analysis corrected this error.

Unfortunately, the Jones humidity data was not inserted into the 7 level model due to coding problems.

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[3]This analysis error may be due to features of the Flattery analysis scheme or to poor "satellite bogus" humidity data. An effort has been started to locate the sources of this error.

The second case selected was

Case II 00Z 19 November 1977

This was selected because of a major blizzard in Minnesota and a suggestion by Dr. G. Cressman that this storm was an example of one which was important to forecast correctly. The 00Z time was chosen because that is the better time for data over the Pacific Ocean. The final (48-hour) surface map has a low center in northern Minnesota (Figure 15), very much like that of case I (Figure 2).

Forecasts to 48 hours were decided upon as the best test because

a. They are long enough to reflect improvements in numerical method

b. They are long enough that dynamic initialization effects should not dominate (e.g. the establishment of vertical motion patterns)

c. They are long enough so that improved forecasts will be very useful

d. They are not so long that they are inevitably corrupted over the central U.S. by initial data problems over the Pacific.

e. The tests should not require exorbitant computing time.

The following forecasts were made. CPU time is shown in units of approximately 1 hour for a 48-hour forecast on the IBM 195.

Model	Vert. level	Horiz. resolution at 45° (km)	Case I	Case II	CPU units
6 lvl*	6	349	-	X	0.5
7 lvl	7	349	X	-	0.7
7 lvl**	7	174	X	X	1
7 lvl	7	87	X***	X	8
NGM_2 (2 grid)	10	198	X	X	1.2
NGM_3 (3 grid)	10	99	X	X	3
NGM_3 (3 grid)	16	62	(24 hr only)	-	16

*Old operational hemispheric model
**New operational hemispheric model after 18 January 1978.
***Forecast data tape inadvertently overwritten after graphical output but before computation of error statistics.

The MFM model was run only on Case I. That model is a regional model, relying upon lateral boundary data from an earlier hemispheric forecast model. When run with this boundary data from the original operational 6 lvl forecast it produced a pronounced "locked-in error" very similar to that of the 7 lvl model (Figure 7). Its precipitation forecasts after 24 hours were also bad, presumably because of this circulation error, and it was therefore withdrawn from the exercise. It did perform valuable service however in uncovering the consequence of the excessive moisture in the Flattery analysis.

3. The case of 12Z January 9, 1975.

Figures 1-4 show the initial and verifying sea-level and 500 mb charts. (The latter two from the operational LFM region analysis.) Figures 5-8 show the 48-hour forecast charts from the three 7-lvl forecasts and the two NGM forecasts. (The analysis charts in the upper right corner of these four figures are from the Flattery analysis. This analysis often fails to indicate the extreme values of low centers. In this case note that Figure 2 shows a central low pressure of 966 mb compared to the 969 mb on Figures 5 and 6.)

Figure 5 indicates

a. A pronounced improvement in the 7 lvl obtained by going from 349 to 174 km.

b. The cyclonic circulation even in the 87 km resolution extends too far southward into the New Orleans area, however.

c. A minor tightening of the cyclonic circulation is achieved by the 87 km over the 174 km resolution (e.g. the 996 contour is moved from the southern to the northern edge of Tennessee), but changes are generally negligible between the 174 and 87 km resolutions.

Figure 6 (note the copy of the 7 lvl 87 km forecast for reference) shows the NGM surface forecasts.

d. This model produced a very successful forecast even at 198 km resolution. (The low is about 150 km east of the verifying position.)

e. The 99 km resolution produced little change except for a slight tightening of the isobars.

The 500-mb charts in Figures 7 and 8 contain the height contours (the 5400 meter contour is a heavy line) and isolines of forecast height error (dashed lines). The innermost contours of the error field are heavy dashed lines and are labelled. The zero error contour is a dotted line. We note

f. A persistent positive error near Salt Lake. It reflects a failure to keep enough cold air in the southwestern quarter of the United States. It occurred in all models and therefore might be due to initial data problems in the Pacific or extreme western Canada.

g. The large typical "locked-in" error field couplet of ∿480 meters in the 349 km 7 level (Figure 7) is reduced to about 360 meters by a 4-fold reduction in grid size to 87 km.

h. The NGM forecast (Figure 8) has a markedly smaller locked-in error couplet (∿180 meters) than the 7 level model, but undergoes no significant reduction as its resolution is increased to 99 km.

Figure 9 shows the observed 12-hour precipitation amounts for the 36-48 hour forecast period. The dominant features are the 1-2 inch amounts over the southern Appalachians associated with the cold front (see Figure 2), the amounts up to 1 inch located to the west of the 48-hour surface low, and the smallness of the precipitation in Ohio and Pennsylvania.

Figures 10 and 11 show the predicted precipitation together with an analysis of the observed precipitation. Isolines on the former charts are for values of .01", .5", 1", 1.5", etc.[4]

i. The 7 lvl forecasts at 349 and 174 km resolution are both bad, with the two centers located in regions of little observed precipitation.

j. The 87 km 7 lvl result is an improvement, although the southeastern center is still too far west, and the northern centers have not yet been "swept" far enough around to the west of the low center.

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[4]These forecast charts are prepared by a graphical package using forecast data interpolated onto the standard NMC grid (349 km at 45^{o}). Forecast grid point values from models having finer resolution than 349 km can suffer in this output process, because it tends to diffuse and smooth the precipitation fields.

k. The NGM forecasts on Figure 11 are better, with two centers being recognized even with 198 km resolution. The 99 km results are an improvement, the 1" center near Lake Superior being now located with respect to the forecast low center in exactly the same way as the observed precipitation and pressure centers.

The improvement with resolution in the NGM is clearer on the grid point values of the precipitation, shown on Figures 12 and 13 for the 198 and 99 km cases, respectively.[5] The excess precipitation in Ohio is reduced somewhat, and the maximum values in the southeast and northwest are both more accurate on Figure 13 than on Figure 12.

4. The case of 00Z 19 November 1977

The presentation here follows the same pattern as that used for case I. Although the final surface low center (Figure 15) is about exactly where it was on case I (Figure 2), it is not as deep, and its 48-hour path was less meridional. The latter is consistent with the more zonal course of the 500 mb contours of Figure 16 compared to those of Figure 3. A major difference is also the location of the cold fronts of Figures 15 and 2.

In this case, the operational 6-level model at 349 km was available, and the 349 km 7 level model was therefore not run.

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[5]Note the sharper contrast from rain to no rain in these grid point values compared to the smoothed graphical results on Figure 11, especially in Mississippi, Alabama, and Minnesota. Appreciable detail is lost in the graphical product.

The sea-level forecasts on Figures 18 and 19 give rise to the same results as enumerated for case I, except that the excess west wind in Arkansas-Louisiana now gives a definitely erroneous location to the cold front of the 7 lvl forecast. The NGM handles the front location well, although the low center is 7 mb too deep. The change to 87 and 99 km in the two models now makes no noticeable improvement at all. At 500 mb (Figures 20 and 21) the 6-7 level combination now shows no improvement with resolution in the size of the locked-in error couplet (420, 420, 480 m). The NGM has a smaller error than the 7-lvl model. It again shows only a minor improvement in the error couplet with resolution, although the depth of the low center is improved significantly at 99 km resolution.

For reference, Figures 22 and 23 show the operational LFM 2 (116 km) forecasts. They are not as good as the coarser 7 level results.

Figure 24 shows the 12 hour observed precipitation amounts. It differs from case I in that the cold frontal showers are well separated from those 300 km further east in Alabama and central Tennessee, and there is a more continuous connection between the northern and southern maxima. The more zonal path of the center in this case is also reflected in the extensive area of precipitation in North Dakota west of the surface low.

The 6 and 7 level model results on Figure 25 do not capture the essentials of the precipitation pattern and show no improvement with increasing resolution. The NGM results on Figure 26 are much better, but to see improvement from resolution we must again turn to the grid point values, on Figures 27 and 28. These show, when compared with

Figure 24, that both resolutions predict the Alabama-Tennessee center, but with slightly larger and more realistic values in the finer resolution. The finer resolution NGM is especially good at separating the cold front and southeastern centers. The northern Indiana center is erroneously increased in intensity, however, on the finer resolution.

5. Statistical measures

Although the samples are small, statistical verification against radiosondes in the region 25°-60°N, 50°-105°W were carried out. These are shown in Tables I and II. There is no systematic evidence of improvement with resolution in NGM results or 7 lvl results. Between the two models the NGM does better at 48 hours (except in T at 850 mb)[6] whereas at 24 hours the 7 level does better in some instances.

Table III summarizes the improvement in statistical scores as the horizontal resolution is increased as indicated for each model. (To get this table the values at the four levels have been averaged. In the case of rms $\vec{v}$, z, and T, individual level values were squared before being averaged.) The results bear out the discussion of flow pattern forecasts in section 3 and 4 in that the changes are insignificant.

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[6]The NGM has a 2 and 4 degree warm bias in 850 mb temperature at 24 and 48 hours. This might be due to its omission of radiation and the effect of a downward turbulent flux of sensible heat over land areas without radiative transfer between ground and air.

Table 1

Forecasts from 12Z 9 Jan 1975
Verified against Radiosondes 25°-60°N, 50°-105°W
(7 lvl 87 km tape overwritten)

		NGM_2 (198 km)	NGM_3 (99 km)	NGM_3 (62 km)	7 lvl (174 km)
		*******	S1	*******	
24 hr	850	41.9	44.4	46.3	39.8
	500	36.0	37.7	38.3	35.4
	300	39.5	39.9	39.7	38.0
	200	36.8	36.5	37.3	not done
48 hr	850	33.7	37.9	(not	35.4
	500	31.4	31.5		42.7
	300	33.9	34.3	fcst)	46.7
	200	35.2	32.4		not done
		***** RMS Vector Wind Error (m/sec) *****			
24 hr	850	7.8	7.6	7.3	8.4
	500	6.5	6.8	7.1	7.8
	300	14.3	15.5	15.3	10.6
	200	13.4	13.0	12.5	not done
48 hr	850	9.3	10.7	(not	10.9
	500	13.1	13.8		16.7
	300	19.8	20.3	fcst)	23.5
	200	17.3	16.8		not done
		***** RMS Height Error (meters) *****			
24 hr	850	42.8	41.7	34.7	21.2
	500	45.6	44.3	35.8	28.4
	300	66.4	66.4	60.0	43.9
	200	77.3	78.6	65.1	not done
48 hr	850	49.2	53.8	(not	45.8
	500	82.3	82.9		89.2
	300	120.4	120.3	fcst)	127.5
	200	134.4	131.4		not done
		***** RMS Temp. Error (deg C) *****			
24 hr	850	4.6	4.2	3.7	3.0
	500	1.9	1.8	1.8	1.8
	300	2.9	3.1	2.9	2.6
	200	4.7	4.6	3.4	not done
48 hr	850	7.7	7.0	(not	4.8
	500	3.8	3.8		4.0
	300	3.5	3.6	fcst)	3.0
	200	4.4	4.4		not done

Table 2

Forecasts from 00Z 19 Nov 1975
Verified against Radiosondes 25°-60°N, 50°-105°W

		NGM (198 km)	NGM (99 km)	7 lvl (174 km)	7 lvl (87 km)
		********** S1 **********			
24-hr	850	34.7	33.1	31.5	31.2
	500	27.5	27.2	26.7	26.8
	300	29.1	27.7	28.9	28.4
	200	26.2	26.4	25.2	25.1
48-hr	850	52.1	50.8	69.5	68.8
	500	43.2	43.8	56.7	56.9
	300	36.7	39.3	51.3	52.9
	200	28.5	30.6	35.9	36.5
		***** RMS Vector Wind Error (m/sec) *****			
24-hr	850	5.5	5.4	6.0	6.0
	500	7.3	6.8	7.3	7.3
	300	10.6	10.0	9.8	9.3
	200	9.3	9.5	9.0	9.6
48-hr	850	10.8	10.1	14.8	14.5
	500	10.3	10.8	15.5	16.3
	300	12.3	12.5	19.8	18.7
	200	11.4	12.1	13.3	12.8
		***** RMS Height Error (meters) *****			
24-hr	850	19.6	17.8	16.6	15.8
	500	27.2	24.7	22.7	23.0
	300	36.8	34.8	31.3	31.5
	200	43.8	43.3	35.7	36.1
48-hr	850	61.9	58.5	82.7	87.8
	500	59.9	59.1	103.8	106.1
	300	64.6	62.8	115.8	114.8
	200	76.2	75.9	65.0	63.4
		***** RMS Temp. Error (deg C) *****			
24-hr	850	4.4	4.5	2.3	2.2
	500	1.6	1.5	1.7	1.6
	300	2.7	2.6	2.3	2.2
	200	1.8	1.7	2.1	2.2
48-hr	850	6.6	4.9	3.7	4.1
	500	3.3	3.3	3.3	3.5
	300	4.3	4.0	3.2	3.4
	200	3.7	3.9	6.0	6.5

Table 3

Average Change in Statistics
Accompanying Finer Resolution
NGM 198 to 99 km
2 cases 4 levels combined

	24 hr	48 hr	
S1	+.15	+.74	
rms $\vec{v}$	+.06	+.31	m sec^{-1}
rms z	-.50	-.75	m
rms T	-.07	-.4	deg

7 lvl 174 to 87 km
1 case 4 levels combined

	24 hr	48 hr	
S1	-.1	+.2	
rms $\vec{v}$	+.02	-.03	m sec^{-1}
rms z	+.13	+1.3	m
rms T	-.05	+.34	deg

6. The NGM at 62.5 km

As a test of improvement with further resolution, the NGM was run with 16 levels and a horizontal resolution of 62.5 km on the inner grid C. This was done only on case I, 12Z 9 January 1975. At 24 hours this forecast overpredicted the pre-cold frontal rain center, then located on a line from Louisiana through northeastern Arkansas, as shown on Figure 29.[7]

That the precipitation in the 62.5 km forecast is excessive is borne out by the much denser network of 24-hour precipitation reporting stations, which reported a maximum 24-hour amount from 12Z 9 January to 12Z 10 January of 4 inches. The excessive rain also produced too much horizontal convergence and generation of excess cyclonic vorticity in the lower troposphere over western Mississippi. Figures 31 and 32 are zonal cross sections from the 99 km forecast along the heavy line shown in Figure 30. [The vertical coordinate is -ln (pressure/sfc press).] The southerly wind maximum predicted near the Alabama-Mississippi border is quite reasonable on the 99 km resolution, but a similar cross section from the 62.5 km forecast (not shown) gives values of around 50 m/sec at 700 mb. The former agreed better with the wind reports at 700 mb shown on Figure 33.

[7]No model predicted the convective line extending from St. Louis to Chicago (.88" at Chicago). The thunderstorms in this region presumably originated in the unstable warm air situated above the layer of cold surface air then located in the central Mississippi Valley as shown on Figure 30. This miss could be due to the convective parameterization schemes used which tend to assume that convective clouds start only in or just above the bottom layer of a model.

It appears that the Kuo convective parameterization used in the NGM is not capable of preventing the growth of unstable cumulus clouds in the large-scale motion field under all conditions. This process can be understood from the frequency formula for non-hydrostatic internal gravity waves of the form exp i $(\alpha x+\beta z-\omega t)$:

$$\omega^2 = \frac{N^2 \alpha^2}{\alpha^2+\beta^2}, \qquad (1)$$

$$N^2 = \frac{g}{\bar{\theta}} \frac{d\bar{\theta}}{dz}. \qquad (2)$$

For unstable conditions, N^2 in (2) will be negative, and ω^2 in (1) will be negative (i.e. unstable motion). The magnitude of ω^2 is bounded by $|N^2|$, this limit being obtained for large α^2 and small β^2--i.e. tall thin convective cells. When the hydrostatic approximation is made, however, the α^2 in the denominator of (1) is missing,

$$\omega^2_{(\text{hydrostatic})} = \frac{N^2 \alpha^2}{\beta^2}. \qquad (3)$$

This is larger in magnitude than the non-hydrostatic value.

It is this unstable convective process which cumulus parameterization is supposed to represent, and keep N^2 from becoming less than zero. The Kuo parameterization as used in the NGM seems to have performed reasonably well at 99 km. But when the horizontal grid mesh in the NGM is reduced to 62.5 km from 99 km, the maximum α^2 in (3) is tripled, evidently allowing the large-scale moist instability to become too active.[8]

The test of the 62.5 km resolution therefore presents a warning note that the parameterization of moist convection will become more critical as models with finer horizontal resolution are used.

The successful prediction of the pre-frontal convective activity in the lower Mississippi Valley 12-24 hours into the forecast--i.e. at the right place and time--might not be an accident. Recent theoretical ideas about the formation of fronts suggest that the rapid frontogenetic process should be accompanied by the generation of a low-altitude internal gravity wave pulse which moves ahead into the warm air.[9] Frontogenesis seems to have occurred in this case in both the real world (cf. Figures 1 and 30) and the NGM model.

7. Conclusions and recommendations

If one bears in mind the limited sample of this study, the following conclusions about finer resolution *per se* are reasonable.

Firstly, with respect to flow pattern forecasts made from Flattery analyses:

1. Little or no improvement in 48-hour forecasts is achieved by changing the 7 lvl from 174 to 87 km or the NGM from 198 to 99 km.

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[8]The hydrostatic versus non-hydrostatic aspect is of course not the main reason why parameterization is required. The latter would be needed even in a non-hydrostatic model so that the convection does not directly generate excess kinetic energy on the grid point scale.

[9]Ley, B., and W. Peltier, 1978: Wave generation and frontal collapse. J. Atmos. Sci., 35, 3-17.

2. The NGM does a better job of predicting flow patterns at 48 hours from the Flattery analysis than does the 7 lvl model, in these cases of "locked-in error."[10]

Secondly, with respect to precipitation forecasts:

3. In the NGM, with a decent regional humidity analysis, there was improvement in going from 198 to 99 km, but overprediction of pre-cold frontal rain at 62.5 km.

4. In case I the 7 lvl improved some at 87 km, but there was no improvement at 87 km in case II. These were with the Flattery moisture analysis.

From the larger point of view of improved forecasts from the NMC prediction models when more powerful computers become available, the picture is indeed promising--although these improvements will evidently not come about automatically from further horizontal resolution of current operational models, numerical methods and models do exist which can bring about the improvement. Even more important is the further evidence that computer precipitation forecasts can be significantly improved in some of the most important winter storms.

The following recommendations seem appropriate:

1. The Flattery moisture analysis must be improved.

2. The regional analysis program should be improved to the point where the winds and height fields are in better balance.

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[10]This also happened in the cases of January 9, 1977 and April 18, 1975 that were tested in May 1977.

3. Tests of finer resolution can be resumed once 1 and 2 are accomplished.

4. The warm low-level temperature bias in the NGM should be corrected by more realistic physics.

5. Pending the arrival of more powerful computers, experimentation and development to improve the 7 level model should be made, including changes in the moist convection process and changes in the hydrodynamical finite-differences. The latter aspect should consider the advantages of the 4th order semi-implicit experimental model tested by Campana.[11]

[11] Campana, K., 1977, "Real data experimentation with higher order finite differencing in the semi-implicit version of the Shuman-Hovermale model." NMC Office Note 163.

Appendix

1. The Nested Grid Model

Vertical structure - sigma coordinate, with one sigma domain from surface to p=o. The number of vertical levels was chosen so as to maintain an average value of .01 for the ratio: (Height increment/ horizontal increment on grid C.) Sigma layers are closer together at large and small sigma values than they are at sigma $\sim$.5.

Horizontal structure - (See Figure 34) Hemispheric (grid A) on a stereographic projection, with either one (grid B) or two (grid C) interior grids, each with half the mesh interval of its outer neighbor. Two grids were used for the 198 km forecasts, three grids were used for the 99 and the 62.5 km forecasts.

Lateral boundaries - Symmetry conditions at the equator for grid A. Each pair of grids (A,B and B,C) overlaps enough to provide lateral boundary conditions for each other by spatial interpolation.

Numerical methods - Two-step "Lax-Wendrof" using the Eliassen space-time staggered location of grid points. The ratio $\Delta t/\Delta x$ is the same on each grid. Arakawa's vertical differencing is used to conserve θ^2 and to correctly compute orographic form drag.

Input data - Flattery analysis of u, v, and z at the 12 mandatory levels (no T analysis is used). Flattery humidity data, except that the R. Jones analysis was used in the LFM area.

Initialization - (a) Divergence in the latitude belt 0-20°N is removed following enforcement of equatorial symmetry in that region. (b) Fields around Himalayas are changed by a precomputed amount to minimize generation of gravity waves by pressure force truncation error.

Radiation - None.

Large-scale precipitation - Saturation criterion of 90%. No evaporation of falling precipitation.

Convective precipitation - Original Kuo method except that until layer reaches 81% of saturation, convection is only allowed to moisten it (not heat it). Convective rain evaporates on way down.

Vertical turbulent flux - a) Surface skin drag. b) Evaporation and sensible heat flux from ocean, but not over land. c) Vertical austausch on all variables at all levels inversely proportional to $|Ri|+.25$. d) Dry adiabatic adjustment where $d\theta/dz<0$.

Horizontal smoothing - Every three hours a filter of the form $(1-\partial^4/\partial i^4)(1-\partial^4/\partial_j{}^4)$ is applied to u, v, θ, and q (but not surface pressure). (i and j are the horizontal grid indices). No horizontal diffusion in forecast equations.

2. The 7 level model

Vertical structure - Surface layer of 50 mb. Three equally spaced sigma layers above this up to a material surface ("tropopause"). Three layers of equal thickness between this material surface and 50 mb.

Horizontal structure - Square region enclosing equator on stereographic projection.

Lateral boundaries - Free slip at the square outer boundary. South of 9°N, the Coriolis parameter and map scale factor are kept at 9°N value.

Numerical methods - The Shuman "semi-momentum" form with pressure gradient averaging.[11]

Input data - Flattery u, v, z, T at mandatory levels, relative humidity at bottom 6 levels, surface T analysis. Analysis of tropopause pressure.

Initialization - None (forecast divergence used only in operational version).

Radiation - Short wave heating. Infra-red cooling of 1.44°/day except below highest layer with humidity >60%.

Large-scale precipitation - Saturation criterion of 90%. Falling precipitation must saturate lower layers before reaching ground.

Convective precipitation - Parcel instability from a layer to the next higher layer results in convective precipitation but no latent heat release.

Vertical turbulent flux - a) Surface skin drag. b) Sensible heat flux over ocean (upward only). c) Oceanic evaporation is modeled only only by keeping relative humidity >30%. d) Dry and/or moist adiabatic adjustment.

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[11]Brown, J. and K. Campana, 1978. An economical time-differencing system for numerical weather prediction. Submitted to Monthly Weather Review.

Horizontal smoothing - Horizontal diffusion (1.5×10^5 m^2 sec^{-1}) on u, v, q, θ, $\partial p/\partial \sigma$ in forecast equations.

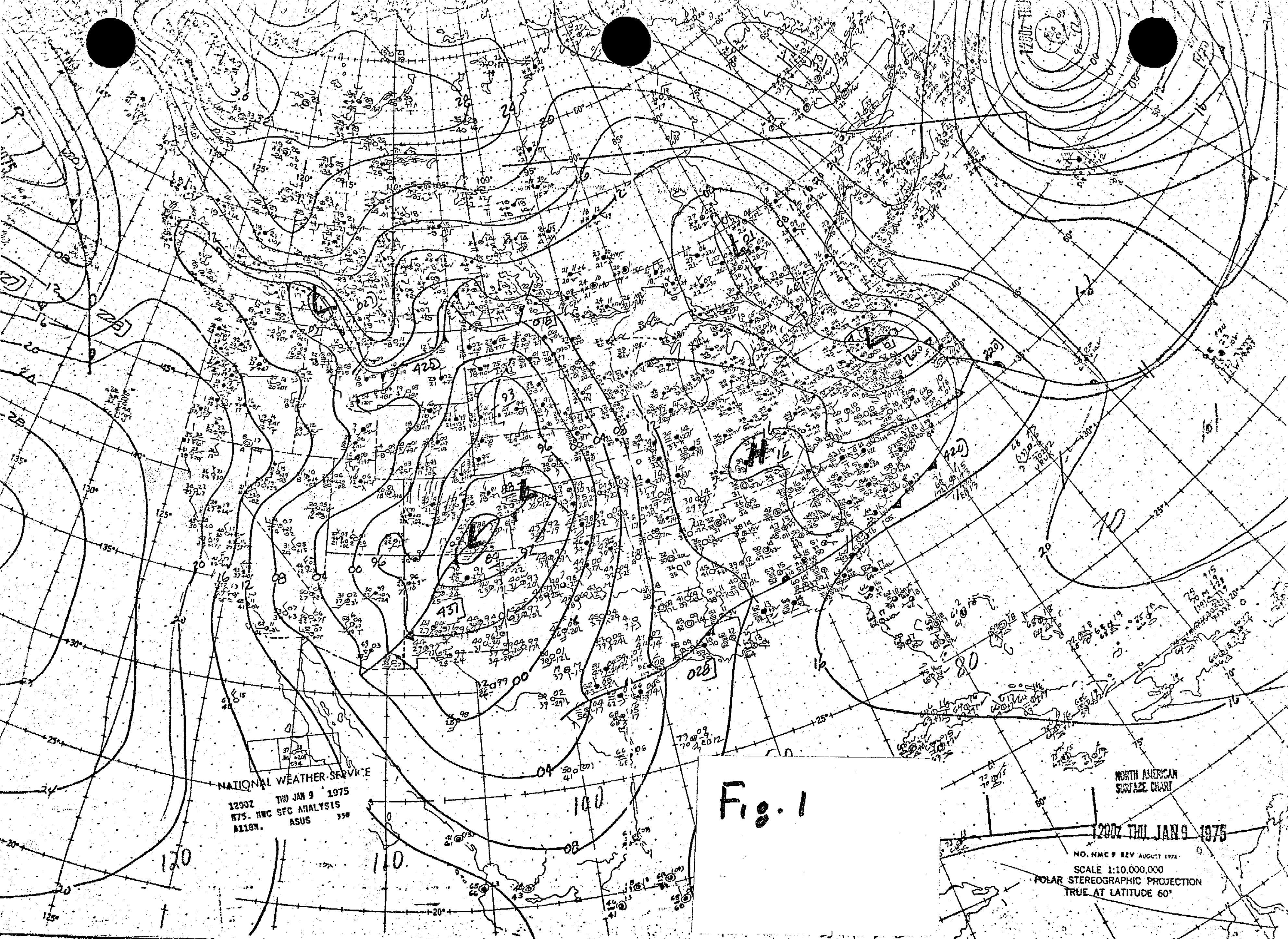

NATIONAL WEATHER SERVICE
1200Z THU JAN 9 1975
N75. NMC SFC ANALYSIS
A118N. ASUS 350
NORTH AMERICAN SURFACE CHART
1200Z THU JAN 9 1975
NO. NMC 9 REV AUGUST 1974
SCALE 1:10,000,000
POLAR STEREOGRAPHIC PROJECTION
TRUE AT LATITUDE 60°

Fig. 1

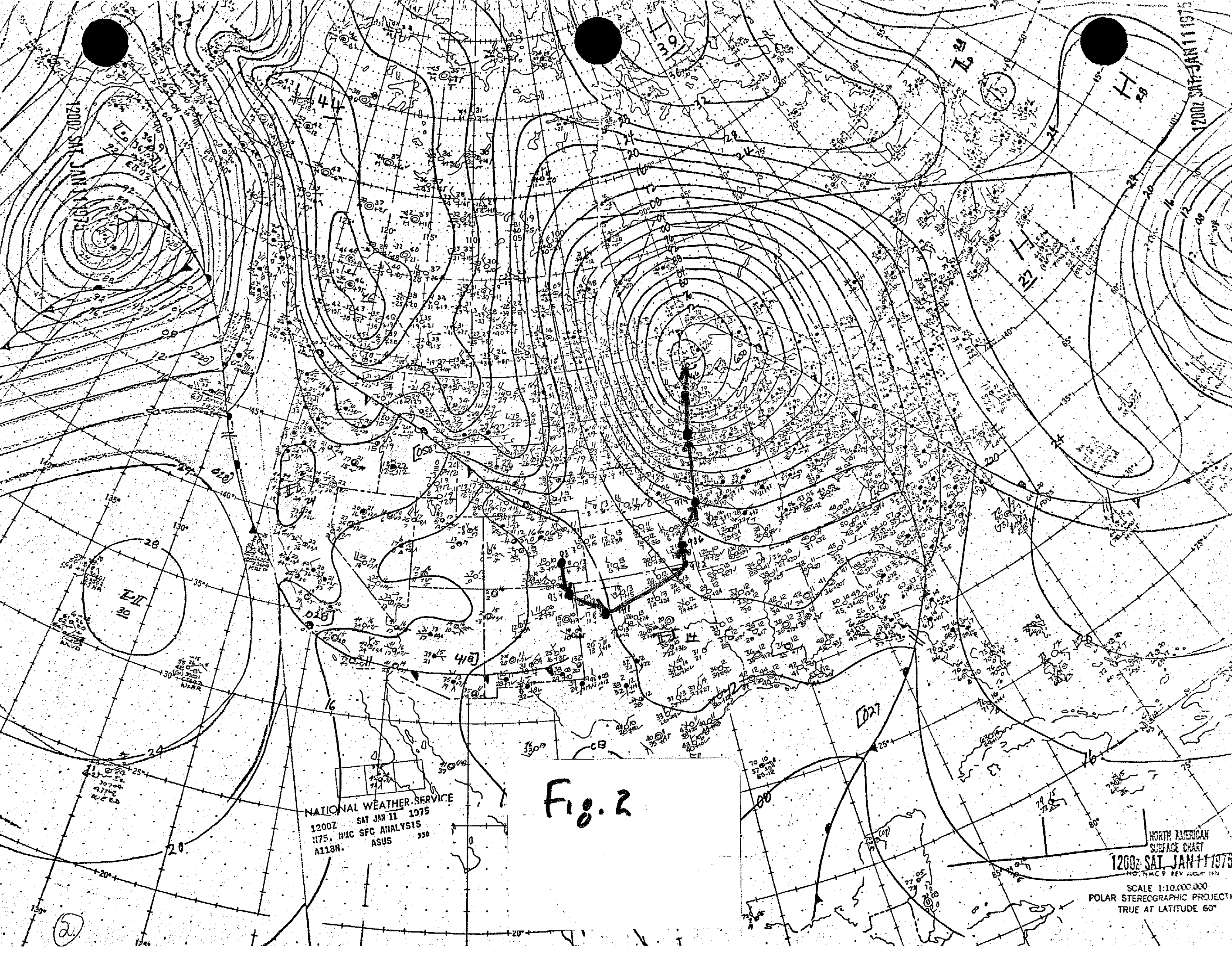

NATIONAL WEATHER SERVICE
1200Z SAT JAN 11 1975
1175. NMC SFC ANALYSIS
A118N. ASUS 330
NORTH AMERICAN SURFACE CHART
1200z SAT JAN 11 1975
SCALE 1:10,000,000
TRUE AT LATITUDE 60°

Fig. 2

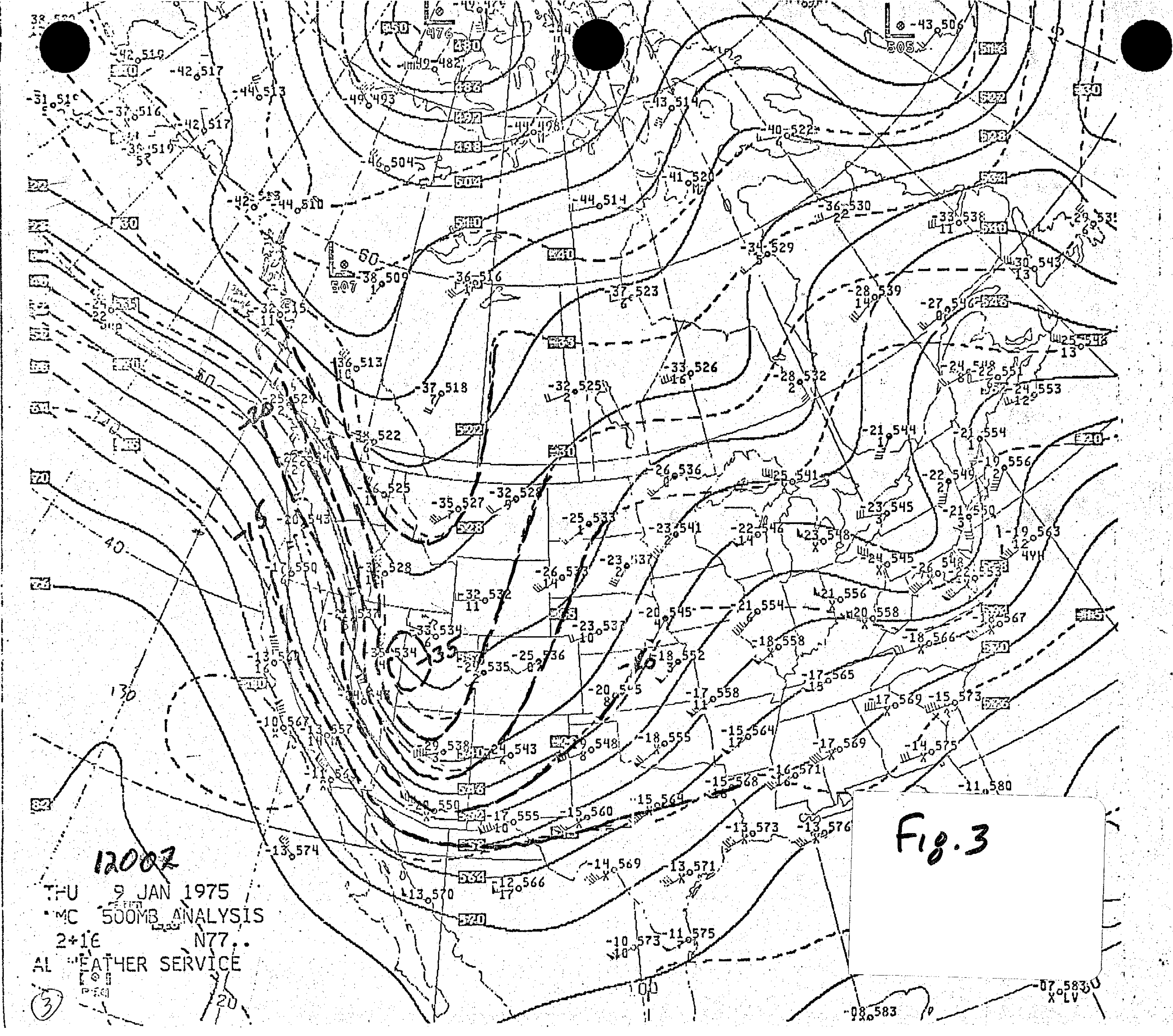

1200Z
THU 9 JAN 1975
MC 500MB ANALYSIS
2+16 N77..
AL WEATHER SERVICE

Fig. 3

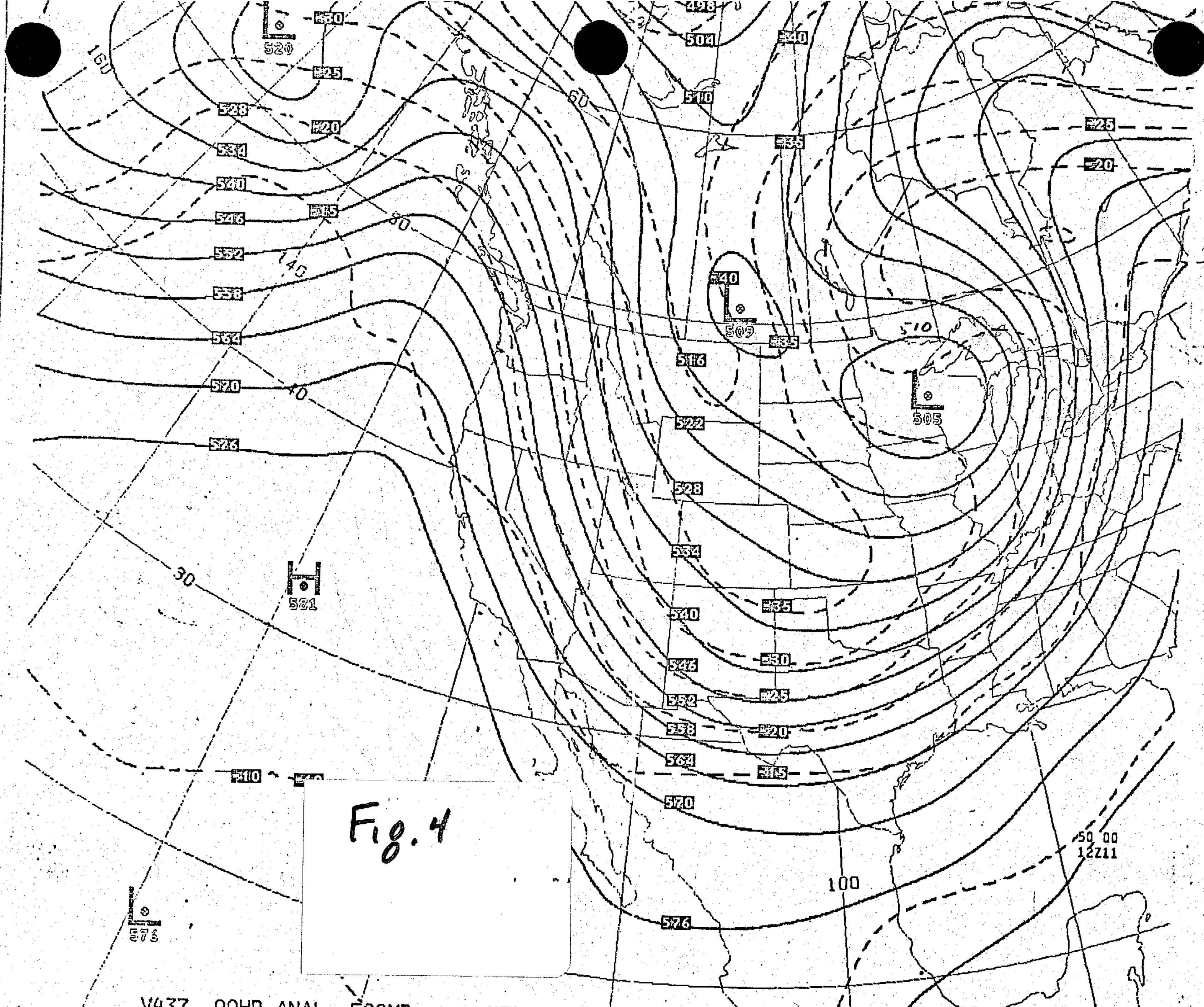


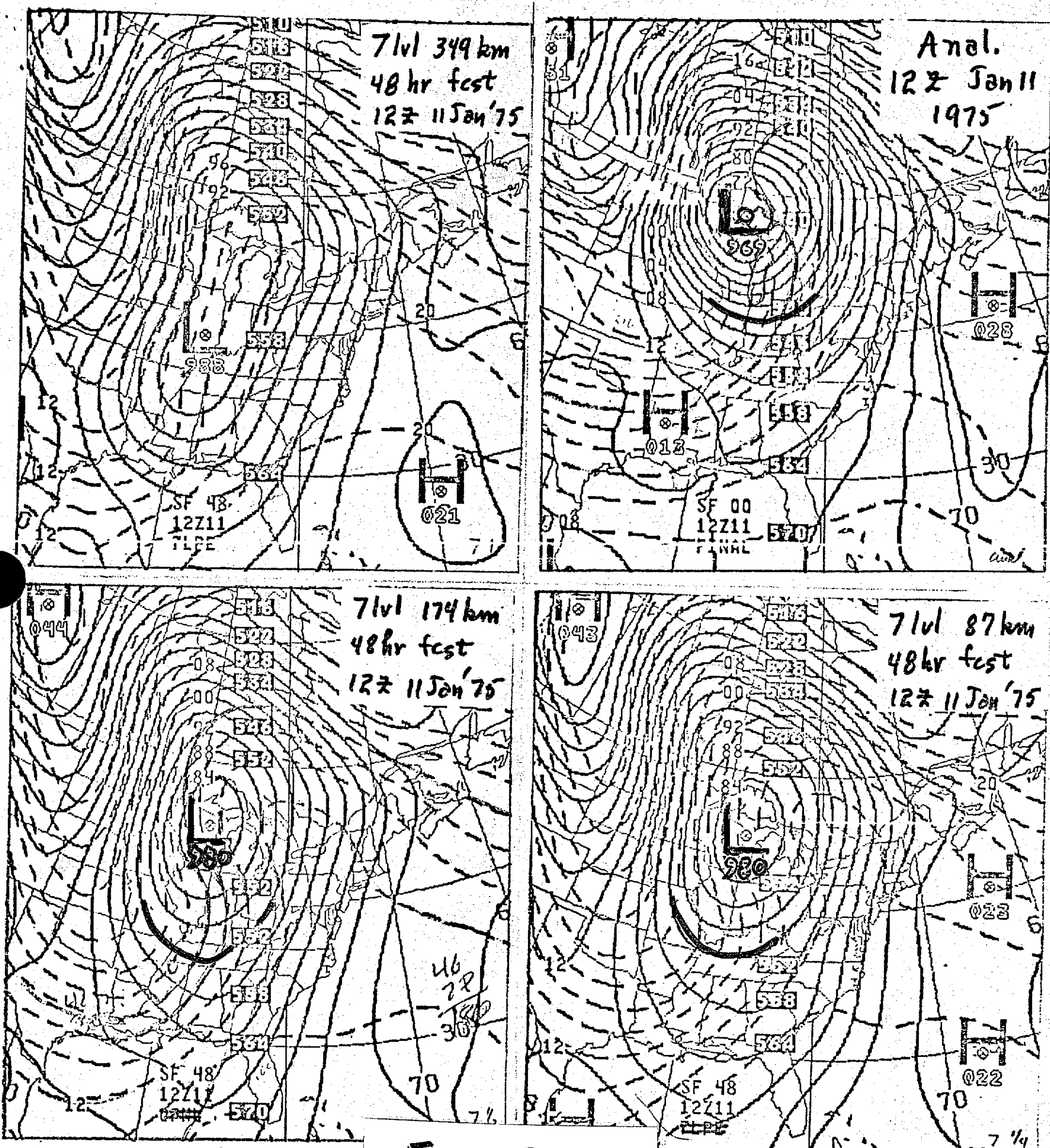
Fig. 4

(4)

V437 00HR ANAL 500MB HEIGHTS/TEMPERATURE VALID 12Z SAT 11 JAN 1975 V437

A140N 00HR ANAL 700MB HEIGHTS/TEMPERATURE VALID 12Z SAT 11 JAN 1975 A140N

N086 00HR ANAL 700MB HEIGHTS/TEMPERATURE VALID 12Z SAT 11 JAN 1975 N086



7 lvl 349 km
48 hr fcst
12Z 11 Jan '75
SF 48
12Z11
Anal.
12Z Jan 11
1975
SF 00
12Z11
FINAL
7 lvl 174 km
48 hr fcst
12Z 11 Jan '75
SF 48
7 lvl 87 km
48 hr fcst
12Z 11 Jan '75
SF 48
12Z11

Fig. 5

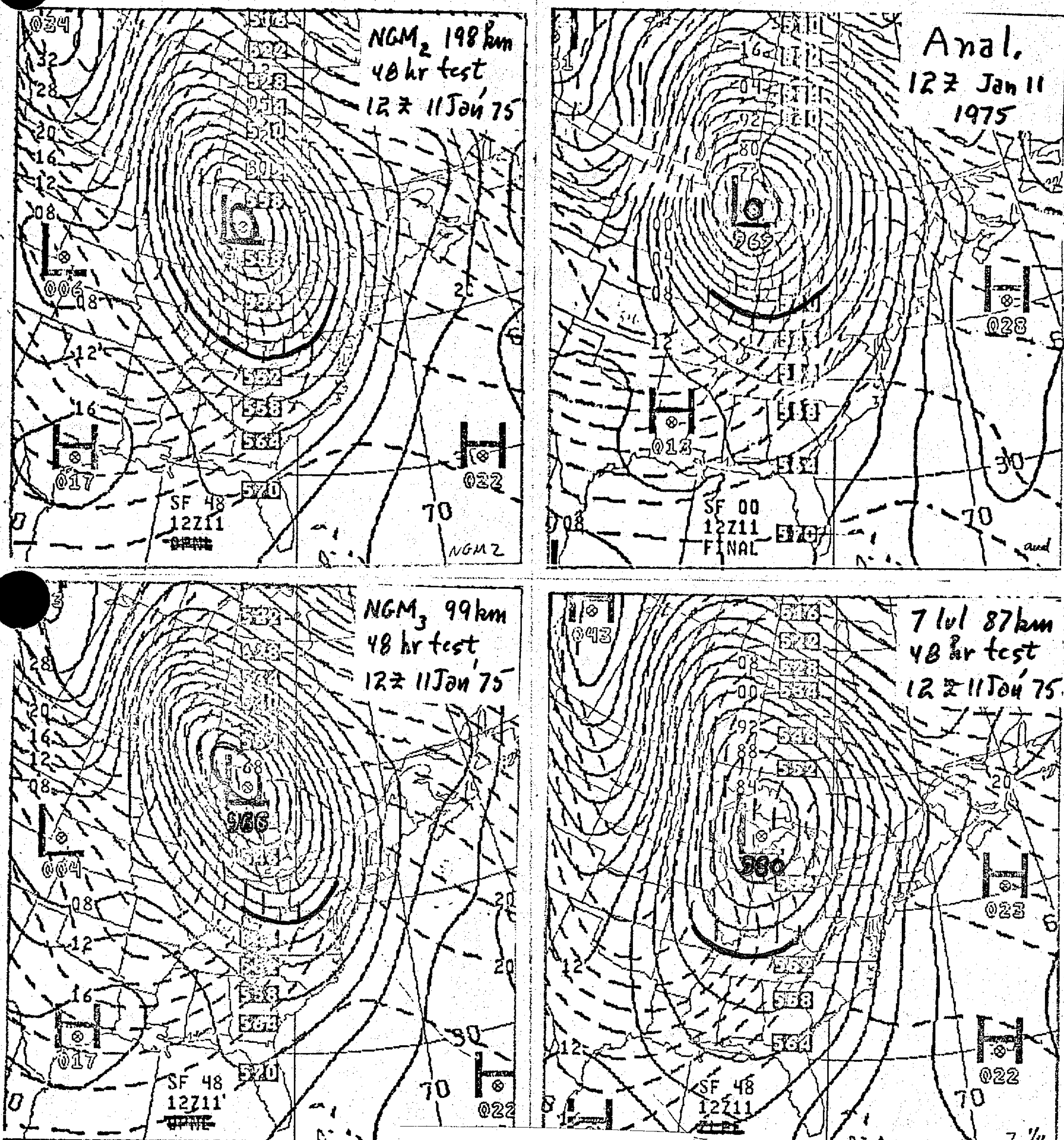

NGM₂ 198 km
48 hr test
12 Z 11 Jan 75
SF 48
12Z11
Anal.
12 Z Jan 11
1975
SF 00
12Z11
FINAL
NGM₃ 99 km
48 hr test
12 Z 11 Jan 75
SF 48
12Z11
7 lvl 87 km
48 hr test
12 Z 11 Jan 75
SF 48
12Z11

Fig. 6

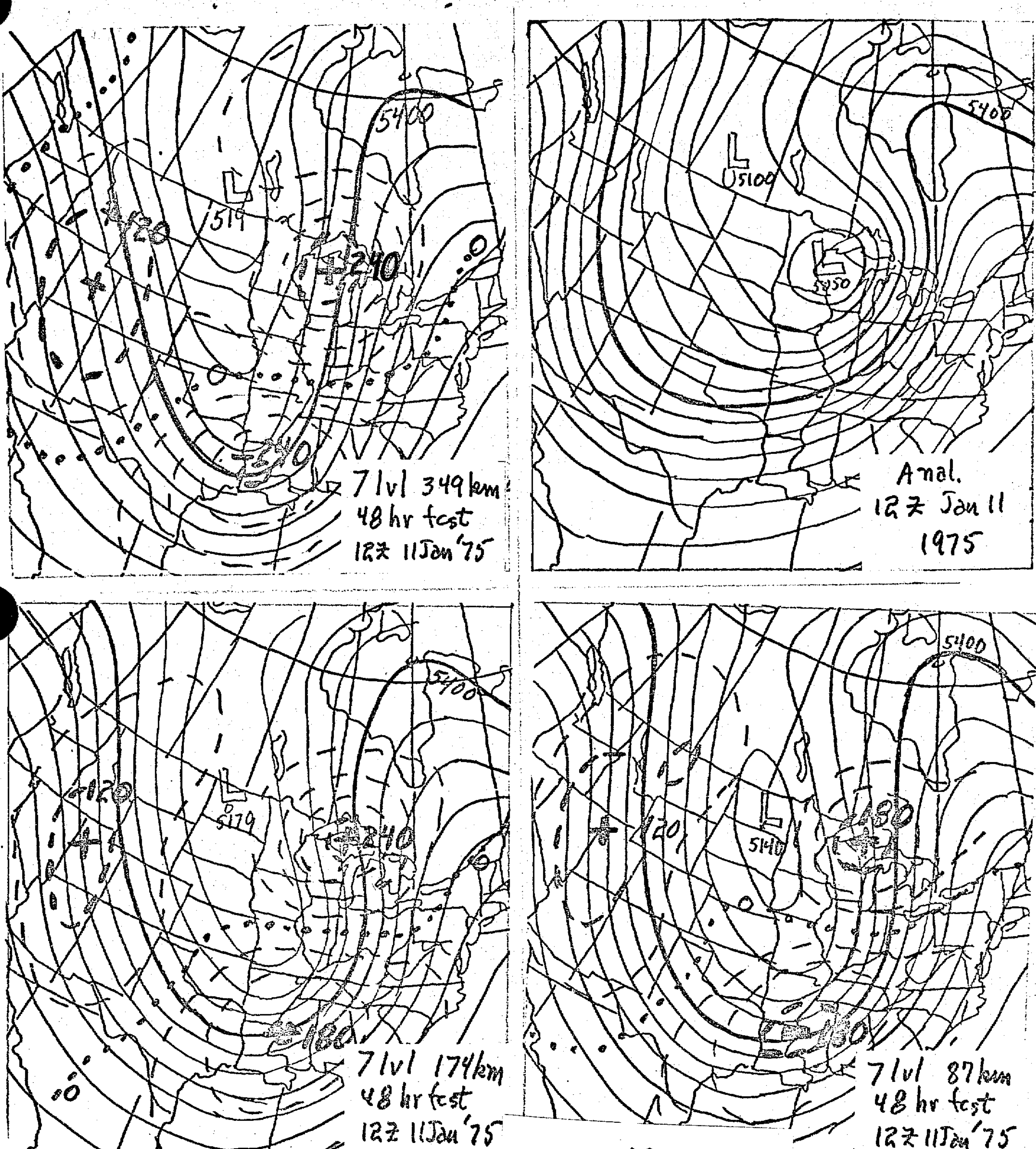

7 lvl 349 km
48 hr fcst
12Z 11 Jan '75
Anal.
12Z Jan 11
1975
7 lvl 174 km
48 hr fcst
12Z 11 Jan '75
7 lvl 87 km
48 hr fcst
12Z 11 Jan '75
5400
L
5100

Fig. 7

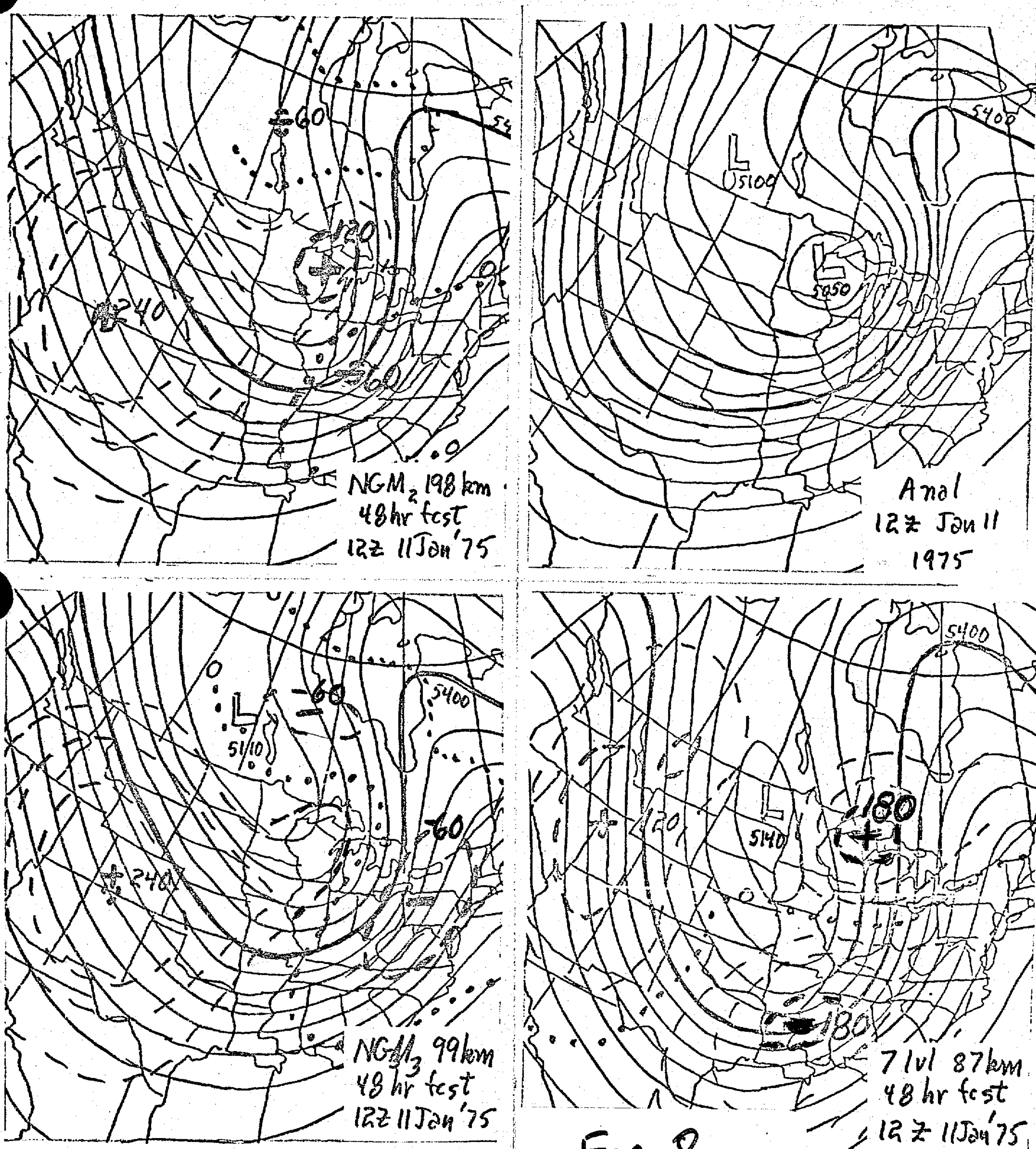

NGM2 198 km
48 hr fcst
12Z 11 Jan '75
Anal
12Z Jan 11
1975
5400
5100
5050
NGM3 99 km
48 hr fcst
12Z 11 Jan '75
5400
5110
7 lvl 87 km
48 hr fcst
12Z 11 Jan '75
5400
5140
180

Fig. 8

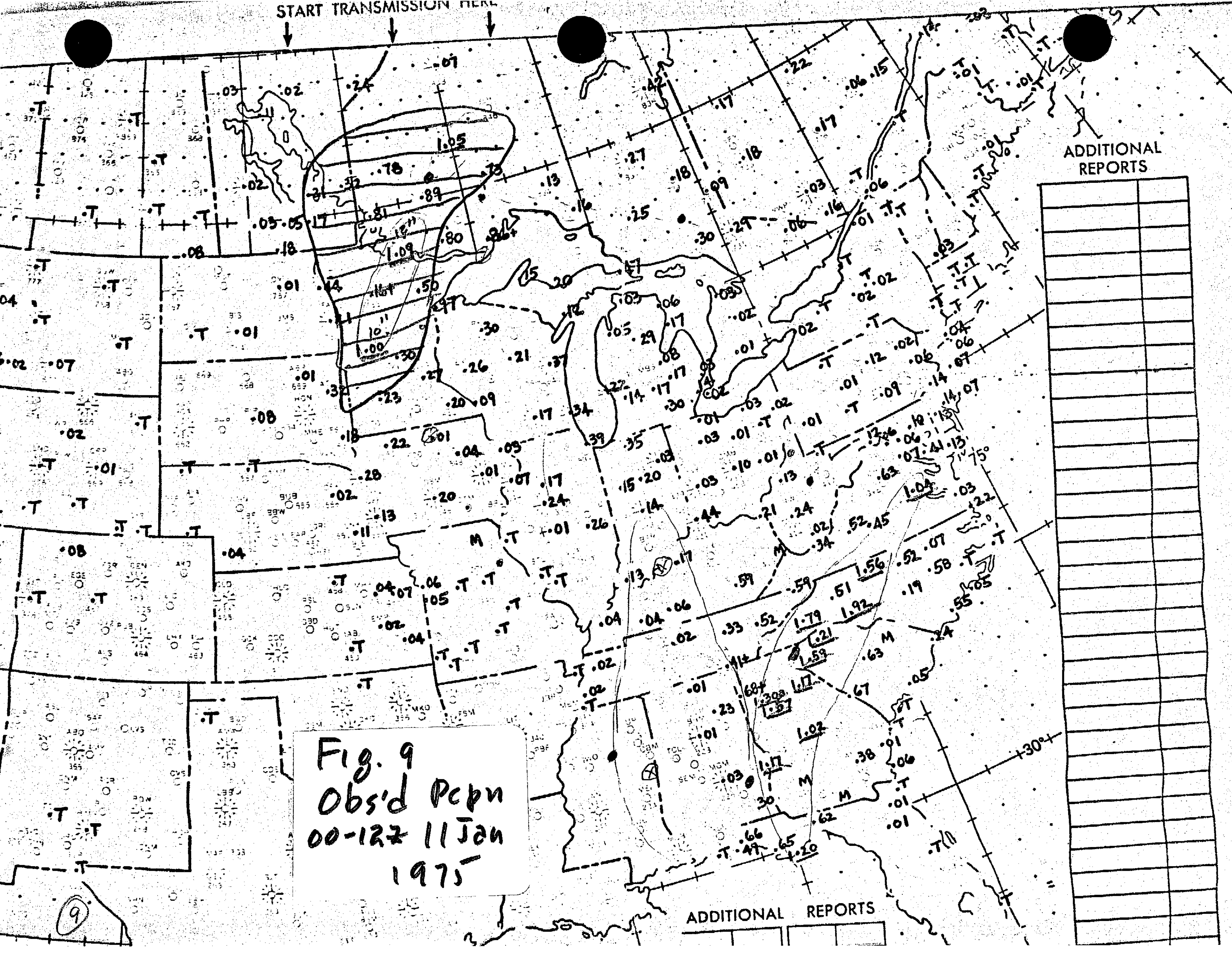
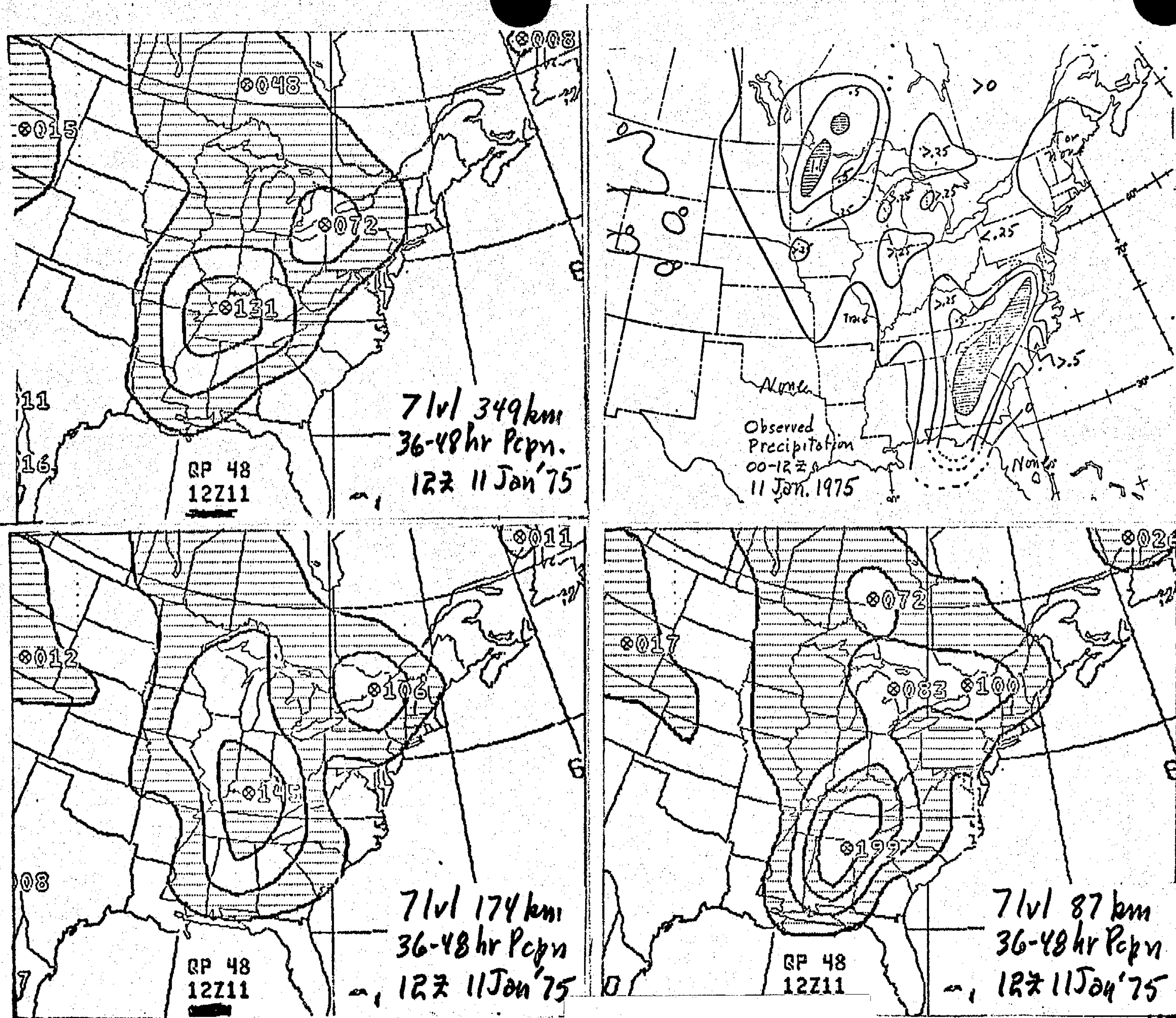


Fig. 9
Obs'd Pcpn
00-12Z 11 Jan
1975



⊗015
⊗048
⊗008
⊗072
⊗131
11
16
7lvl 349km
36-48hr Pcpn.
12Z 11 Jan '75
QP 48
12Z11
>0
>.25
<.25
>.5
Trace
None
Observed
Precipitation
00-12Z
11 Jan. 1975
⊗011
⊗012
⊗106
⊗145
08
7lvl 174km
36-48hr Pcpn
12Z 11Jan'75
QP 48
12Z11
⊗072
⊗017
⊗083
⊗100
⊗199
7lvl 87km
36-48hr Pcpn
12Z 11Jan'75
QP 48
12Z11

Fig. 10

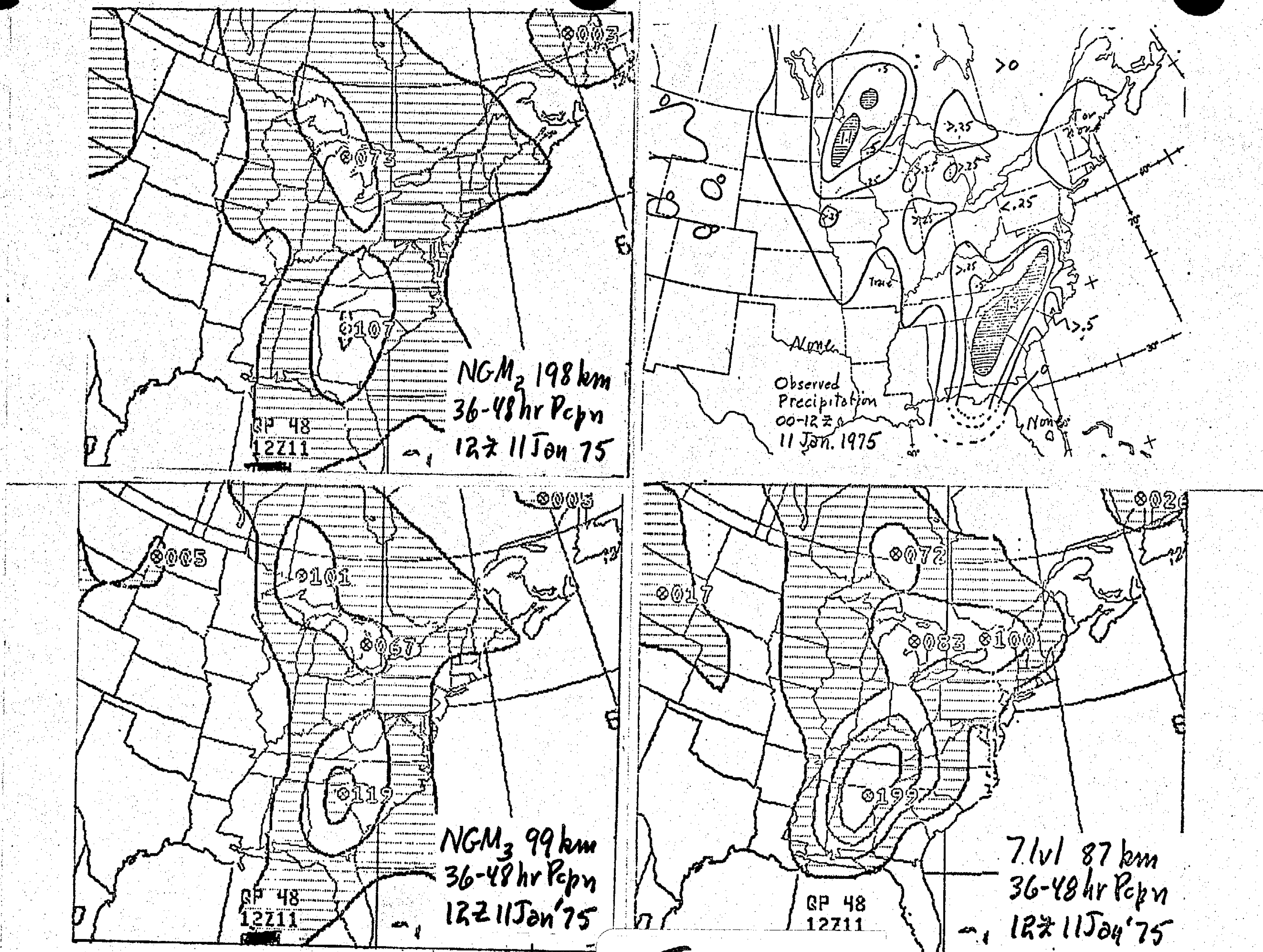

NGM2 198 km
36-48 hr Pcpn
12Z 11 Jan 75
QP 48
12Z11
Observed
Precipitation
00-12Z
11 Jan. 1975
None
Trace
NGM3 99 km
36-48 hr Pcpn
12Z 11 Jan '75
QP 48
12Z11
7 lvl 87 km
36-48 hr Pcpn
12Z 11 Jan '75
QP 48
12Z11

Fig. 11

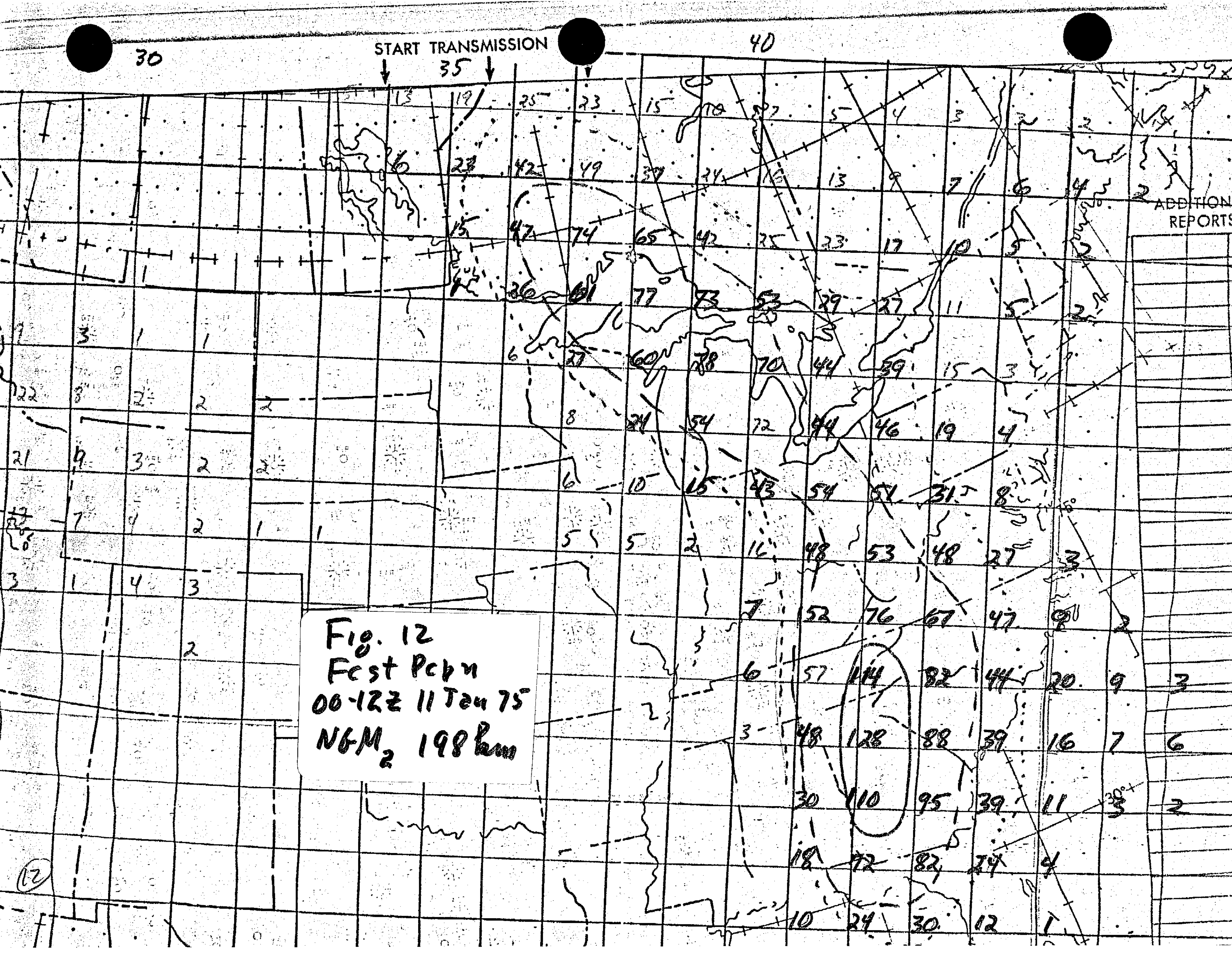


Fig. 12
Fcst Pcpn
00-12Z 11 Jan 75
NGM$_2$ 198 km

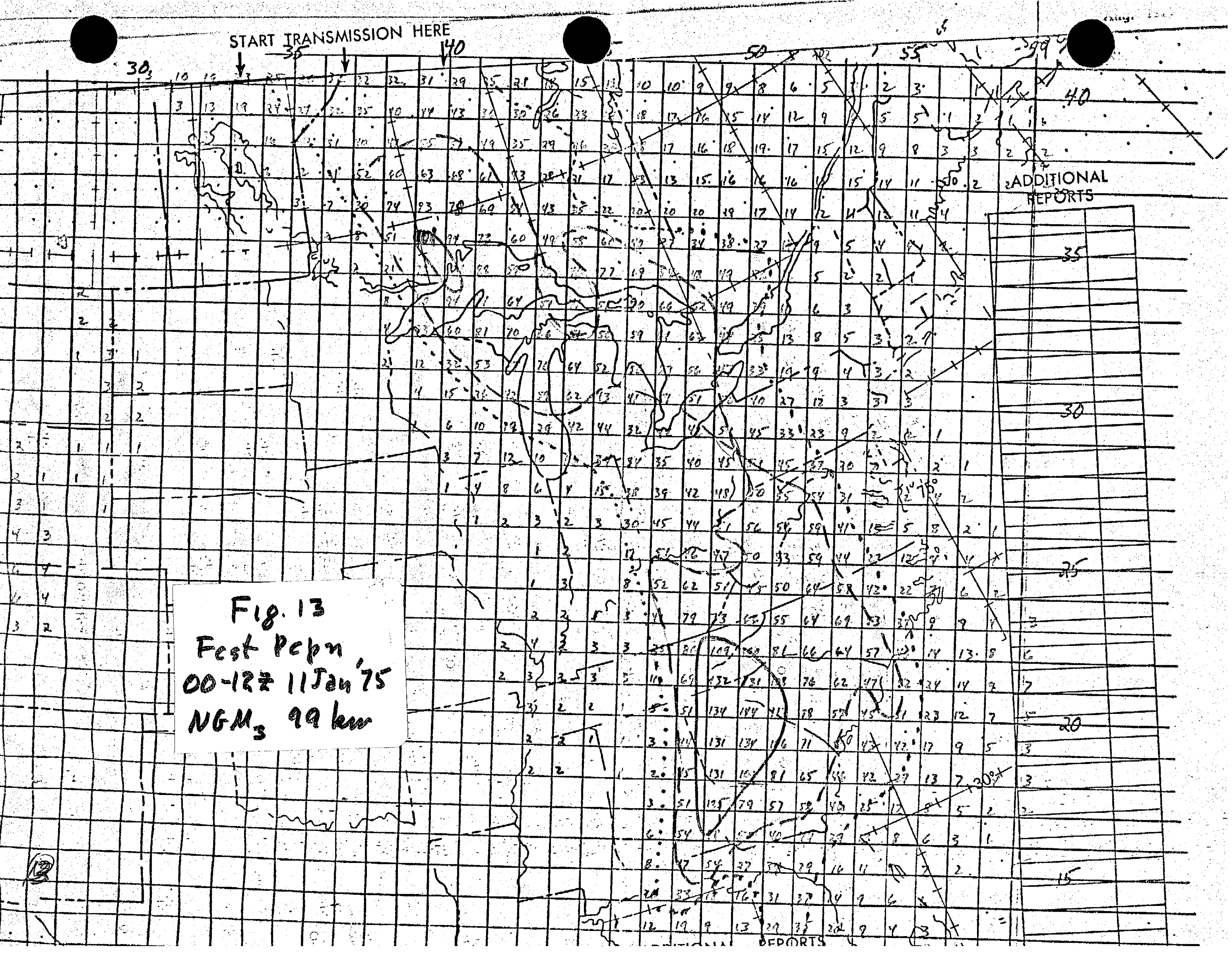
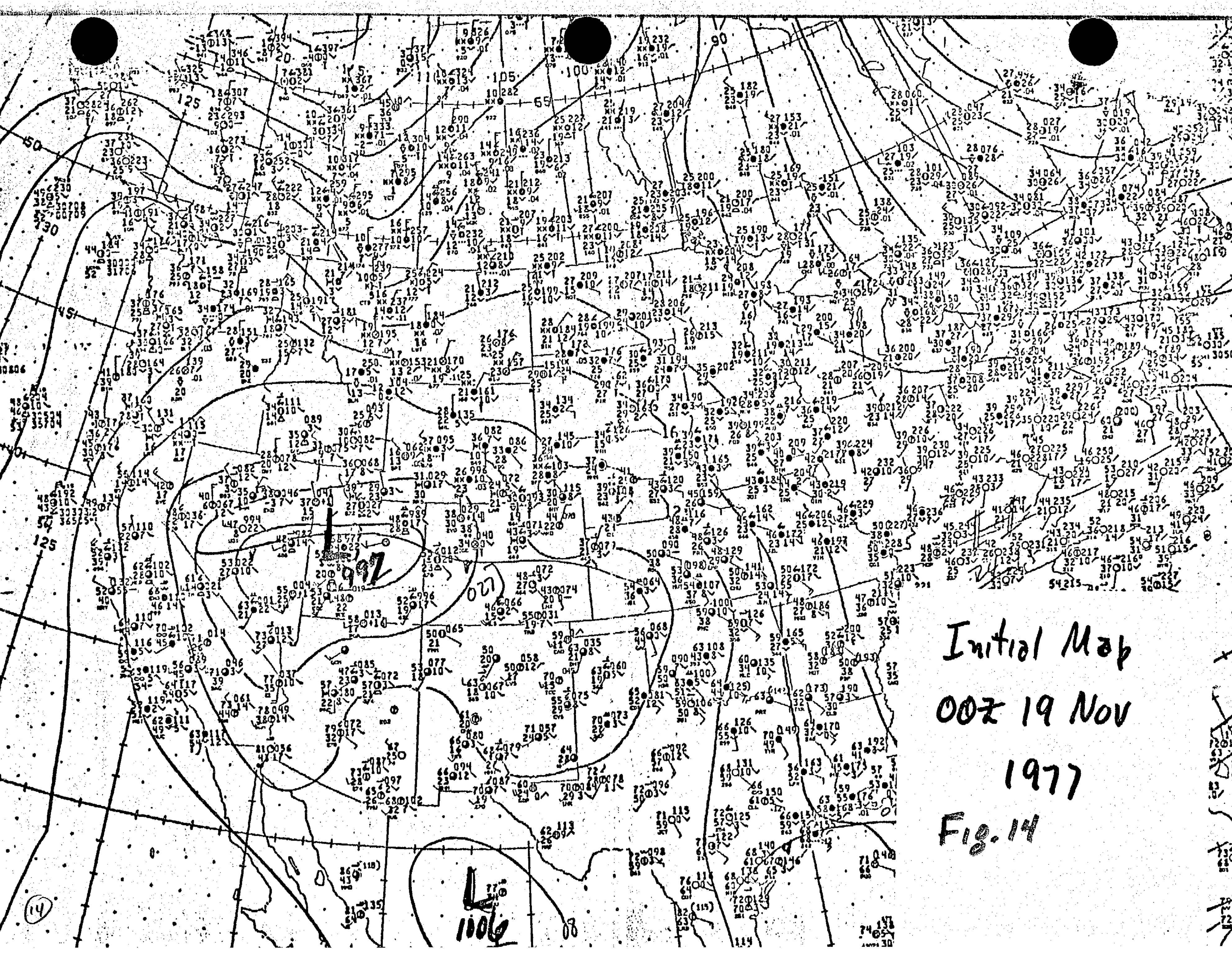
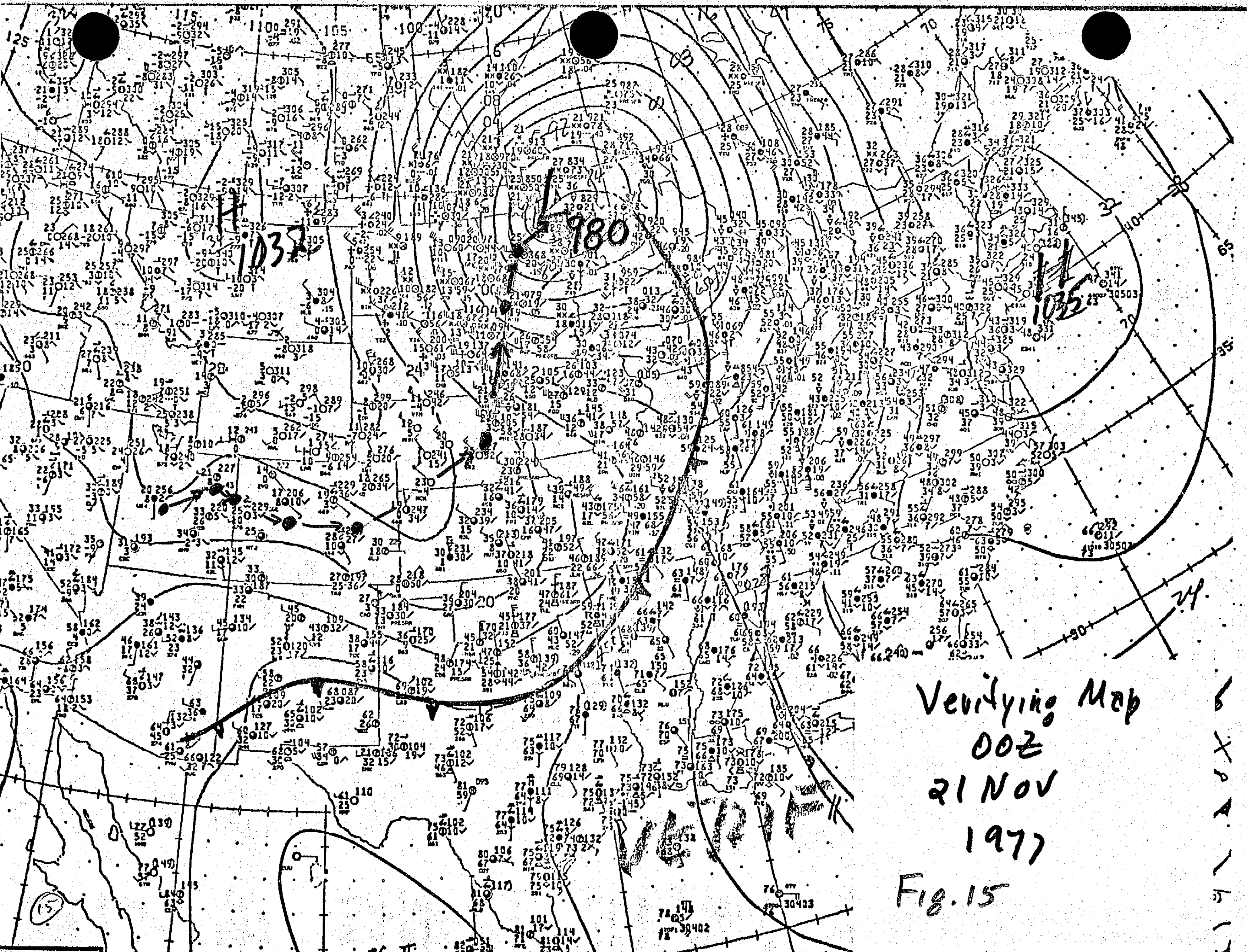


Fig. 13 Fcst Pcpn 00-12Z 11Jan'75 NGM_3 99 km



Initial Map
00Z 19 Nov
1977
Fig. 14



Verifying Map
00Z
21 NOV
1977
Fig. 15

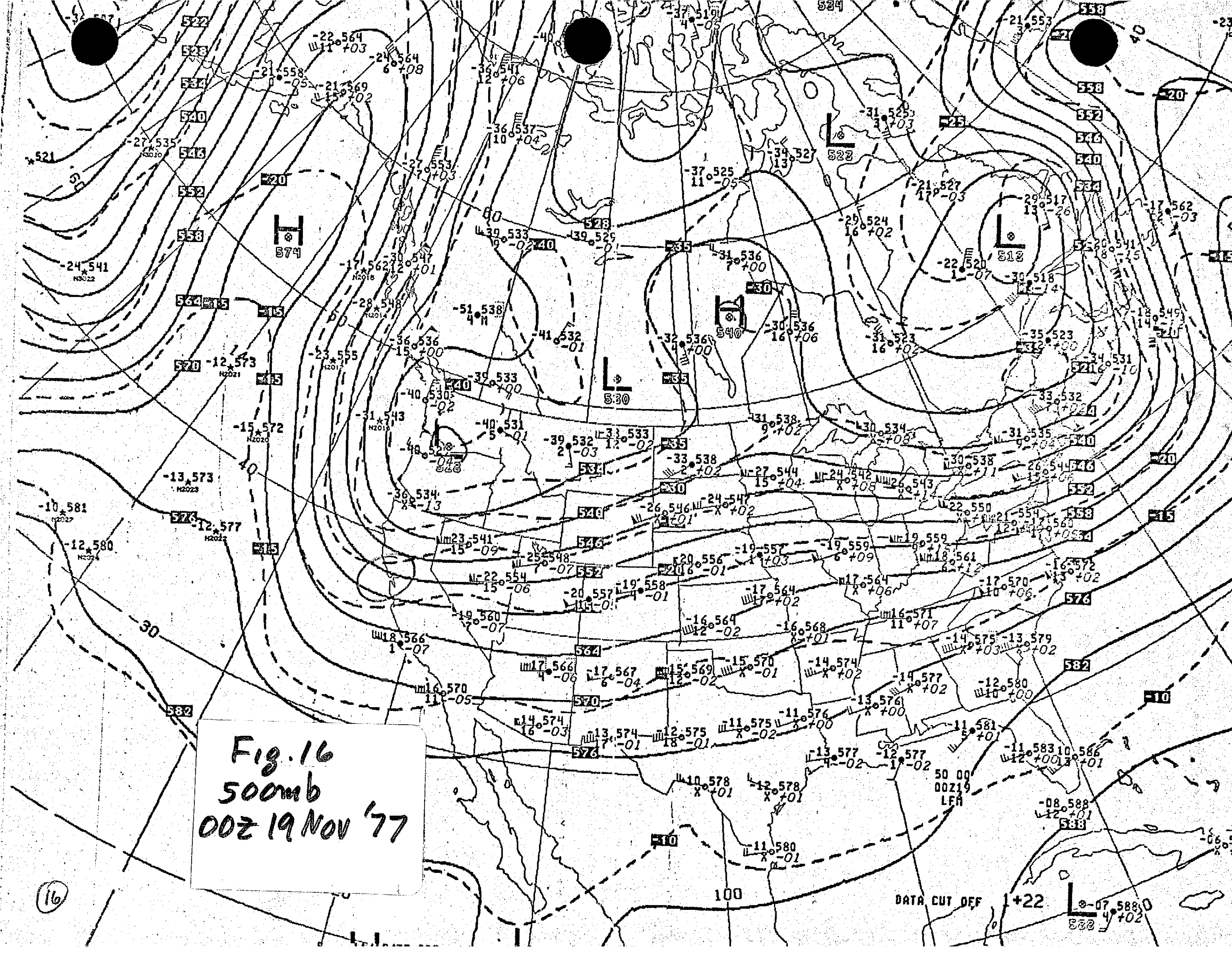


Fig. 16
500mb
00z 19 Nov '77

(16)

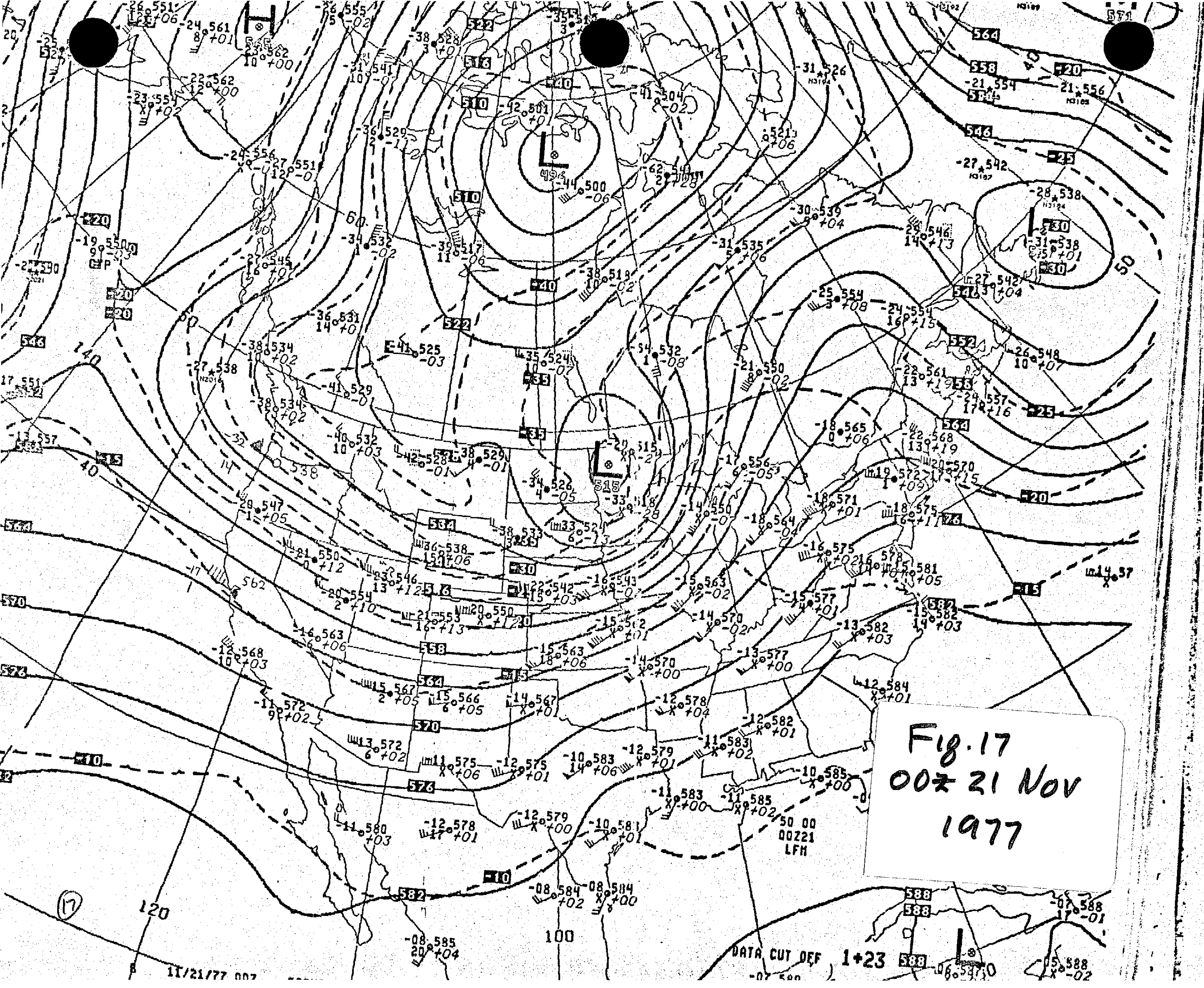


Fig. 17
00Z 21 Nov
1977

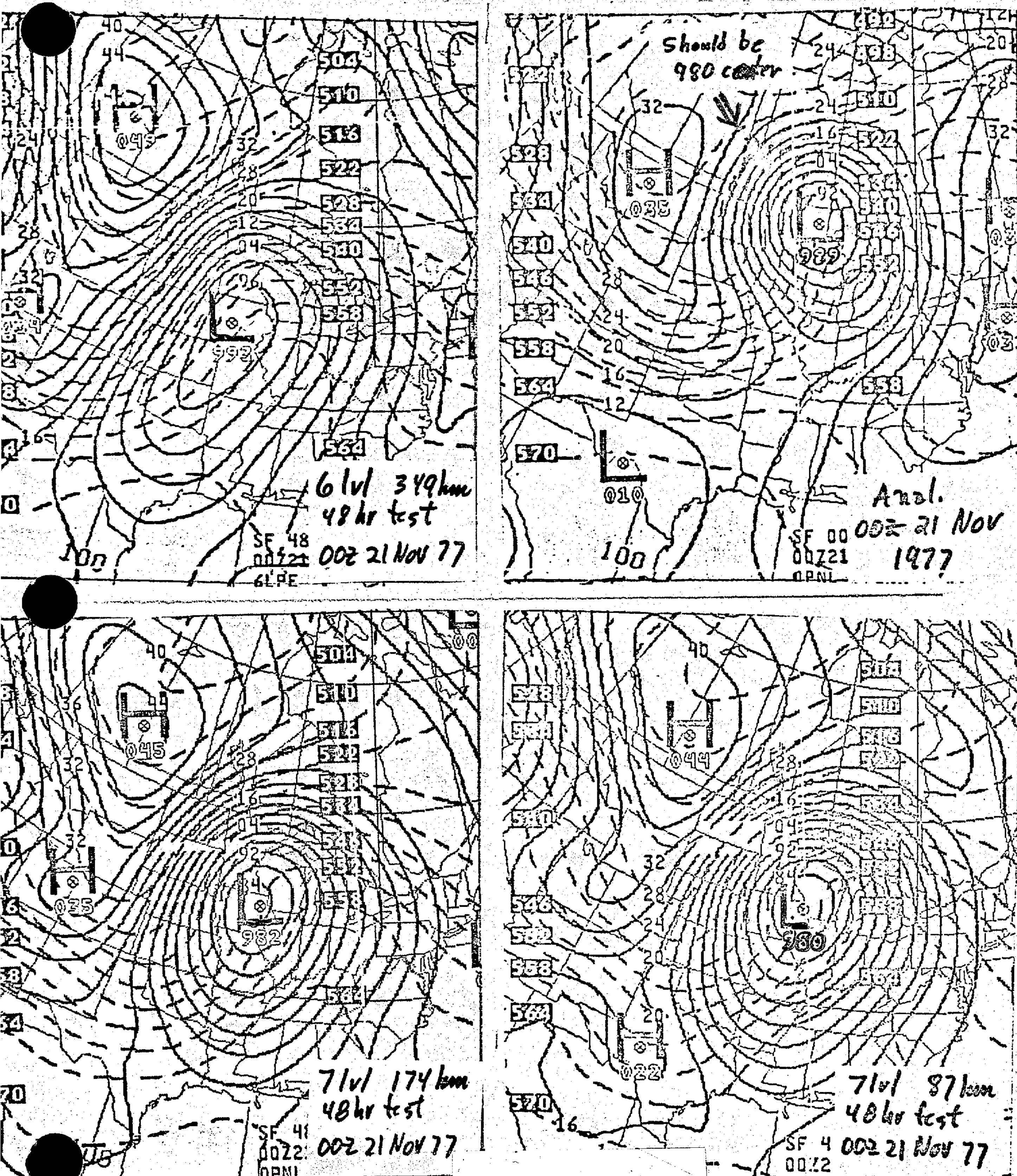

6 lvl 349 km
48 hr fcst
00Z 21 Nov 77
SF 48
6LPE
Should be 980 center
Anal.
00Z 21 Nov 1977
SF 00
OPNL
7 lvl 174 km
48 hr fcst
00Z 21 Nov 77
7 lvl 87 km
48 hr fcst
00Z 21 Nov 77

Fig. 18

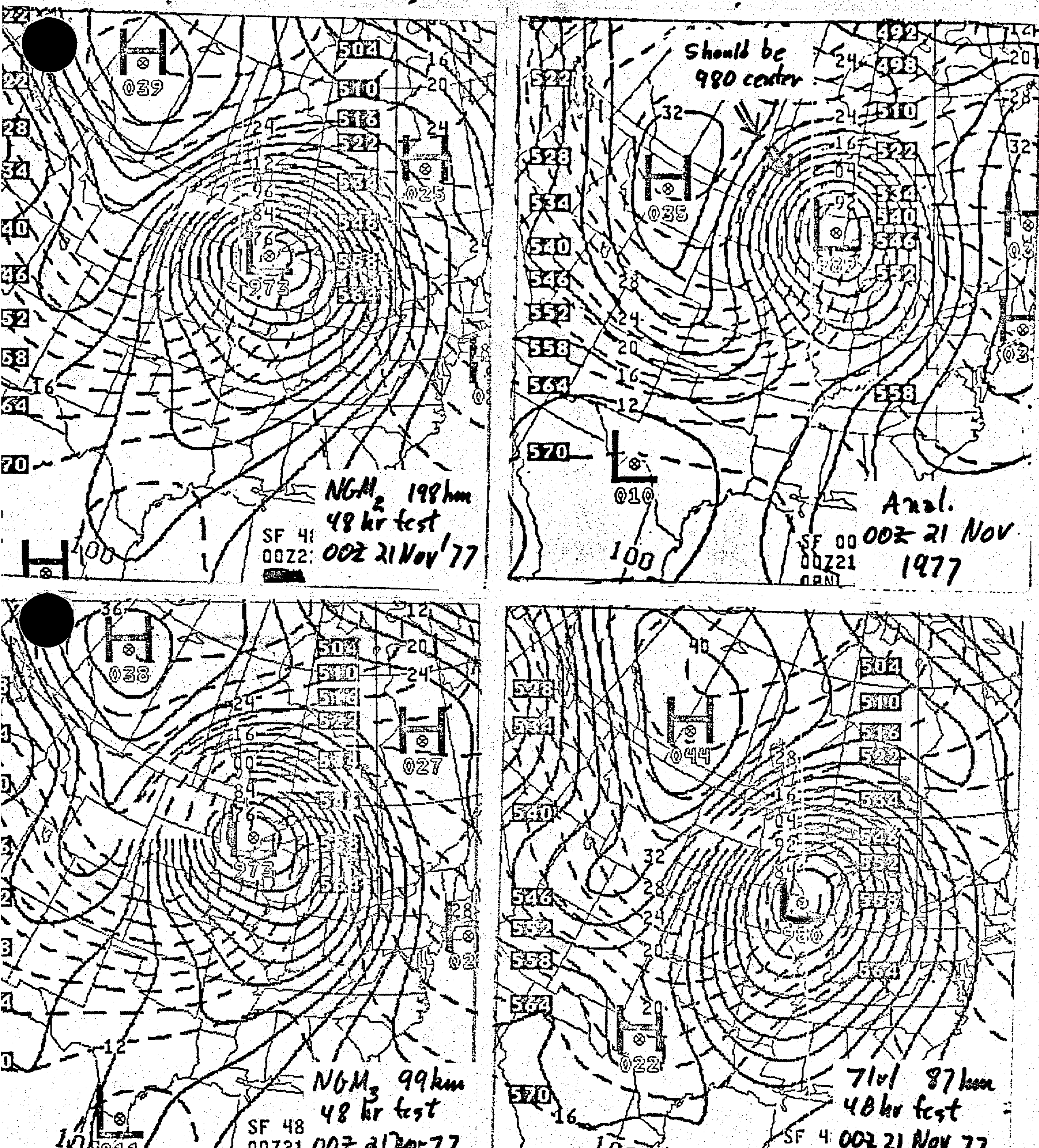

Should be 980 center
NGM2 198 km
48 hr fcst
00Z 21 Nov '77
Anal.
00Z 21 Nov
1977
NGM3 99 km
48 hr fcst
SF 48
00Z21
00Z 21 Nov 77
7 lvl 87 km
48 hr fcst
00Z 21 Nov 77

Fig. 19

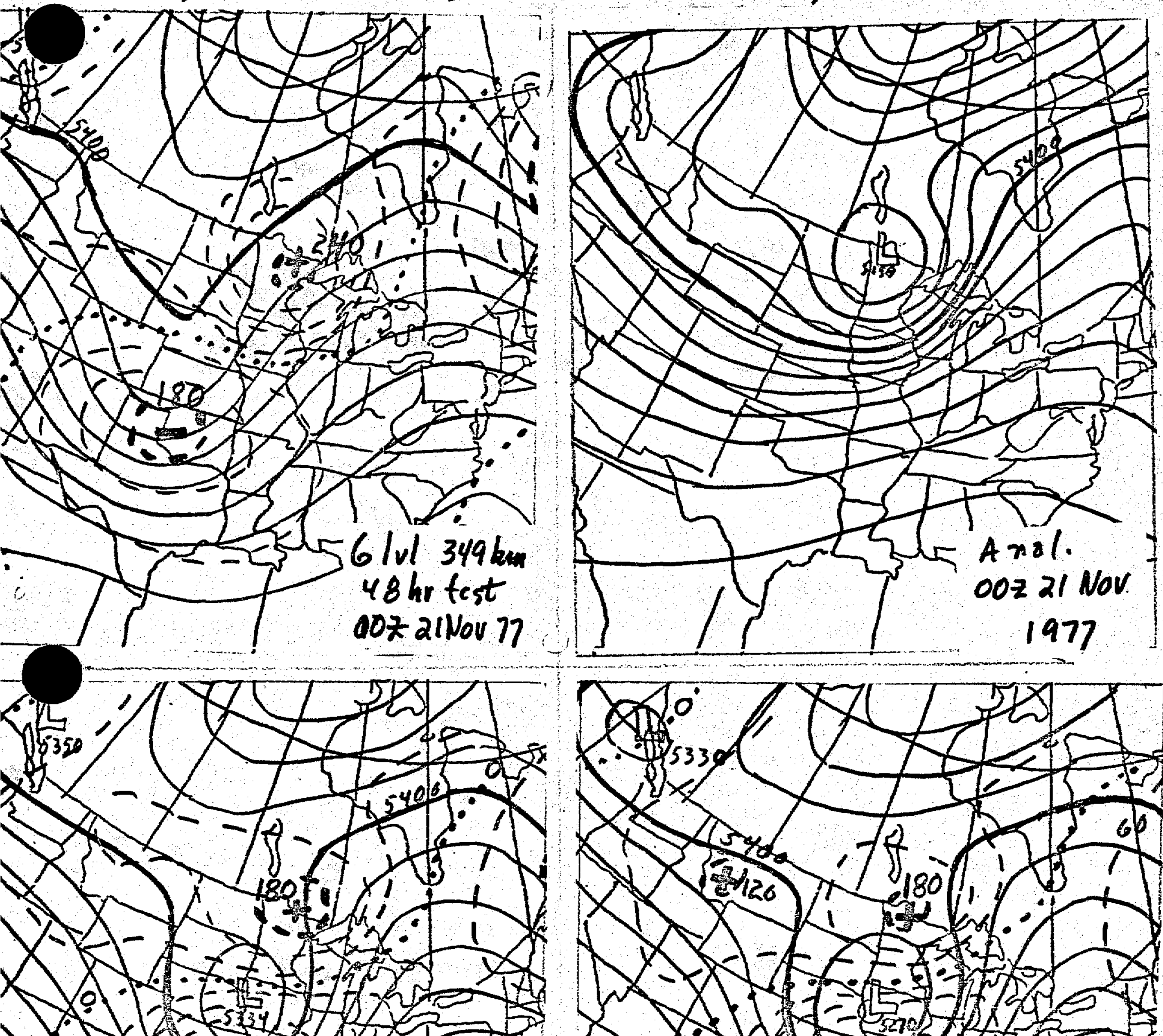

6 lvl 349 km
48 hr fcst
00Z 21Nov 77
5400
240
180
Anal.
00Z 21 NOV
1977
5400
7 lvl 174 km
48 hr fcst
00Z 21Nov 77
5350
5400
180
5334
7 lvl 87 km
48 hr fcst
00Z 21 Nov 77
5330
5400
126
180
60
300

Fig. 20

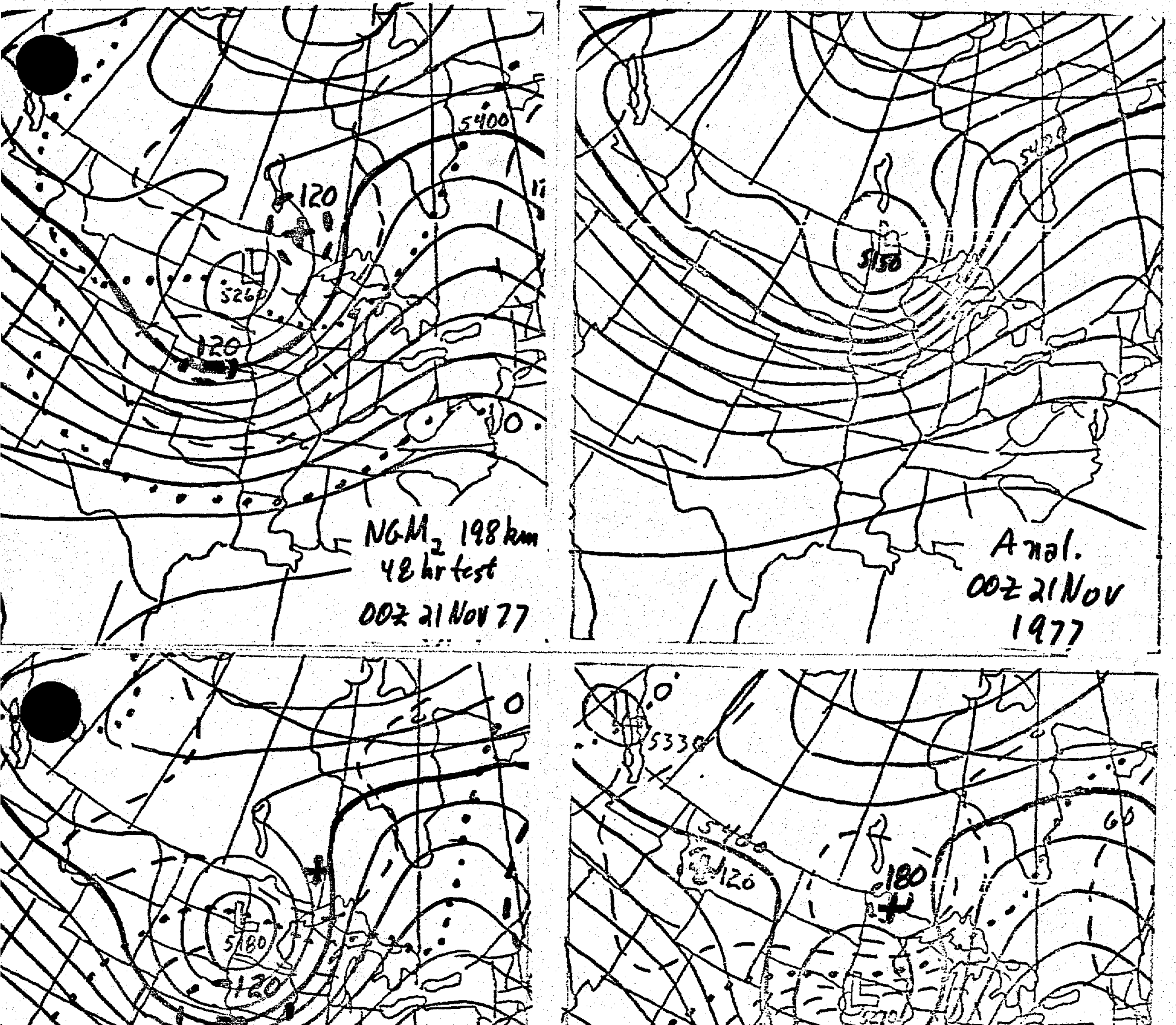
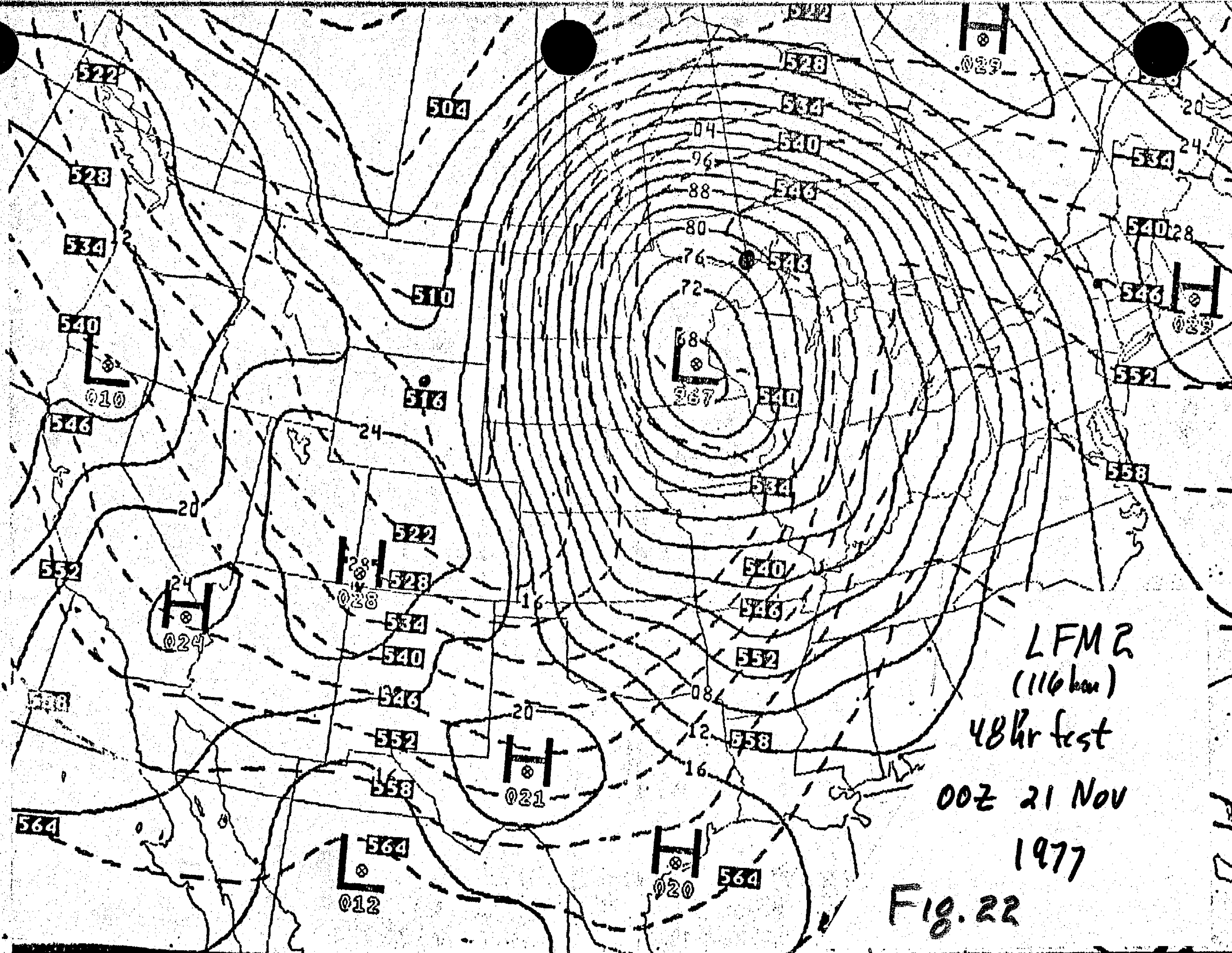

5400
120
5260
120
NGM2 198 km
48 hr fcst
00z 21 Nov 77
5400
5150
Anal.
00z 21 Nov
1977
5180
120
NGM3 99 km
48 hr fcst
00z 21 Nov 77
5330
5400
120
180
300
7 lvl 87 km
48 hr fcst
00z 21 Nov 77

Fig. 21



LFM 2
(116 km)
48 hr fcst
00Z 21 Nov
1977

Fig. 22

22

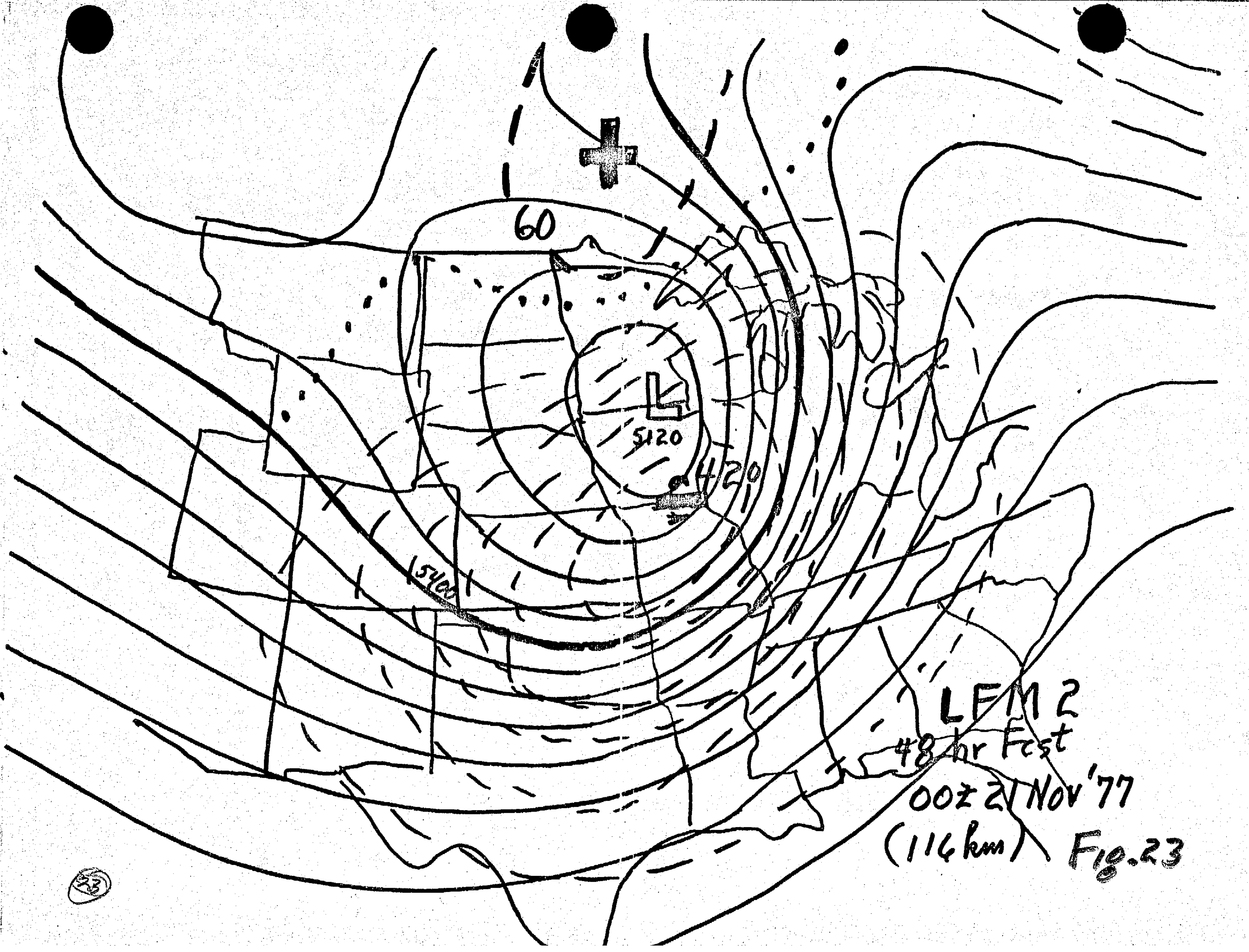


Fig. 23

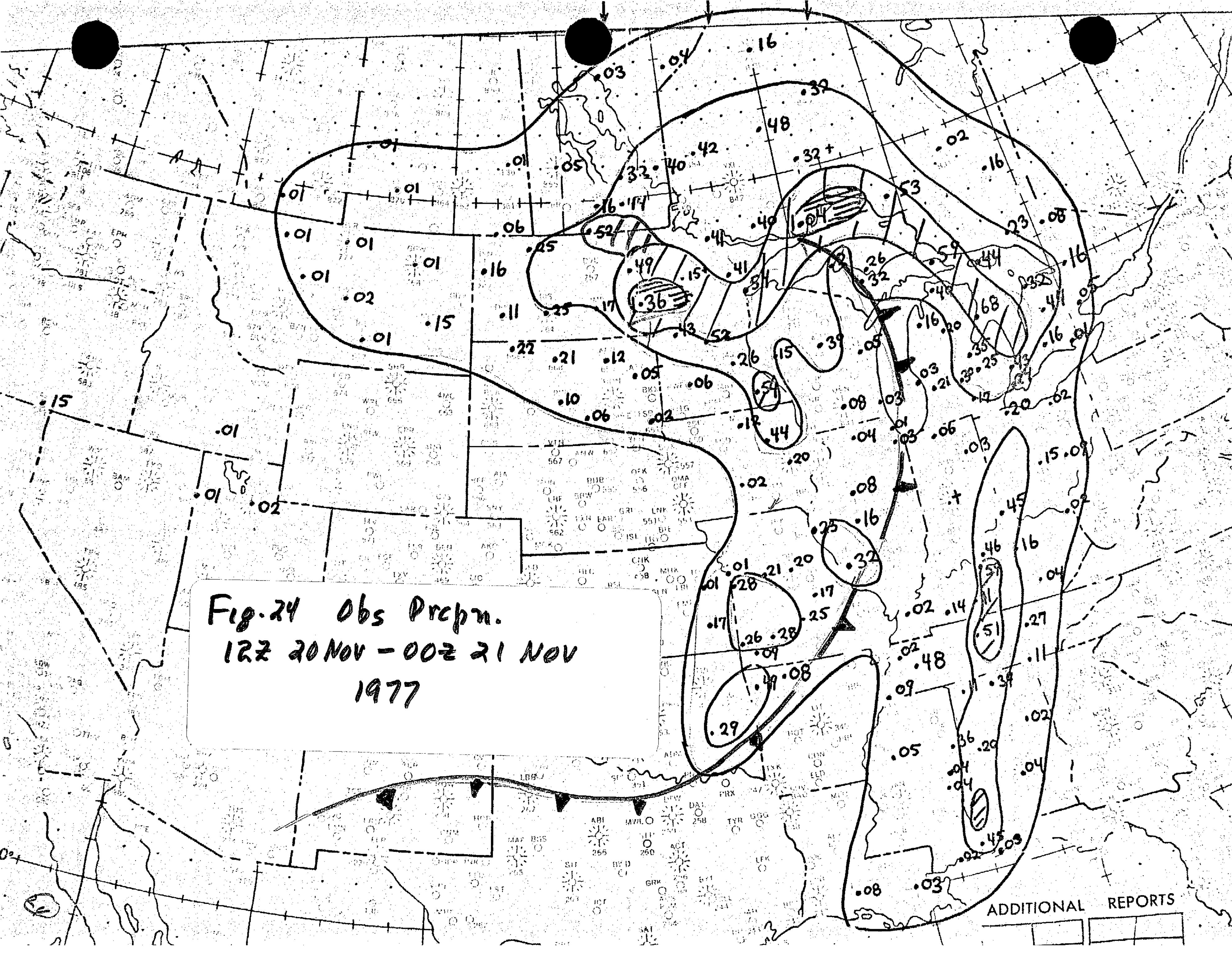


Fig. 24 Obs Prcpn.
12Z 20 Nov – 00Z 21 Nov
1977

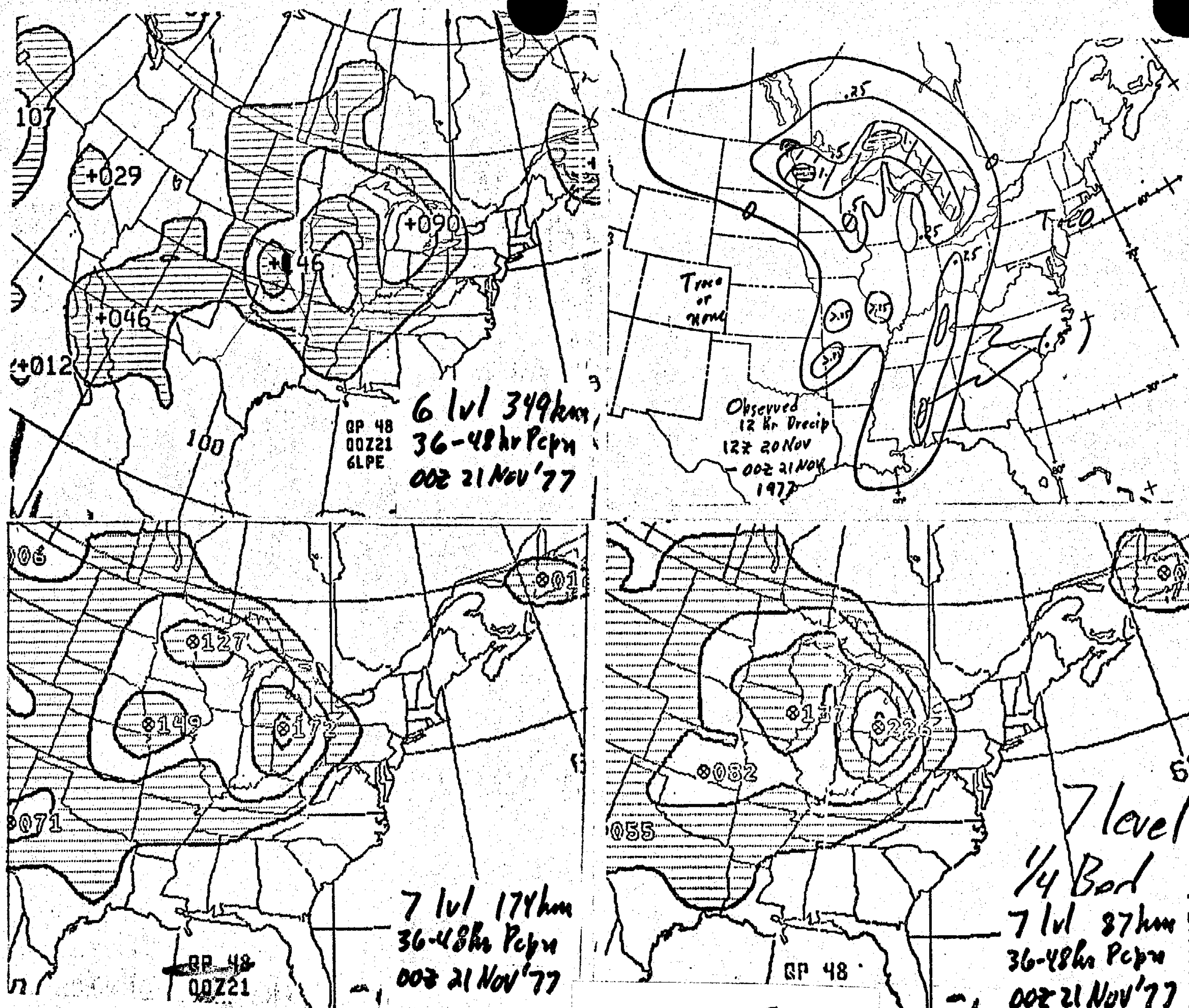

+029
+090
+046
+012
100
QP 48
00Z21
6LPE
6 lvl 349km
36-48hr Pcpn
00Z 21 Nov '77
Trace or none
Observed 12 hr Precip
12Z 20 Nov
- 00Z 21 Nov
1977
⊗127
⊗149
⊗172
071
QP 48
00Z21
7 lvl 174km
36-48hr Pcpn
00Z 21 Nov '77
⊗137
⊗226
⊗082
055
QP 48
7 level
1/4 Bod
7 lvl 87km
36-48hr Pcpn
00Z 21 Nov '77

Fig. 25

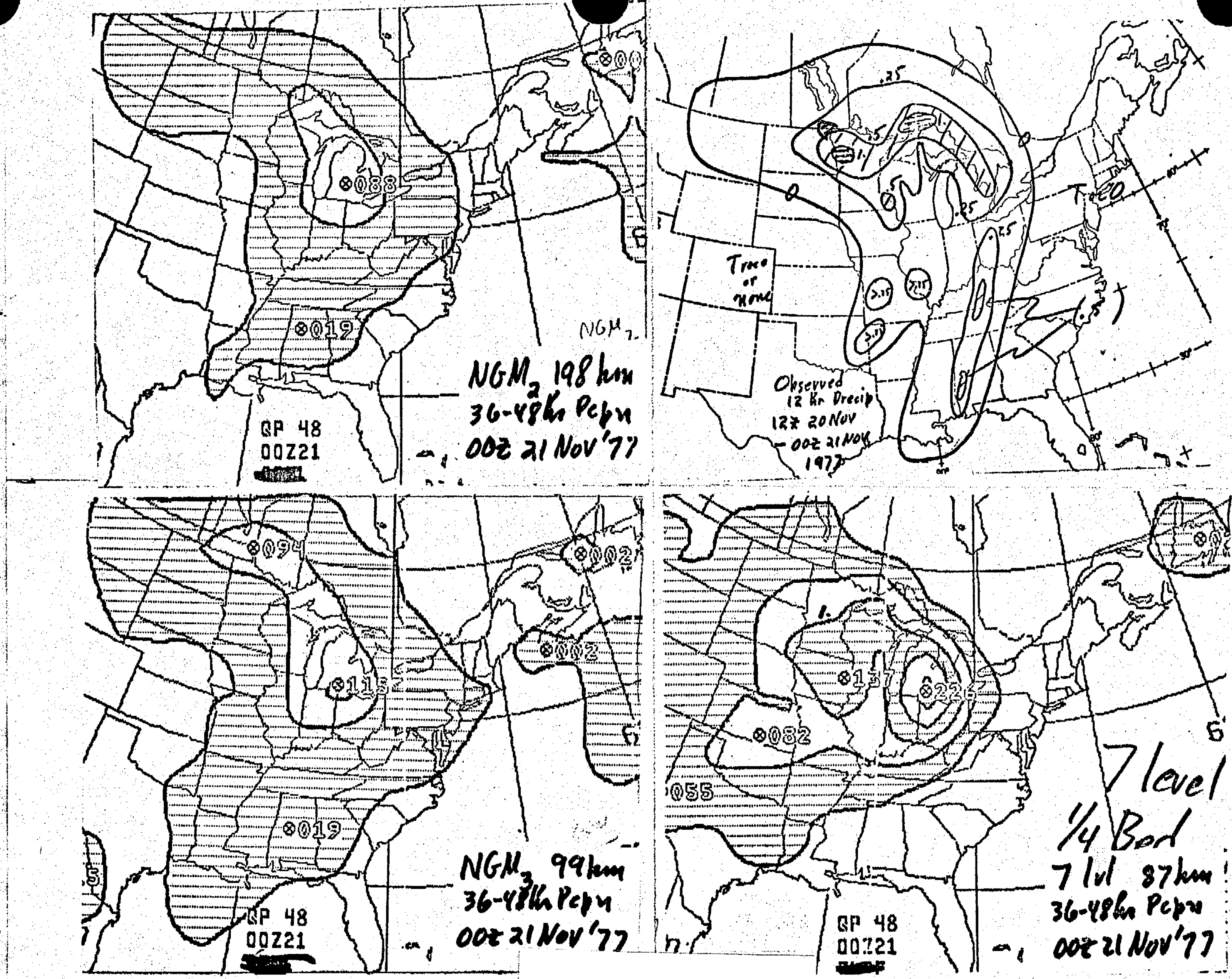

⊗088
⊗019
QP 48
00Z21
NGM2 198 km
36-48hr Pcpn
00z 21 Nov '77
Trace or none
.25
Observed 12 hr Precip
12z 20 Nov
- 00z 21 Nov
1977
⊗094
⊗002
⊗115
⊗002
⊗019
QP 48
00Z21
NGM3 99km
36-48hr Pcpn
00z 21 Nov '77
⊗137
⊗226
⊗082
055
QP 48
00Z21
7 level
7 lvl 87km
36-48hr Pcpn
00z 21 Nov '77

Fig. 26

6

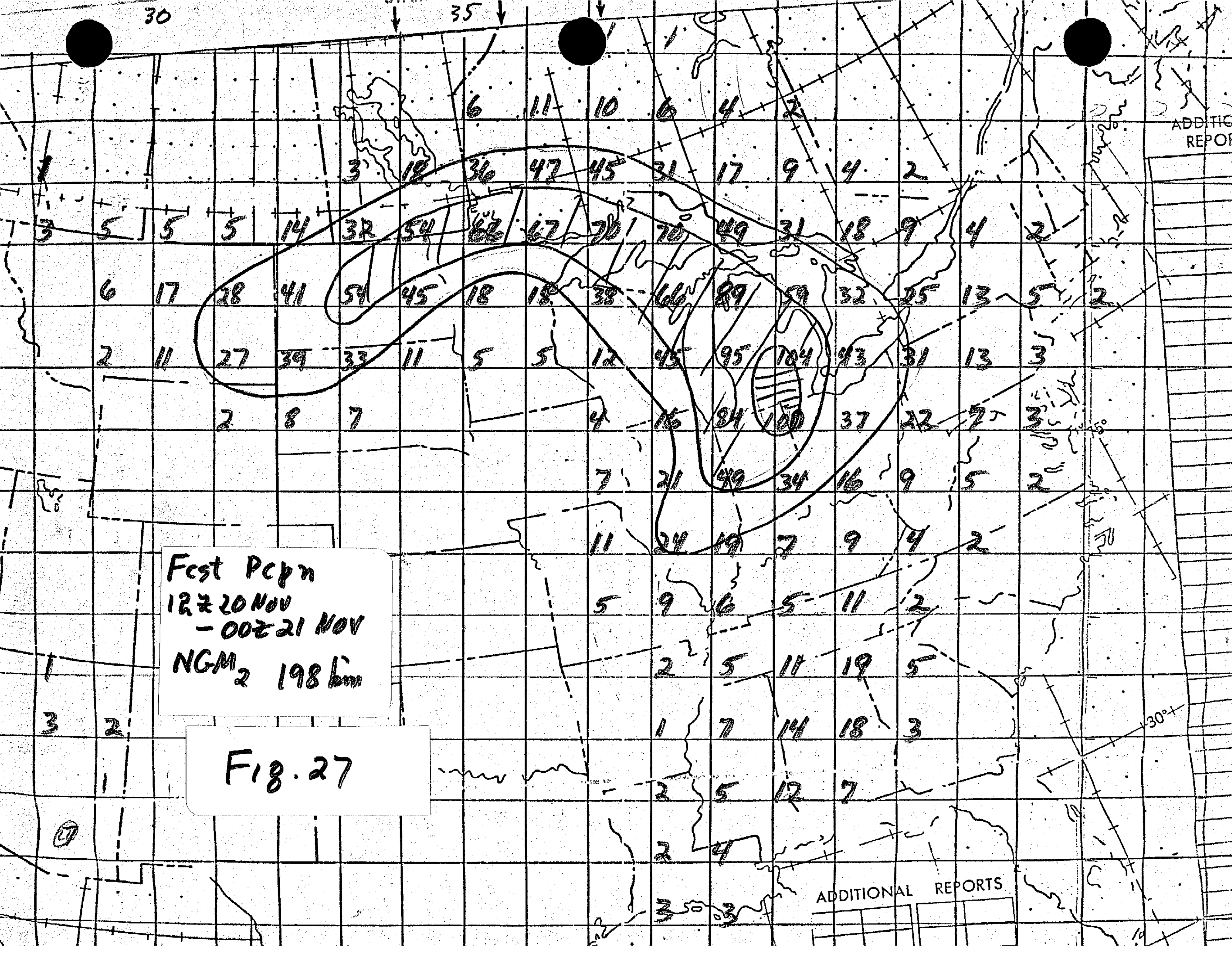

Fcst Pcpn
12Z 20 NOV
- 00Z 21 NOV
NGM2 198 km
ADDITIONAL REPORTS

Fig. 27

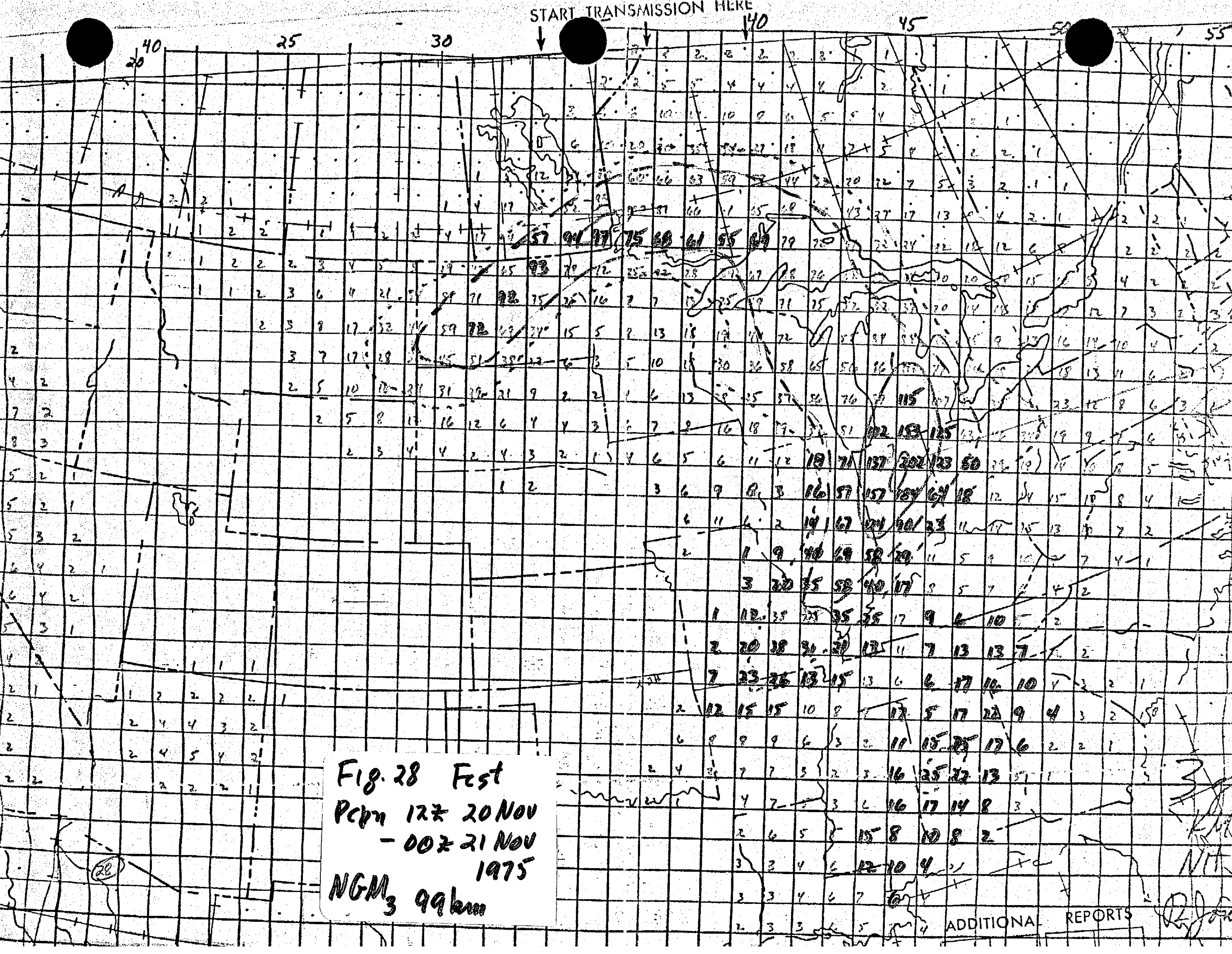
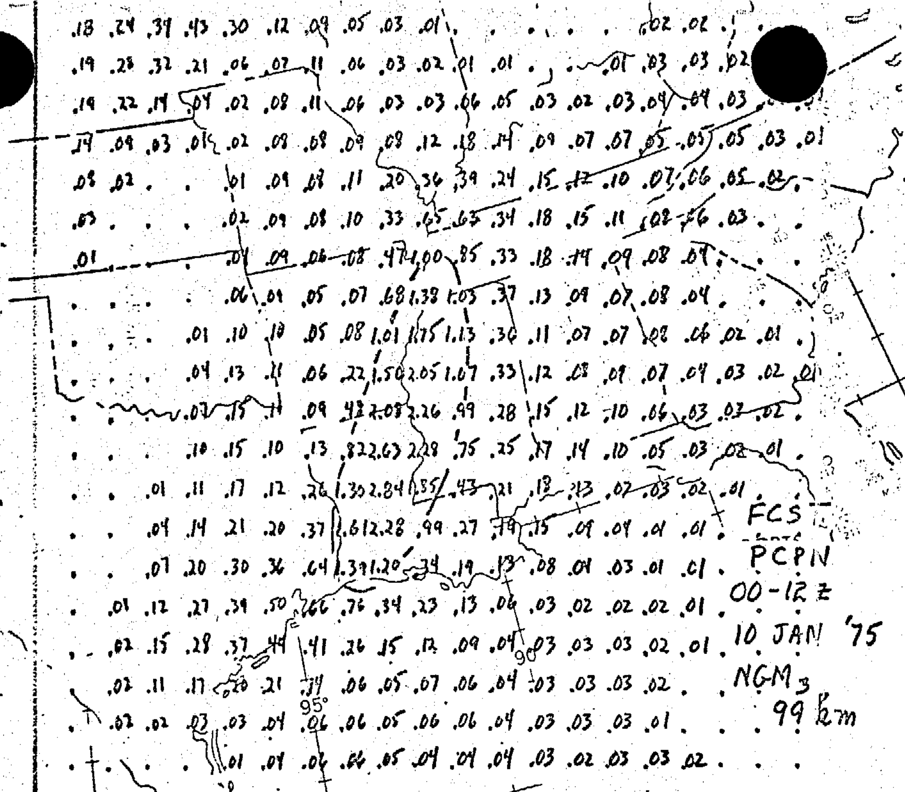
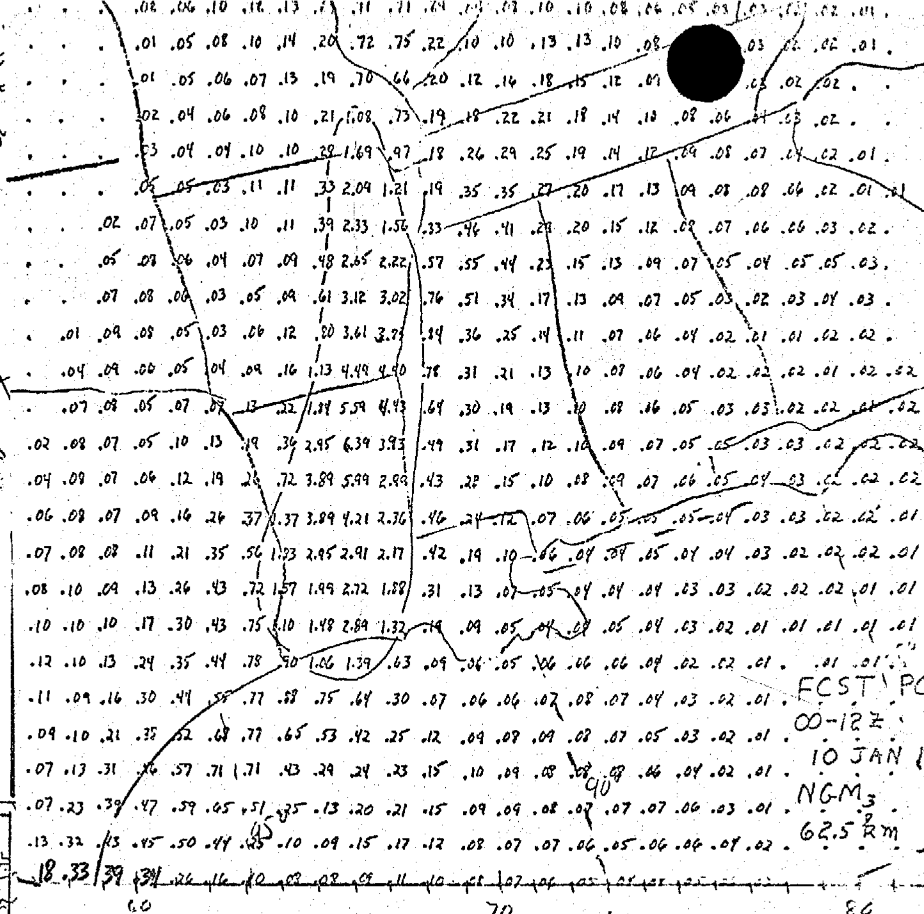
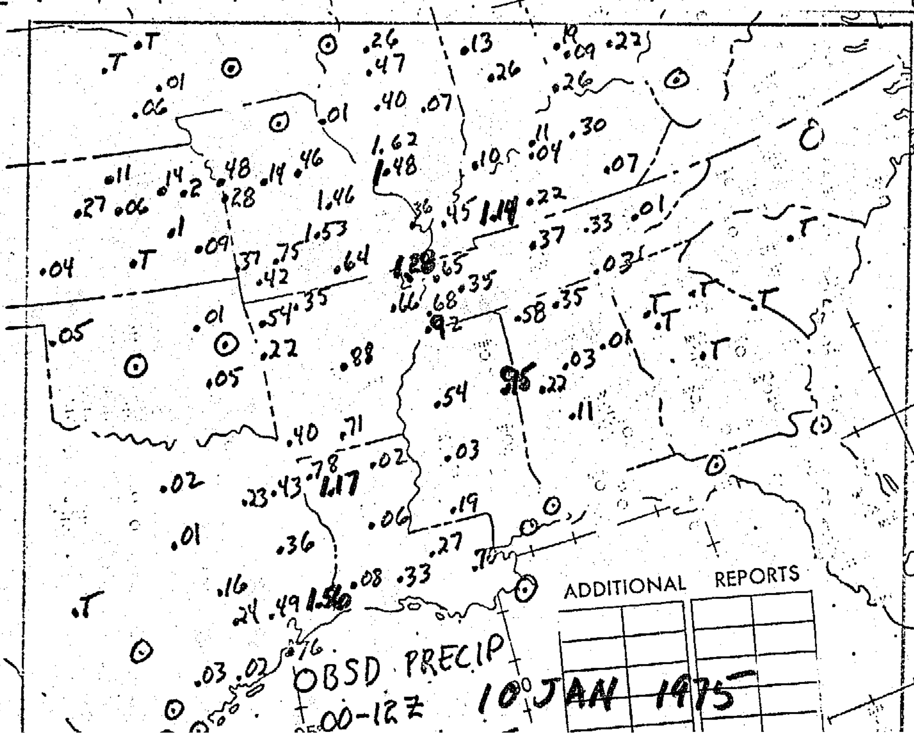


Fig. 28 Fcst Pcpn 12Z 20 Nov - 00Z 21 Nov 1975 NGM$_3$ 99km







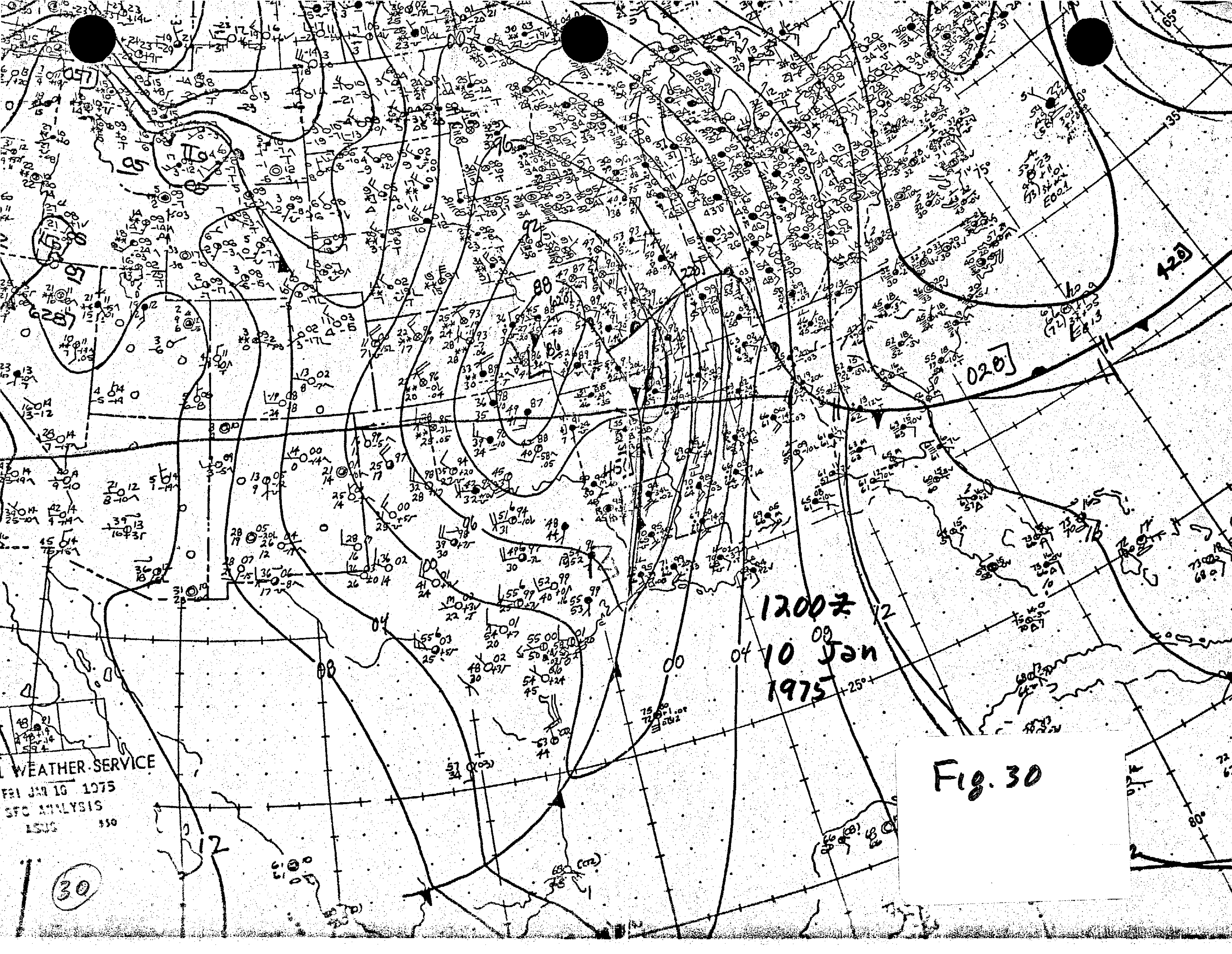
↑ Fig 29 ↗

99 km 62.5 km

Pcpn 00-12Z

10 Jan '75

← OBSD


WEATHER SERVICE
FRI JAN 10 1975
SFC ANALYSIS
1200Z
10 Jan
1975
Fig. 30
30

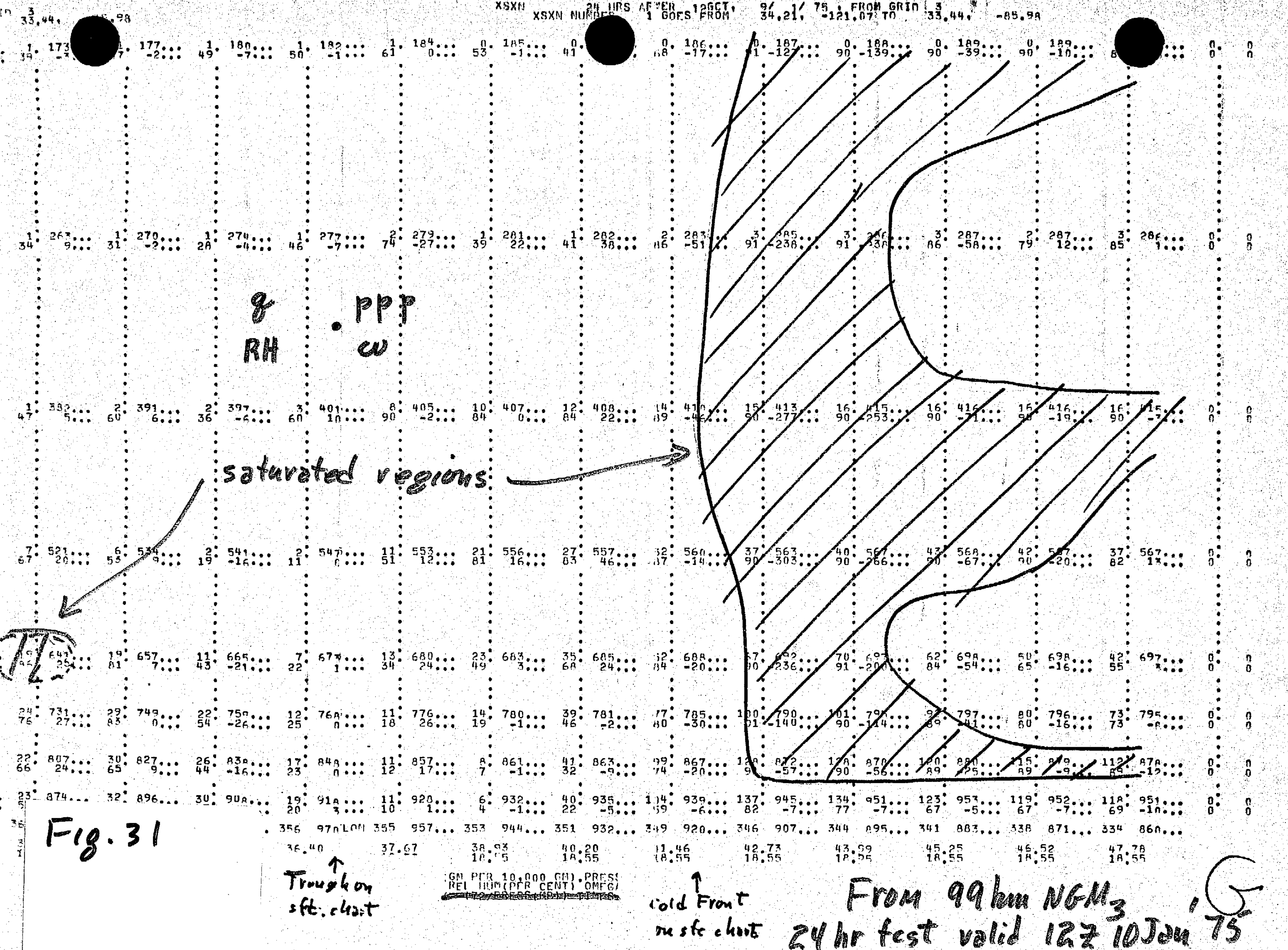
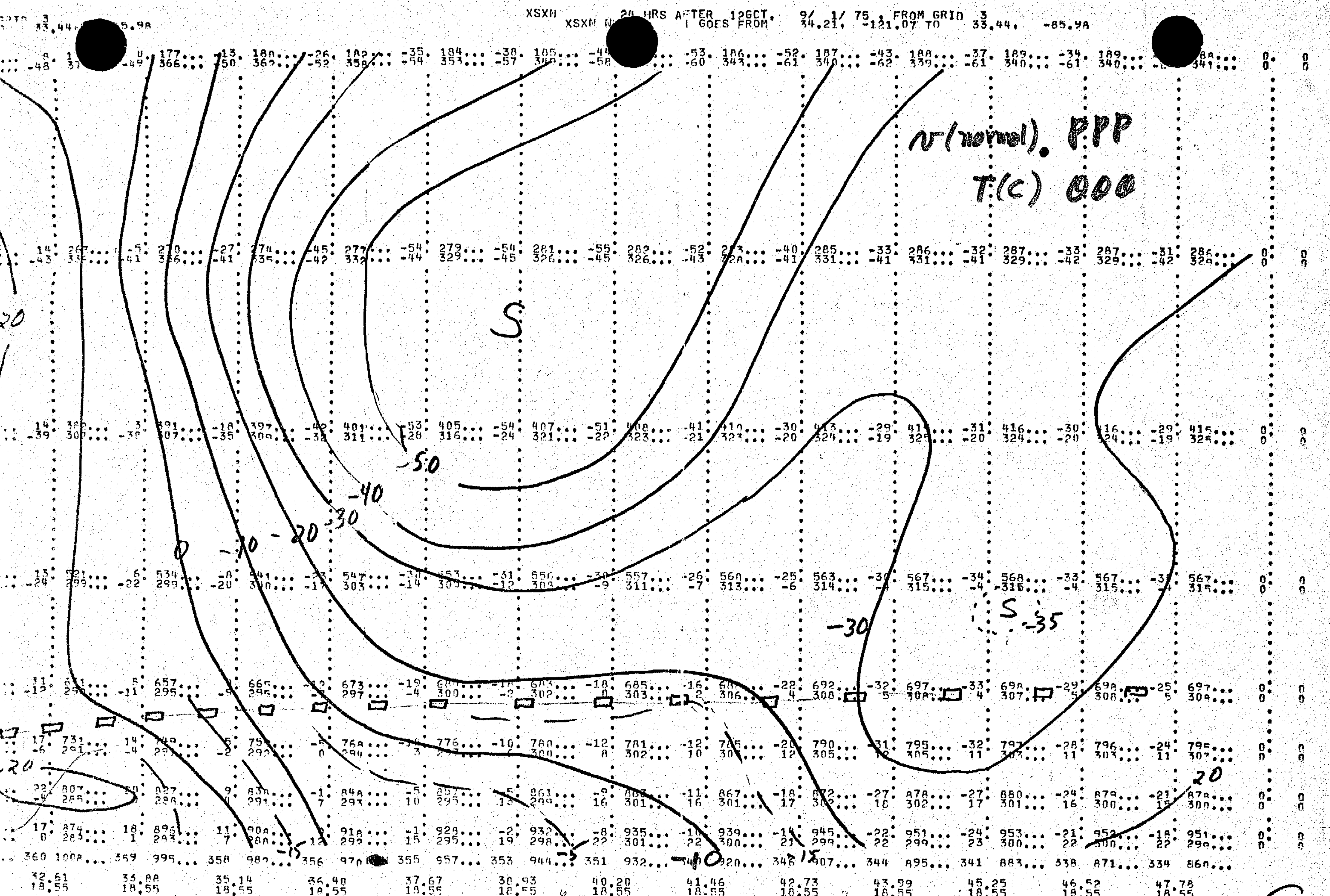


Fig. 31

From 99 km NGM3
24 hr fcst valid 12Z 10Jan 75



▭ ▭ ≡
700 mb sfc

↑ Trough on sfc chart

Fig. 32

↑ Cold Front on sfc chart

From 99 km NGM$_3$
24 hr fcst valid 12Z 10 Jan 75

(32)

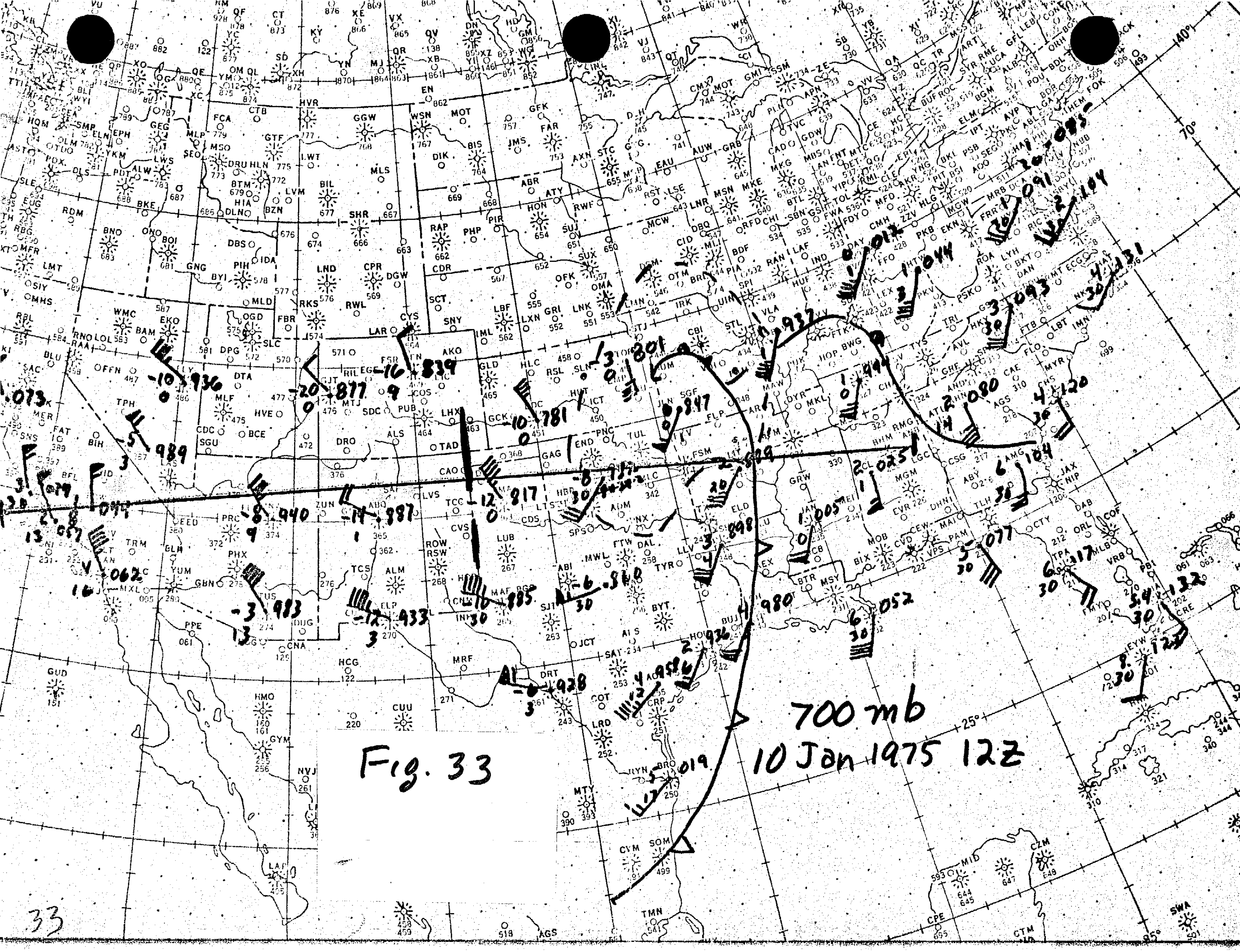


Fig. 33

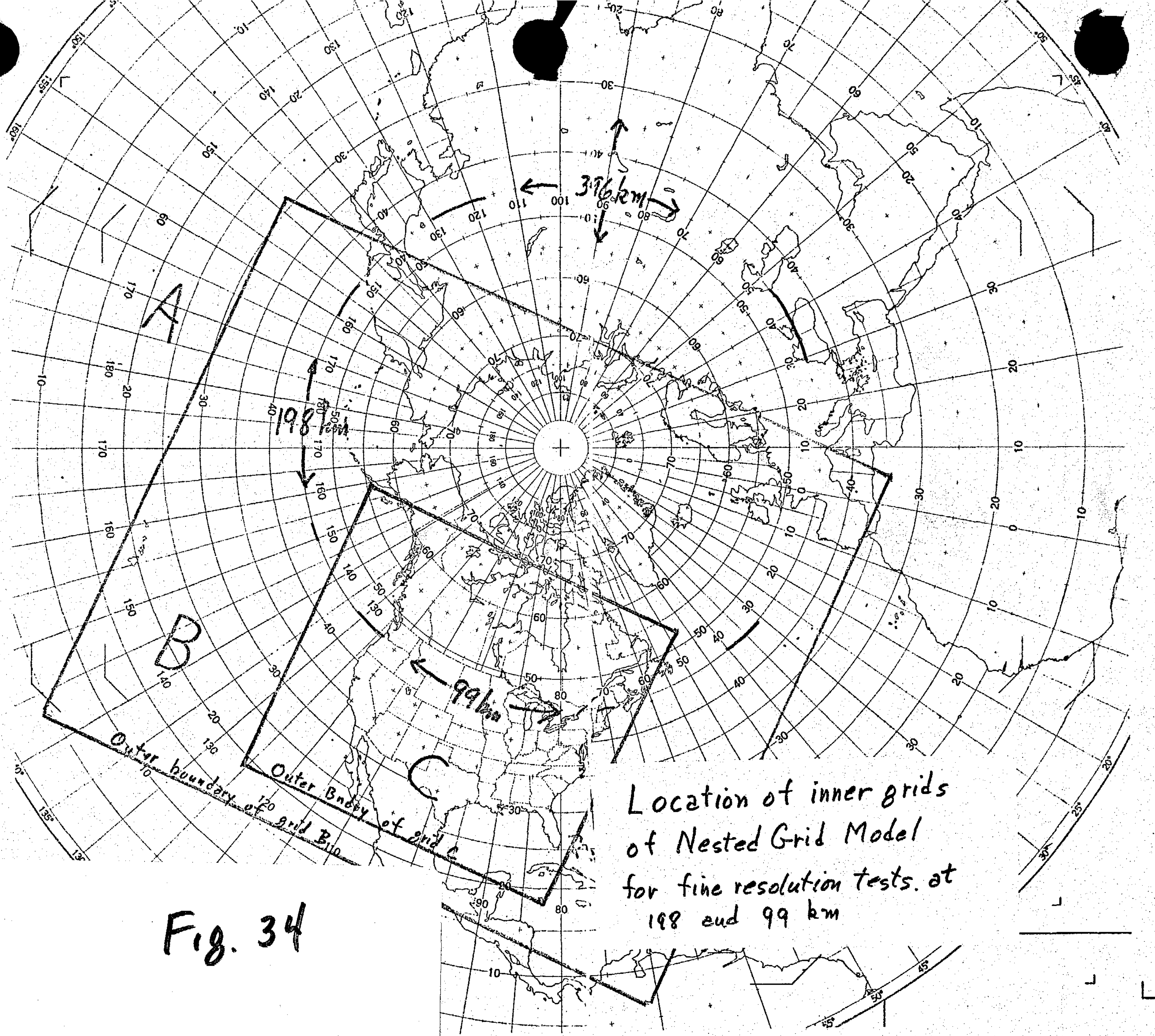


Fig. 34

Location of inner grids of Nested Grid Model for fine resolution tests at 198 and 99 km