(NASA-TM-85042) A STUDY OF THE INFLUENCE OF SOIL MOISTURE ON FUTURE PRECIPITATION (NASA) 130 p HC A07/MF A01 CSCL 04B
N83-28825
Unclas
G3/47 28018

NASA

Technical Memorandum 85042

A Study of the Influence of Soil Moisture on Future Precipitation

M. J. Fennessy and Y.C. Sud

May 1983

Laboratory for Atmospheric Sciences
Global Modeling and Simulation Branch

National Aeronautics and
Space Administration

Goddard Space Flight Center
Greenbelt, Maryland 20771

NASA Technical Memorandum 85042

A Study of the Influence of Soil Moisture on Future Precipitation

M. J. Fennessy and Y. C. Sud

May 1983

Laboratory for Atmospheric Science
Modeling and Simulation Branch

NASA/Goddard Space Flight Center
Greenbelt, MD 20771

Table of Contents

PART I: HYDROLOGICALLY DERIVED SOIL MOISTURE

ABSTRACT

Forty years of precipitation and surface temperature data observed over 261 Local Climatic Data (LCD) stations in the Continental United States was utilized in a ground hydrology model to yield soil moisture time series at each station. Using Thornthwaite's (1948) empirical functions to calculate potential evapotranspiration and Nappo's (1975) moisture availability function to then calculate actual evapotranspiration, a month-by-month soil moisture dataset was constructed for each year. The data was averaged to obtain forty year mean fields. The forty year monthly mean soil moisture field shows a marked seasonal cycle across most of the country, with driest conditions ocurring in September. The calculated soil moisture is close to the saturation limit throughout the winter months.

1) Introduction

Several papers have mentioned the role of soil moisture as an important boundary forcing parameter influencing the seasonal mean circulation and convective precipitation (eg. Sutcliffe, 1956, Namias, 1959 Schickendanz, 1976). Some recent investigations with General circulation models have been carried out to study the influence of soil moisture on precipitation and climate (e.g. Walker and Rowntree (1977), Shukla and Mintz (1982), Miakoda et al. (1979)). However, to date there has been no systematic direct measurement of soil moisture as a meteorological variable. Therefore researchers have either created their own soil moisture fields via hydrological models (e.g. Mintz and Serafini, 1983), or inferred soil moisture values from satellite data (e.g. Soer, 1980, Schmugge et al., 1980). The authors themselves faced this problem in the following study of the influence of soil moisture on ensuing precipitation. For this purpose, observed monthly mean surface temperature and precipitation data supplied by the National Climate Center (NCC) was used in a ground water balance model to calculate soil moisture time series at each of the 261 local climatic data (LCD) stations across the contiguous 48 states in the United States. The mean fields resulting from this calculation are approximately representative of climatic normals.

Forty year monthly means and standard deviations of temperature, precipitation and soil moisture over 261 NCC LCD stations are presented on U.S. maps as well as in tabular form on microfiche. The raw data utilized is described in section 2, and the surface water balance model used to derive the soil moisture from the temperature and precipitation fields is described in section 3.

2) Data

Monthly Local Climatic Data (LCD) consisting of precipitation and surface temperature fields, from 261 stations over the contiguous 48 states in the U.S. was obtained from the National Climatic Center (NCC) in Asheville, North Carolina. These monthly means were tabulated from actual data collected at hourly or three hour intervals. The data cover a period of 40 years (1940-1980). Incomplete data years at any given station were ignored as opposed to filling in the data by interpolation. Table 1 shows the station names, sequence numbers, WBAN identification numbers and station altitudes. The sequence numbers are shown in Fig. 1 to aid in locating the stations on the plots. Fig. 2 shows the number of complete data years (maximum of forty) at each station.

Means and standard deviations of temperature and precipitation were calculated at each station for all complete data years. These fields are shown plotted on U.S. maps in figures (3a,b) and (4a,b) as well as in tabular form on the microfiche inside the back cover.

3) Calculation

a. Determination of evapotranspiration:

In order to determine the evapotranspiration a ground water balance model similar to that employed by Mintz and Serafini (1982) was used. While this model is a simple representation of the extremely complicated processes of evapotranspiration on land covered by a variety of vegetation, it was considered adequate to reproduce the first order soil moisture from the temperature and precipitation fields. Since the model employs a moisture availability parameter based on observations over grass covered land, (Davies and Allen, 1973) the calculation may be somewhat inadequate for dense forests. We expect it to be more accurate for drier regions with sparse vegetation. For a justification of the use of this β-curve for all types of vegetation cover, see Sud and Fennessy (1982).

The potential evapotranspiration, Ep at each station was calculated by Thornthwaite's (1948) method, which was derived from observations of water use in irrigated regions. The method yields Ep as a function of surface temperature, Ts, time of the year and latitude. The influence of different climatic regions on evapotranspiration is taken into account by introducing a yearly mean surface temperature parameter. The empirical relations are as follows:

(i) For Ts > 26.5°C (See Willmott, 1977), the following relation is used:

$$Ep = a + b\,Ts + c\,Ts^2 \qquad (1)$$

where $a = -415.8547$

$b = 32.2441$

$c = 0.4325$

(ii) For Ts < 26.5°C (Thornthwaite, 1948), the formulation is as follows:

$$Ep = 16\,(10Ts/H)^k \qquad (2a)$$

Here

$$H = \sum_{i=1}^{12} (Tsi/5)^{1.514} \qquad (2b)$$

and $k = a' + b'H + c'H^2 + d'H^3$.

where $a' = 0.49239$

$b' = 17.92 \times 10^{-3}$

$c' = -7.71 \times 10^{-5}$

$d' = 6.75 \times 10^{-7}$

(iii) For $Ts < 0°C$

$$Ep \equiv 0. \quad (3)$$

Equations (1) thru (3) yield potential evapotranspiration as a function of surface temperature for different surface temperature conditions. The heat index, H, accounts for differences in evapotranspiration in different climatic zones. Clearly it is a function of mean annual surface temperature. At 26.5°C, the potential evapotranspiration can be determined by either (1) or (2). Obviously the relations are incompatible at this boundary. However, this incompatibility introduces only a small error. In an example equation (1) yields Ep = 4.50 mm/day and equation (2) yields Ep between 4.44 mm/day and 4.60 mm/day depending upon whether Ts was 26.5°C averaged over the year or 26.5°C during the month in question and 0°C for the rest of the eleven months.

Ep is corrected for the days in the month, D, and number of daylight hours, L, in the following way

$$Ep_c = Ep \left(\frac{D}{30}\right) \left(\frac{L}{12}\right) \quad (4)$$

The actual evapotranspiration, E is then obtained by multiplying Ep_c by Nappo's (1975) moisture availability function, M as adopted by Mintz and Serafini (1983). The set of equations are:

$$E = M\ Ep \quad (5)$$

$$M = [\ 1 - e^{-\frac{aw}{w^*}}] \quad (6)$$

Here a is an experimentally determined constant. Its value was set at 6.80. w is the actual soil moisture in mm. The saturation field capacity, w*, was assumed to be identically equal to 150 mm over all land irrespective of soil type or vegetation cover.

ORIGINAL PAGE IS
OF POOR QUALITY

b. <u>Determination of soil moisture</u>:

Neglecting all water transport within the soil, the soil moisture tendency equation is:

$$\frac{\partial w}{\partial t} = P - E \tag{7}$$

where P represents the precipitation rate.

Substituting from (5) and (6) we get

$$\frac{\partial w}{\partial t} = P - [\ 1 - e^{-aw/w^*}\ ]\ Ep_c \tag{8}$$

Obviously (11) is non-linear in w.

It was solved by numerical integration using time steps of one day. In order to avoid precipitation input from the next month, the mean monthly precipitation and surface temperature values were assumed to be constant for the entire month. Correspondingly Ep_c was also calculated from (4) and held constant for each month. The soil moisture, w^{n+1} on day n+1 was obtained from its value w^n on day n by a two step predictor-corrector technique:

$$w^{n+1} = w^n + \frac{dw^n}{dt}\,\Delta t \tag{9}$$

and then,

$$w^{n+1} = w^n + \frac{1}{2}\left[\frac{dw^n}{dt} + \frac{dw^{n+1}}{dt}\right]\Delta t \tag{10}$$

This calculation is fairly accurate for small time steps. The limiting constraint, $w^{n+1} \leq w^*$, was invoked after each time step. In other words if w^{n+1} exceeds w^* at any time, the difference is used to produce runoff. The soil moisture time series was obtained by the above described calculation for each station. For each year the integration was always started from the equilibrium soil moisture on January 1 obtained separately by cyclically integrating the forty year mean monthly data. This avoids complications arising from years with missing data and eliminates the build-up of any systematic errors in the calculations.

The mean monthly soil moisture values and the corresponding standard deviations were calculated from the time series at each station. Plots of these fields are shown in Figure sets (5a) and (5b) respectively. In addition, these values are tabulated by month and station on the microfiche appended at the end of this report.

Discussion

The 40 year mean monthly surface temperature fields are shown in Fig. 3a. The seasonal cycle is clearly depicted in these maps with July being the hottest month. The calculated potential evapotranspiration field (not shown) also reached its maximum in July. The standard deviations of surface temperature (Fig. 3b) were found to be larger inland and during the winter months, as would be expected.

The monthly precipitation fields (Fig. 4a) also agreed well with the known climatology. The standard deviations of precipitation (Fig. 4b) were of the same order as the field itself. The monthly mean temperature and precipitation fields are presented in this report because the soil moisture time series was derived from their time series. The mean soil moisture fraction field shows a distinct seasonal cycle across the contiguous 48 states.

During winter there are two regions with large soil moisture gradients. The mid and northern parts of the west coast are completely satuarted, as is is the majority of the country east of 95°W. However, the region between 115°W and 100°W is quite dry. The strongest gradients lie in the 100°W to 95°W region.

As spring progresses these gradients tend to spread out, with the entire country generally drying. By May very few stations across the country remain saturated.

By late summer the soil moisture has generally reached its driest limit across the U.S. During September the entire country west of 105°W is extremely dry with soil moisture fractional values below 0.1. The rest of the country is also quite dry, with Florida being the only region with values above 0.5.

As fall progresses into winter a gradual increase in wetness is noted. The eastern U.S. again becomes quite wet as does the northwest coast. By December the strong gradient regions are similar to those noted in January.

Overall, the mean of the constructed soil moisture time series seems reasonable, with a strong seasonal cycle, although verification is difficult due to the lack of extensive soil moisture observations. There are considerable interannual variations in the soil moisture field, with standard deviations around half the magnitude of the soil moisture itself. However, this variation is not quite as large as that in the precipitation field, due to the cumulative nature of the soil moisture parameter.

The constructed soil moisture field should be regarded as a first order approximation, because a lot of physical details of the soil moisture and evapotranspiration calculations have been circumvented. In particular, the choice of a single value for the maximum available soil moisture (150 mm) and the neglect of soil characteristics can be questioned. The use of Thornthwaite's empirical formulation for potential evapotranspiration over all types of land regardless of vegetation cover is a major simplification and is a weak link of the system. We followed this approach because no apparent better alternative was available. Nevertheless, the authors believe that the constructed fields of soil moisture are suitable as a first order approximation.

REFERENCES

Davies, J. A. and C. D. Allen, 1973: Equilibrium, potential and acutal evaporation from cropped surfaces in southern Ontario. J. Appl. Meteor., 12, 649-657.

Mintz, Y. and V. Serafini, 1983: Monthly normal global fields of soil moisture and land surface evaporation. (To be published).

Miyakoda, K., G. D. Hambree, and R. F. Strickler, 1979: Cumulative results of extended forecast experiments II: Model performances for summer months. Mon. Wea. Rev., 107, 395-420.

Namais, J., 1959: Persistence of mid-tropospheric circulation between adjacent months and seasons in The Atmosphere and the Sea in Motion. Rossby Memorial Volume, ed. B. Bolin, 240-248.

Nappo, C. T. Jr., 1975: Parameterization of surface moisture and evaporation rate in a planetary boundary layer model. J. Appl. Met., 14, 289-296.

Schickendanz, 1976: Effect of irrigation on precipitation in Great Plains. Final report on an investigation of potential alteration in summer rainfall associated with wider spread irrigation in Great Plains. Univ. of Illinois. Urbana, Illinois. Nov. 1976.

Schumgge, T. J., T. J. Jackson and H. L. McKim 1980: Survey of Methods for soil moisture determination. Water Resources Research, 16, 961-979.

Shukla, J. and Y. Mintz, 1982: The influence of land surface evapotranspiration on earth's climate. Science, 215, 1498-1501.

Soer, G. J. R. 1980: Estimation of regional evapotranspiration and soil moisture conditions using remotely sensed crop surface temperature. Remote Sens. Environment, 9, 27-45.

Sud, Y. C. and M. J. Fennessy 1982: An observational data based evapotranspiration function for general circulation models. Atmosphere-Ocean, 20, 301-316.

Sutcliffe, R. C., 1956: Water balance and the general circulation of the atmosphere. Quart. J. R. Met. Soc., 82, 385-395.

Thornthwaite, C. W., 1948: An approach toward a rational classification of climate, Geog. Rev., 38, 55-94.

Walker, J. and P. R. Rowntree, 1977: The effect of soil moisture and rainfall in a tropical model. Quart. J. Roy. Meteor. Soc., 103, 29-46.

Willmott, C. J., 1977: A Fortran IV algorithm for calculating the climatic water budget. OWRT project No. A-040-DEL. Water Resources Center, Univ. of Delaware, Newark, Delaware.

Figure Legends

Fig. 1. National Climatic Center (NCC) Local Climatic Data (LCD) station sequence numbers.

Fig. 2. Number of complete data years from 1940 to 1980 at each NCC LCD station.

Fig. 3a. Monthly Mean Station Temperature (Deg. C).

Fig. 3b. Standard Deviation of Monthly Temperature (Deg. C).

Fig. 4a. Monthly Mean Precipitation (MM/Month).

Fig. 4b. Standard Devation of Monthly Precipitation (MM)

Fig. 5a. First of the Month Soil Moisture Fraction

Fig. 5b. Standard Deviation of the First of the Month Soil Moisture Fraction.

Table 1. National Climatic Center Local Climatic Data Stations used.

SEQ NO	WBAN NO	STATION NAME	STATE	ALT (M)
1	3103	FLAGSTAFF/PULLIAM	AZ	2139
2	3812	ASHEVILLE	NC	661
3	3813	MACON/LEWIS B WILSON	GA	110
4	3820	AUGUSTA/BUSH	GA	45
5	3822	SAVANNAH/TRAVIS	GA	16
6	3841	OAK RIDGE	TN	179
7	3856	HUNTSVILLE/HSV-MADISON	AL	196
8	3860	HUNTINGTON/TRI STATE	WV	255
9	3870	GREENVILLE-SPARTANBURG	SC	296
10	3872	BECKLEY/RALEIGH	WV	766
11	3927	FT WORTH/REGIONAL	TX	175
12	3928	WICHITA	KS	408
13	3937	LAKE CHARLES	LA	10
14	3940	JACKSON/THOMPSON	MS	101
15	3945	COLUMBIA REG/FRM 13983	MO	274
16	3947	KANSAS CITY 13988	MO	315
17	4725	BINGHAMTON/BROOME CO	NY	499
18	12832	APALACHICOLA	FL	11
19	12834	DAYTONA BEACH	FL	12
20	12835	FT MYERS/PAGE	FL	4
21	12836	KEY WEST	FL	6
22	12839	MIAMI	FL	4
23	12841	ORLANDO/MCCOY	FL	4
24	12842	TAMPA	FL	3
25	12844	WEST PALM BEACH	FL	6
26	12883	LAKELAND	FL	72
27	12912	VICTORIA/FOSTER	TX	36
28	12916	NEW ORLEANS/MOISANT	LA	3
29	12917	PRT ARTHUR/JEFFERSON CO	TX	7
30	12919	BROWNSVILLE/RIO GRAND	TX	6
31	12921	SAN ANTONIO	TX	242
32	12924	CORPUS CHRISTI/CLIFF MAUS	TX	13
33	12944	GALVESTON	TX	16
34	12960	HOUSTON/INTCONT 12918	TX	33
35	13722	RALEIGH/RALEIGH-DURHAM	NC	134
36	13723	GREENSBORO/GSO-HI	NC	270
37	13724	ATLANTIC CITY/MARINA STA	NJ	3
38	13729	ELKINS/RANDOLPH CO	WV	611
39	13733	LYNCHBURG	VA	286
40	13737	NORFOLK REG	VA	9
41	13739	PHILADELPHIA	PA	9
42	13740	RICHMOND/BYRD	VA	50
43	13741	ROANOKE	VA	358
44	13743	WASHINGTON DC/NAT	DC	20
45	13748	WILMINGTON/NEW HANOVER	NC	12
46	13781	WILMINGTON/GREATER	DE	24
47	13865	MERIDIAN/KEY	MS	94
48	13866	CHARLESTON/KANAWHA	WV	290
49	13867	PARKERSBURG	WV	194
50	13873	ATHENS/BEN EPPS	GA	247
51	13874	ATLANTA	GA	315
52	13876	BIRMINGHAM	AL	192
53	13877	BRISTOL/TRI CITY	TN	465
54	13880	CHARLESTON	SC	15
55	13881	CHARLOTTE/DOUGLAS	NC	234
56	13882	CHATTANOOGA/LOVELL	TN	210
57	13883	COLUMBIA/MET	SC	69
58	13889	JACKSONVILLE	FL	9
59	13891	KNOXVILLE	TN	299
60	13893	MEMPHIS	TN	87
61	13894	MOBILE/BATES	AL	67
62	13895	MONTGOMERY/DANNELLY	AL	62
63	13897	NASHVILLE/MET	TN	184
64	13899	PENSACOLA/HAGLER	FL	36
65	13935	ALEXANDRIA/ESLER	LA	36
66	13957	SHREVEPORT	LA	79
67	13958	AUSTIN/MUELLER	TX	189
68	13959	WACO	TX	157
69	13960	DALLAS/LOVE	TX	149
70	13962	ABILENE	TX	534
71	13963	LITTLE ROCK/ADAMS	AR	81
72	13964	FT SMITH	AR	141
73	13966	WICHITA FALLS/MUN	TX	314
74	13967	OKLAHOMA CITY/WILL ROGER	OK	397
75	13968	TULSA	OK	206
76	13970	BATON ROUGE/RYAN	LA	23
77	13984	CONCORDIA/BLOSSER	KS	452
78	13985	DODGE CITY	KS	790
79	13988	KANSAS CITY 03947	MO	229
80	13993	ST JOSEPH/ROSECRANS MEM	MO	249
81	13994	ST LOUIS/LAMBERT	MO	172
82	13995	SPRINGFIELD	MO	387
83	13996	TOPEKA/BILLARD	KS	270
84	14607	CARIBOU	ME	191
85	14732	NEW YORK/LAGUARDIA	NY	16
86	14733	BUFFALO/GRTR BUFFALO	NY	215
87	14734	NEWARK	NJ	9
88	14735	ALBANY/CO	NY	85
89	14737	ALLENTOWN/BETHLEHEM	PA	117
90	14739	BOSTON/LOGAN	MA	9
91	14740	HARTFORD/BRADLEY	CT	55
92	14742	BURLINGTON	VT	104
93	14745	CONCORD	NH	105
94	14751	HARRISBURG/STATE 94718	PA	106
95	14753	BLUE HILL OBS/MILTON	MA	204
96	14755	MT WASHINGTON	NH	1910
97	14756	NANTUCKET/MEM	MA	4
98	14758	NEW HAVEN/TWEED	CT	4
99	14764	PORTLAND	ME	19
100	14765	PROVIDENCE/FRANCIS/GREEN	RI	19
101	14767	READING 14712	PA	62
102	14768	ROCHESTER/MONROE CO	NY	169
103	14771	SYRACUSE/C E HANCOCK	NY	124
104	14792	TRENTON 14706	NJ	58
105	14777	WILKES-BARRE-SCRANTON	PA	289
106	14778	WILLIAMSPORT/LYCOMING	PA	160
107	14819	CHICAGO/MIDWAY	IL	190
108	14820	CLEVELAND/HOPKINS	OH	245
109	14821	COLUMBUS/PORT COLUMBUS	OH	254
110	14822	DETROIT CITY 14853	MI	193
111	14826	FLINT/BISHOP	MI	233
112	14827	FT WAYNE/BAER	IN	252
113	14836	LANSING/CAPITAL CITY	MI	266
114	14837	MADISON/TRUAX	WI	264
115	14838	MARQUETTE	MI	224
116	14839	MILWAUKEE/MITCHEL	WI	211
117	14840	MUSKEGON CO	MI	193
118	14842	PEORIA/GREATER PEORIA	IL	202
119	14847	SAULT STE MARIE	MI	221
120	14848	SOUTH BEND/ST JOE	IN	236
121	14852	YOUNGSTOWN	OH	361
122	14860	ERIE/PORT ERIE	PA	225
123	14861	PITTSBURGH	PA	310
124	14891	MANSFIELD/LAHM	OH	400
125	14895	AKRON/AKRON CANTON	OH	377
126	14898	GREEN BAY/AUSTIN STRABEL	WI	214
127	14913	DULUTH	MN	432
128	14914	FARGO/HECTOR	ND	274
129	14918	INTERNATIONAL FALLS	MN	361
130	14920	LA CROSSE	WI	205
131	14922	MINNEAPOLIS/ST PAUL	MN	255
132	14923	MOLINE/QUADCITY	IL	181
133	14925	ROCHESTER	MN	402
134	14926	ST CLOUD/WHITNEY MEM	MN	318
135	14929	ABERDEEN	SD	396
136	14931	BURLINGTON	IA	214
137	14933	DES MOINES	IA	294
138	14935	GRAND IS	NE	566
139	14936	HURON/WW HOWES	SD	393
140	14939	LINCOLN 14971	NE	362
141	14941	NORFOLK/KARL STEFAN MEM	NE	473
142	14942	OMAHA/EPPLEY	NE	299
143	14943	SIOUX CITY	IA	336
144	14944	SIOUX FALLS/FOSS	SD	435
145	14971	LINCOLN 14939	NE	362
146	22010	DEL RIO	TX	313
147	23009	ROSWELL/WALKER/IND	NM	1027
148	23023	MIDLAND/SLOAN	TX	871
149	23034	SAN ANGELO/MATHIS	TX	582
150	23042	LUBBOCK/WEST AIR TERM	TX	988
151	23043	ROSWELL	NM	1103
152	23044	EL PASO	TX	1194
153	23047	AMARILLO/ENGLISH	TX	1098
154	23050	ALBUQUERQUE/SUNPT-KIRT	NM	1620
155	23051	CLAYTON	NM	1515
156	23061	ALAMOSA	CO	2298
157	23062	DENVER/STAPLETON	CO	1652
158	23065	GOODLAND/RENNER	KS	1124
159	23066	GRAND JUNCTION/WALKER	CO	1475
160	23129	LONG BEACH	CA	17
161	23154	ELY/YELLAND	NV	1909
162	23155	BAKERSFIELD/MEADOWS	CA	150
163	23157	BISHOP	CA	1263
164	23160	TUCSON	AZ	779
165	23169	LAS VEGAS/MCCARRAN	NV	664
166	23174	LOS ANGELES	CA	32
167	23176	MILFORD	UT	1534
168	23183	PHOENIX/SKY HARBOR	AZ	337
169	23185	RENO	NV	1341
170	23187	SANDBERG	CA	1379
171	23188	SAN DIEGO/LINDBERGH	CA	9
172	23194	WINSLOW	AZ	1488
173	23195	YUMA	AZ	63
174	23225	BLUE CANYON	CA	1610
175	23230	OAKLAND	CA	2
176	23232	SACRAMENTO/EXECUTIVE	CA	8
177	23234	SAN FRANCISCO	CA	5
178	23237	STOCKTON/MET	CA	8
179	23272	SAN FRANCISCO	CA	16
180	23273	SANTA MARIA/PUBLIC	CA	73
181	24011	BISMARK	ND	506
182	24018	CHEYENNE	WY	1872
183	24021	LANDER/HUNT	WY	1694
184	24023	NORTH PLATTE/LEE BIRD	NE	849
185	24028	SCOTTSBLUFF	NE	1206
186	24029	SHERIDAN CO	WY	1209
187	24032	VALENTINE/MILLER	NE	792
188	24033	BILLINGS/LOGAN	MT	1088
189	24037	MILES CITY	MT	803
190	24089	CASPER	WY	1612
191	24090	RAPID CITY	SD	966
192	24121	ELKO	NV	1547
193	24127	SALT LAKE CITY	UT	1288
194	24128	WINNEMUCCA	NV	1323
195	24131	BOISE	ID	874
196	24134	BURNS	OR	1271
197	24143	GREAT FALLS	MT	1115
198	24144	HELENA	MT	1188
199	24146	KALISPELL/GLACIER PRK	MT	906
200	24149	LEWISTON/NEZPERCE CO	ID	438
201	24152	MEACHAM/EMERGENCY	OR	1236
202	24153	MISSOULA/JOHNSON-BELL	MT	972
203	24155	PENDLETON/PENDLETON	OR	456
204	24156	POCATELLO	ID	1365
205	24157	SPOKANE	WA	721
206	24193	WENDOVER	UT	1292
207	24213	EUREKA	CA	16
208	24215	MT SHASTA	CA	1093
209	24216	RED BLUFF	CA	108
210	24221	EUGENE/MAHLON SWEET	OR	114
211	24225	MEDFORD/JACKSON CTY	OR	405
212	24227	OLYMPIA	WA	61
213	24229	PORTLAND	OR	12
214	24232	SALEM/MCNARY	OR	61
215	24233	SEATTLE/TACOMA	WA	137
216	24235	SEXTON SUMMIT	OR	1171
217	24237	STAMPEDE PASS	WA	1209
218	24243	YAKIMA	WA	325
219	24281	SEATTLE	WA	6
220	93037	COLO SPRINGS/PETERSON	CO	1881
221	93058	PUEBLO/MEMORIAL	CO	1439
222	93134	LOS ANGELES	CA	156
223	93193	FRESNO AIR TERM/HAMMER	CA	100
224	93721	BALTIMORE/FRIENDSHIP	MD	47
225	93729	CAPE HATTERAS	NC	3
226	93730	ATLANTIC CITY/NAFEC PCMON	NJ	20
227	93738	WASHINGTON DC/DULLES	VA	98
228	93801	ROME/RUSSELL	GA	196
229	93805	TALLAHASSEE	FL	21
230	93809	CAIRO	IL	109
231	93814	COVINGTON/GTR CINN	KY	271
232	93815	DAYTON/JM COX DAY	OH	306
233	93817	EVANSVILLE/DRESS	IN	118
234	93819	INDIANAPOLIS/WEIR COOK	IN	246
235	93820	LEXINGTON/BLUE GRASS	KY	301
236	93821	LOUISVILLE/STANDIFORD	KY	149
237	93822	SPRINGFIELD/CAPITAL	IL	187
238	93842	COLUMBUS	GA	120
239	93890	CINCINNATI/ABBE	OH	191
240	94012	HAVRE CITY-COUNTY	MT	792
241	94014	WILLISTON/SLOULIN	ND	581
242	94102	WALLA WALLA	WA	302
243	94224	ASTORIA/CLATSOP CO	OR	7
244	94240	QUILLAYUTE	WA	62
245	94702	BRIDGEPORT	CT	5
246	94728	NEW YORK/CENTRAL PRK	NY	48
247	94746	WORCESTER	MA	310
248	94789	NEW YORK/J F KENNEDY	NY	10
249	94793	BLOCK IS/BIC STATE	RI	36
250	94814	HOUGHTON LAKE/ROSCOMMON	MI	354
251	94822	ROCKFORD/GRTR ROCKFORD	IL	226
252	94823	PITTSBURGH/GRT PITTSBGH	PA	77
253	94830	TOLEDO	OH	211
254	94846	CHICAGO/OHARE	IL	205
255	94847	DETROIT/METROPOLITAN	MI	202
256	94849	ALPENA/PHELPS COLLINS	MI	210
257	94850	MARQUETTE CO	MI	434
258	94860	GRAND RAPIDS/KENT CO	MI	245
259	94908	DUBUQUE	IA	329
260	94910	WATERLOO	IA	268
261	94918	OMAHA/NORTH OMAHA	NE	406

Fig. 1

NCC LCD STATION SEQUENCE NUMBER

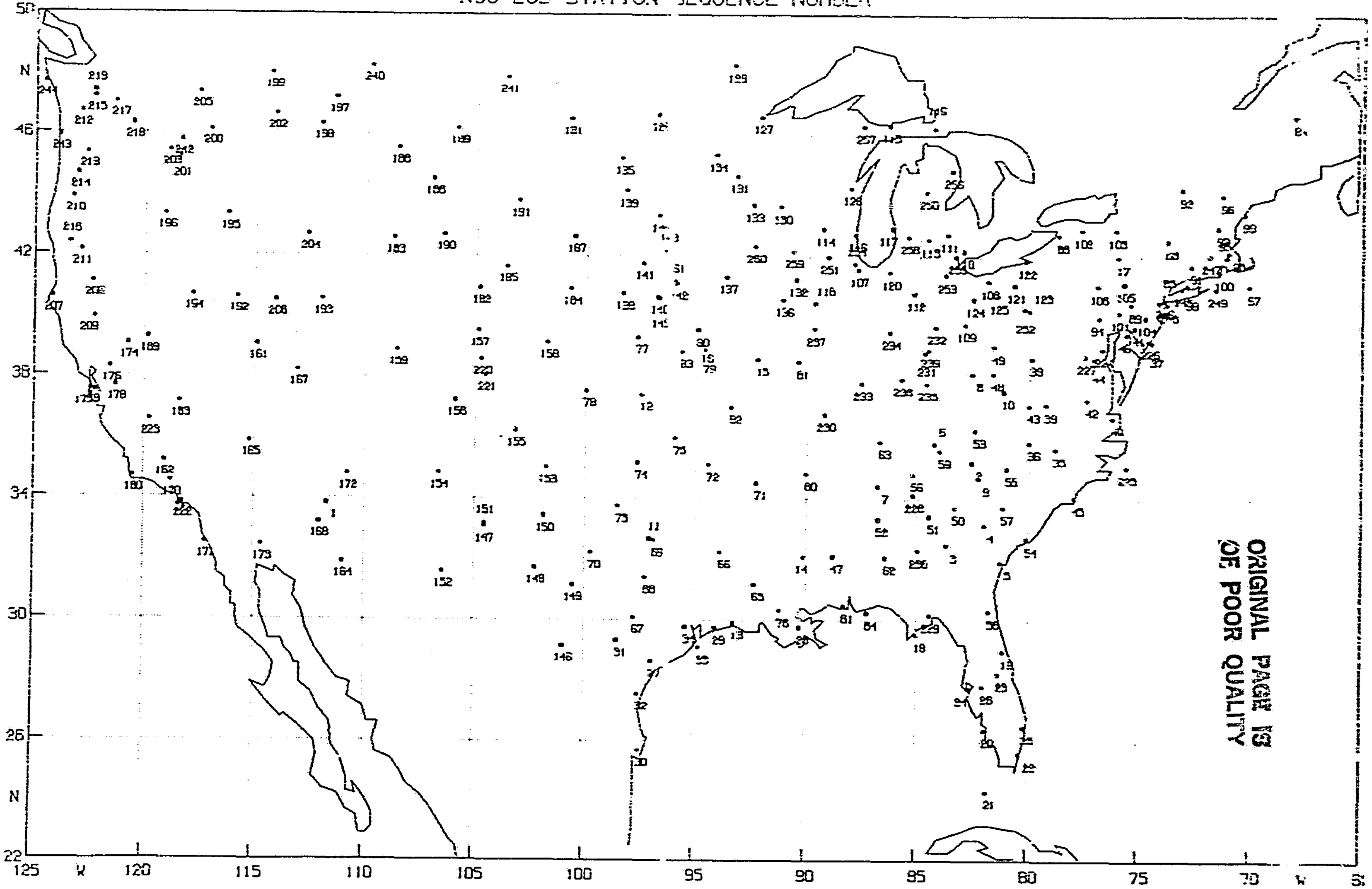


Fig. 2

NCC LCD STATION NO. OF GOOD YEARS

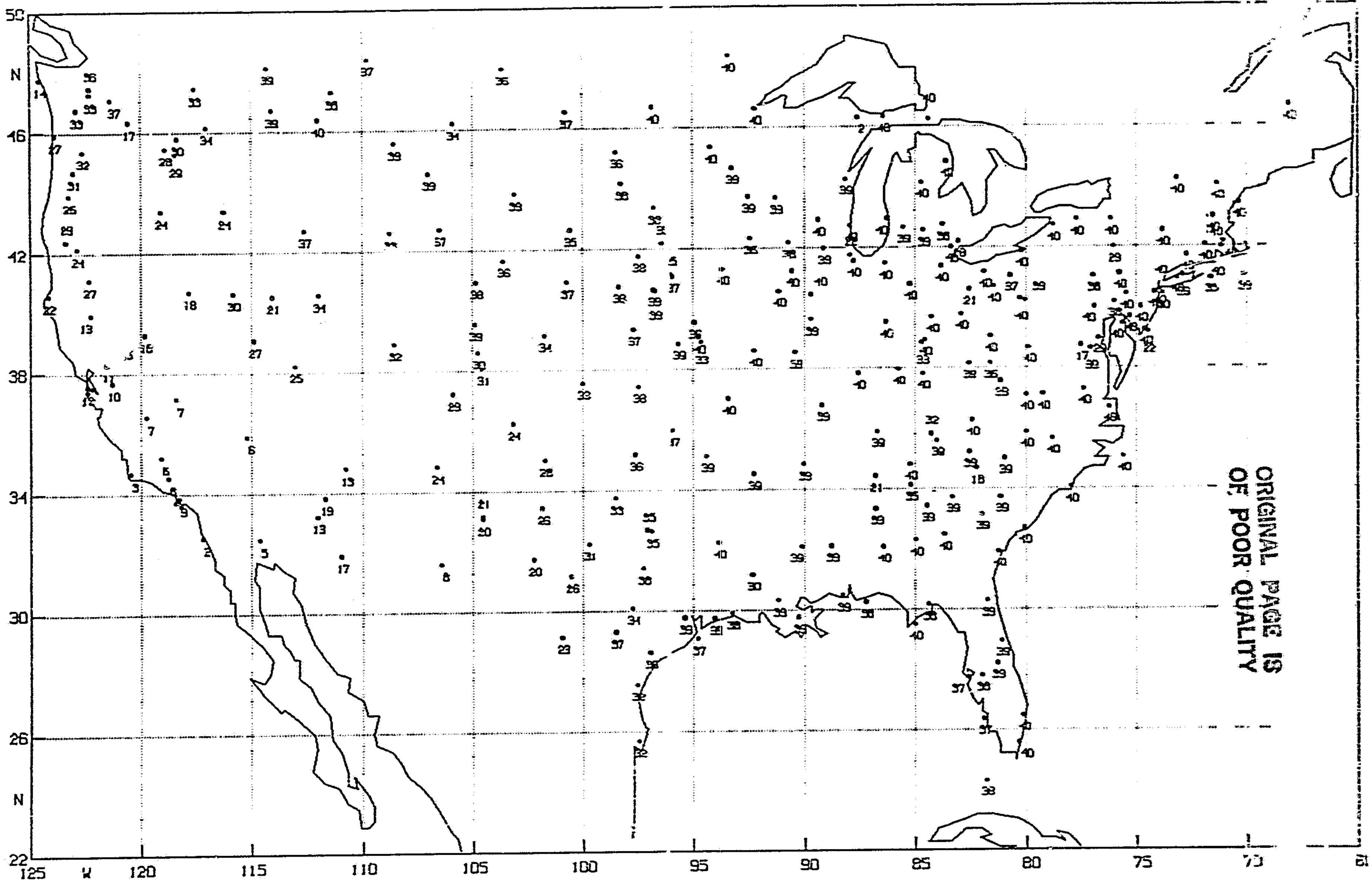


Fig. 3.a.1

JANUARY NCC LCD MEAN TEMPERATURE (DEG C)

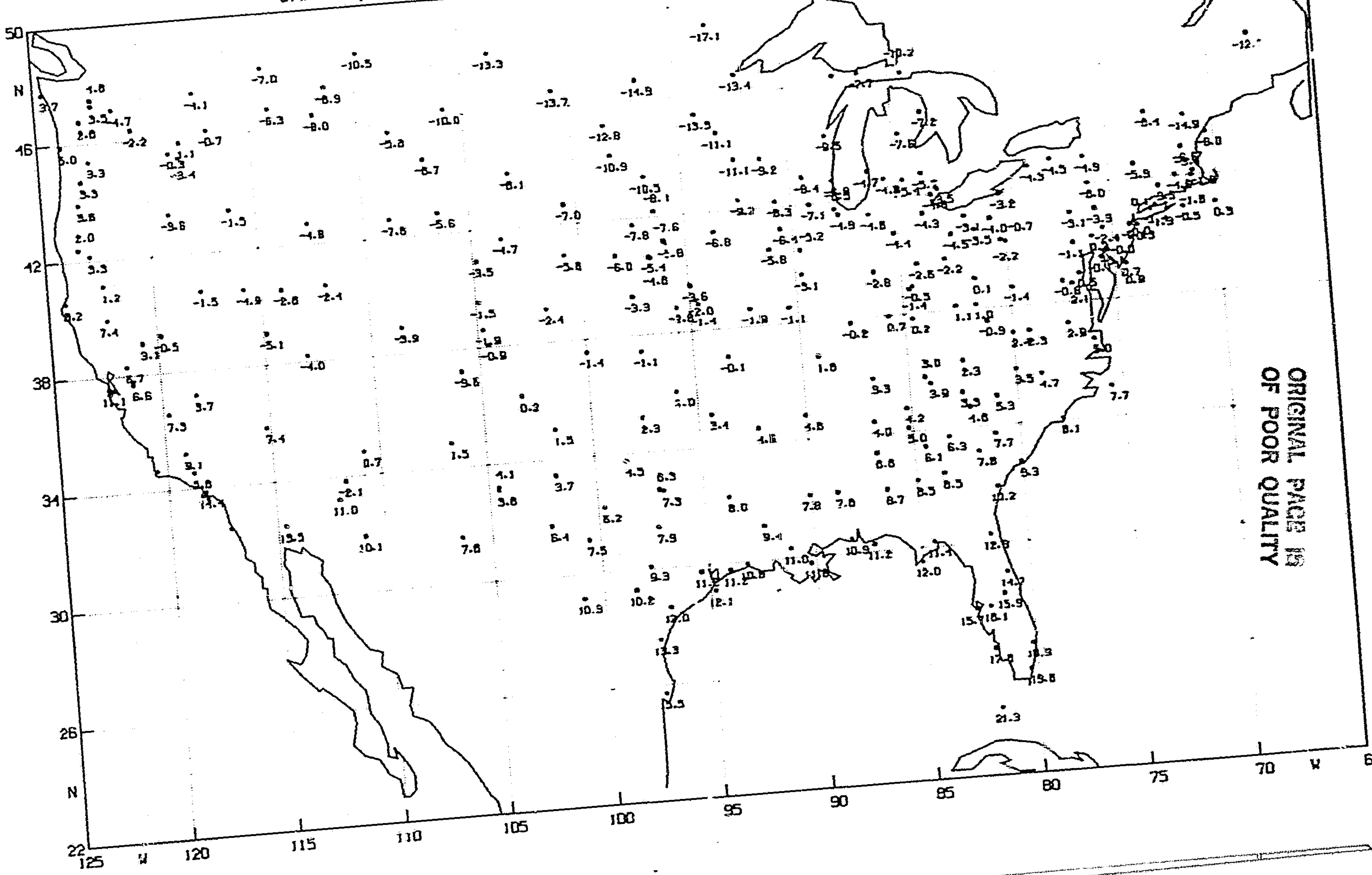


Fig. 3.a.2

FEBRUARY NCC LCD MEAN TEMFERATURE (DEG C)

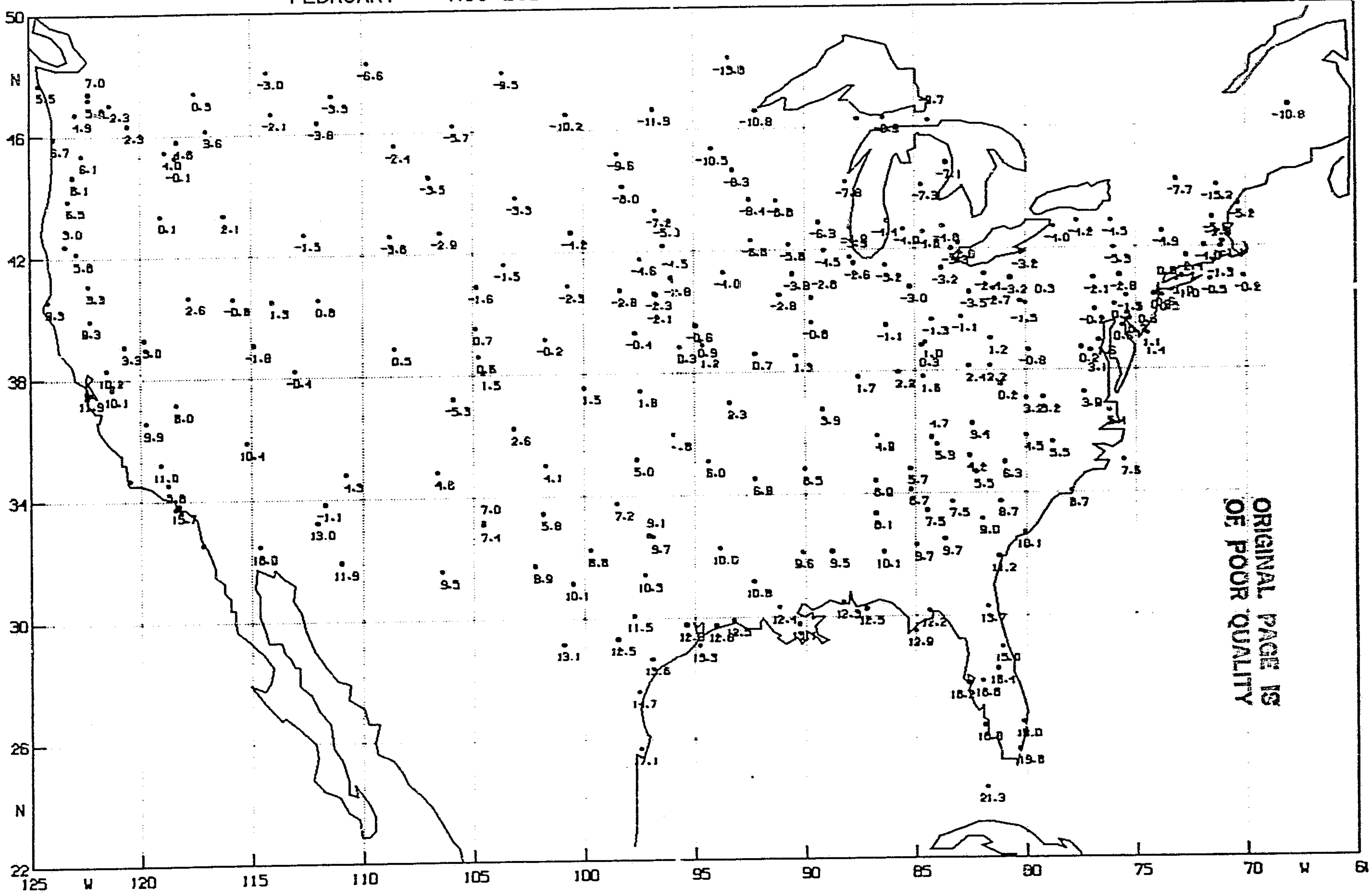


Fig. 3.a.3

MARCH NCC LCD MEAN TEMPERATURE (DEG C)

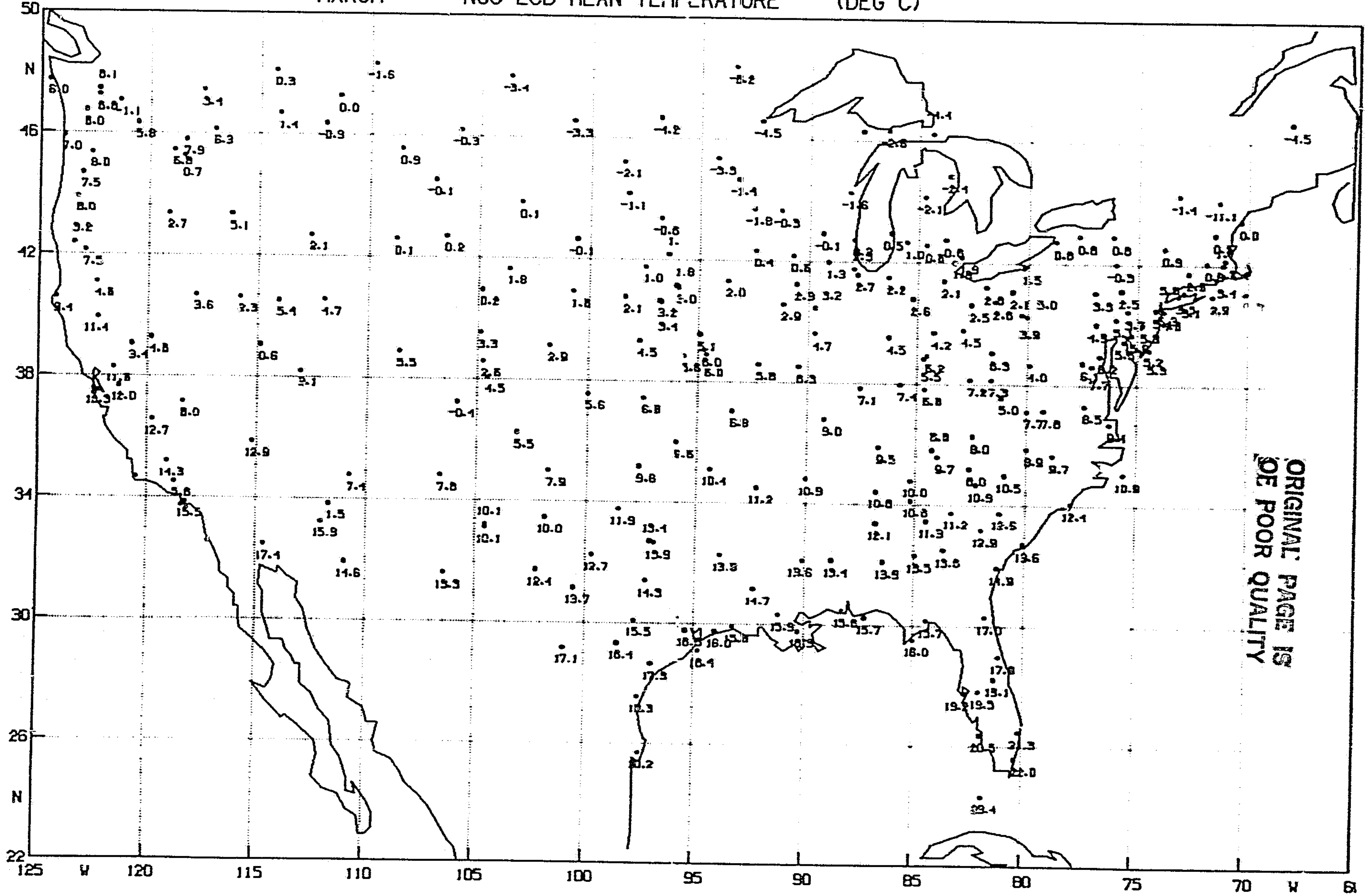


Fig. 3.q.4

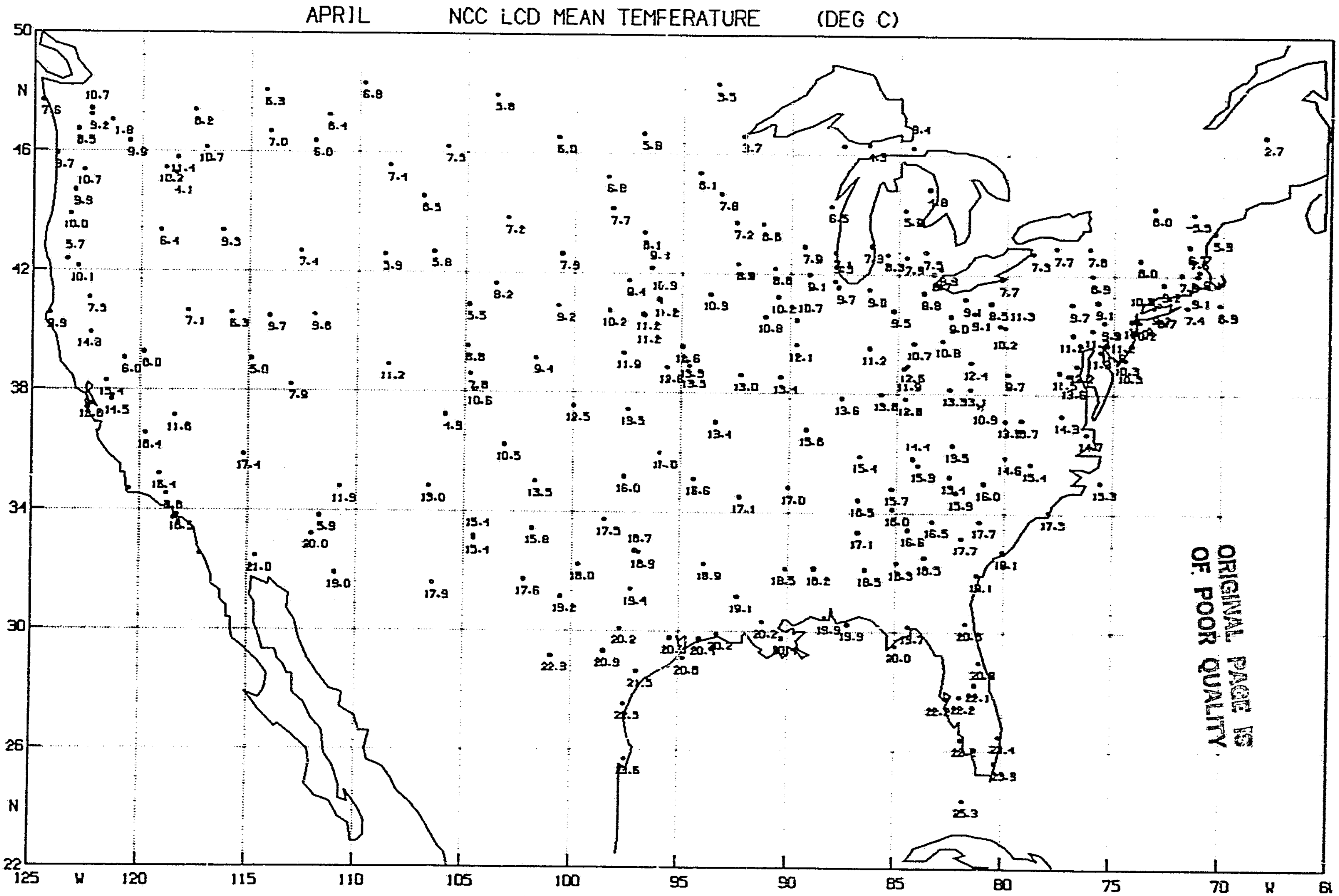

APRIL NCC LCD MEAN TEMPERATURE (DEG C)
50
N
46
42
38
34
30
26
N
22
125
W
120
115
110
105
100
95
90
85
80
75
70
W
65

Fig. 3.a.3

MAY NCC LCD MEAN TEMFERATURE (DEG C)

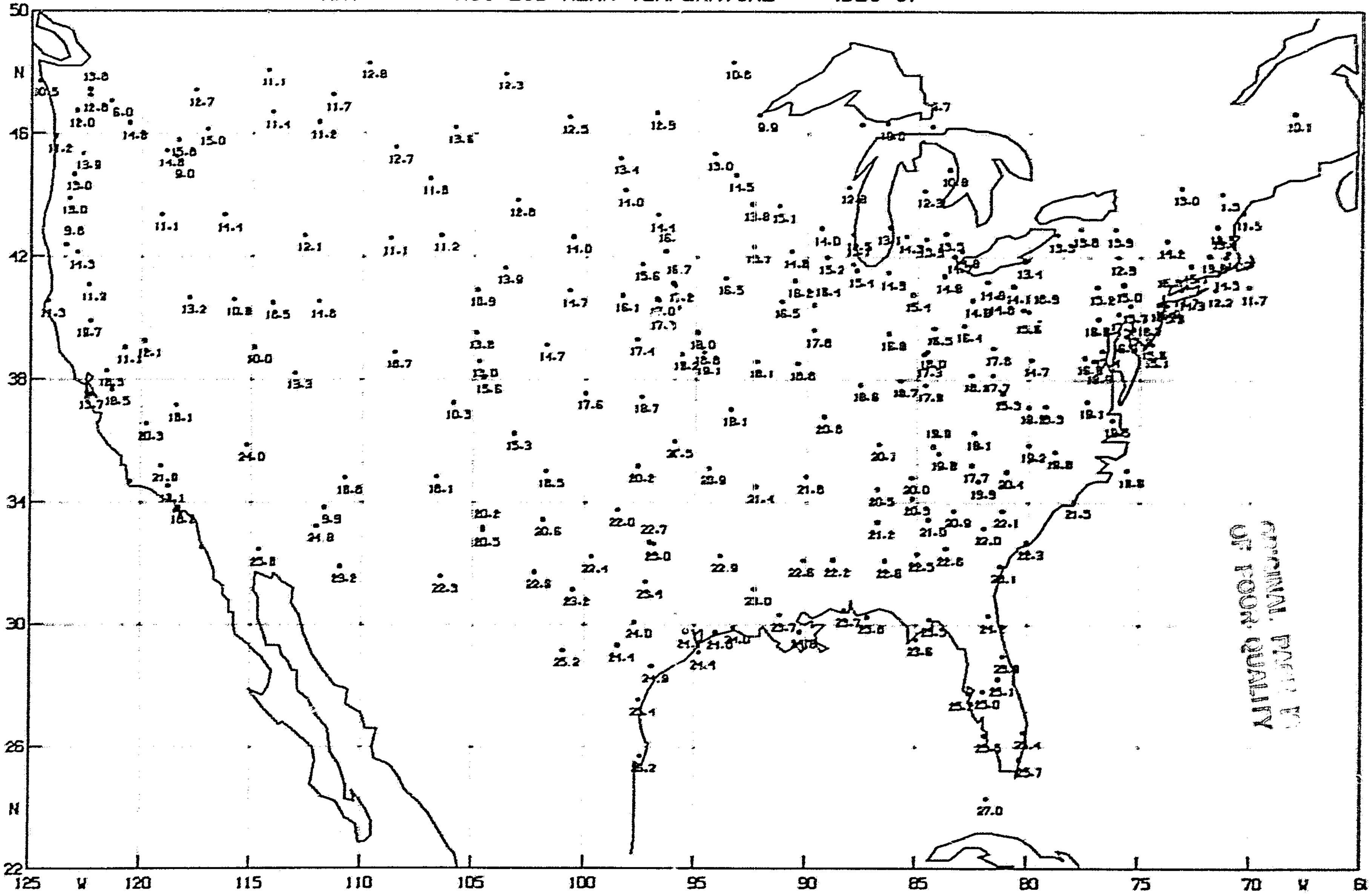


Fig. 3.a.6

JUNE NCC LCD MEAN TEMPERATURE (DEG C)

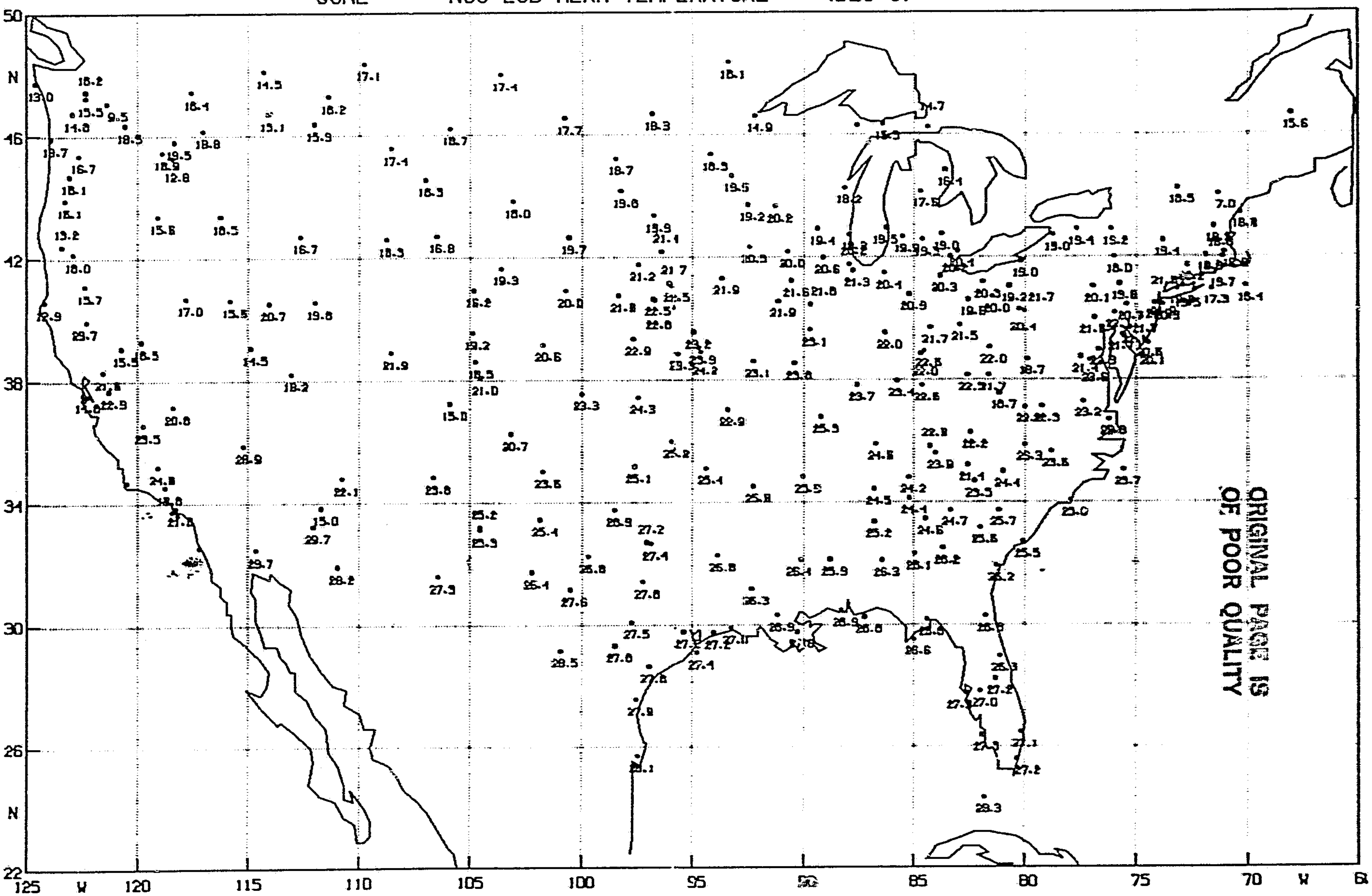


Fig. 3.a.7

JULY NCC LCD MEAN TEMPERATURE (DEG C)

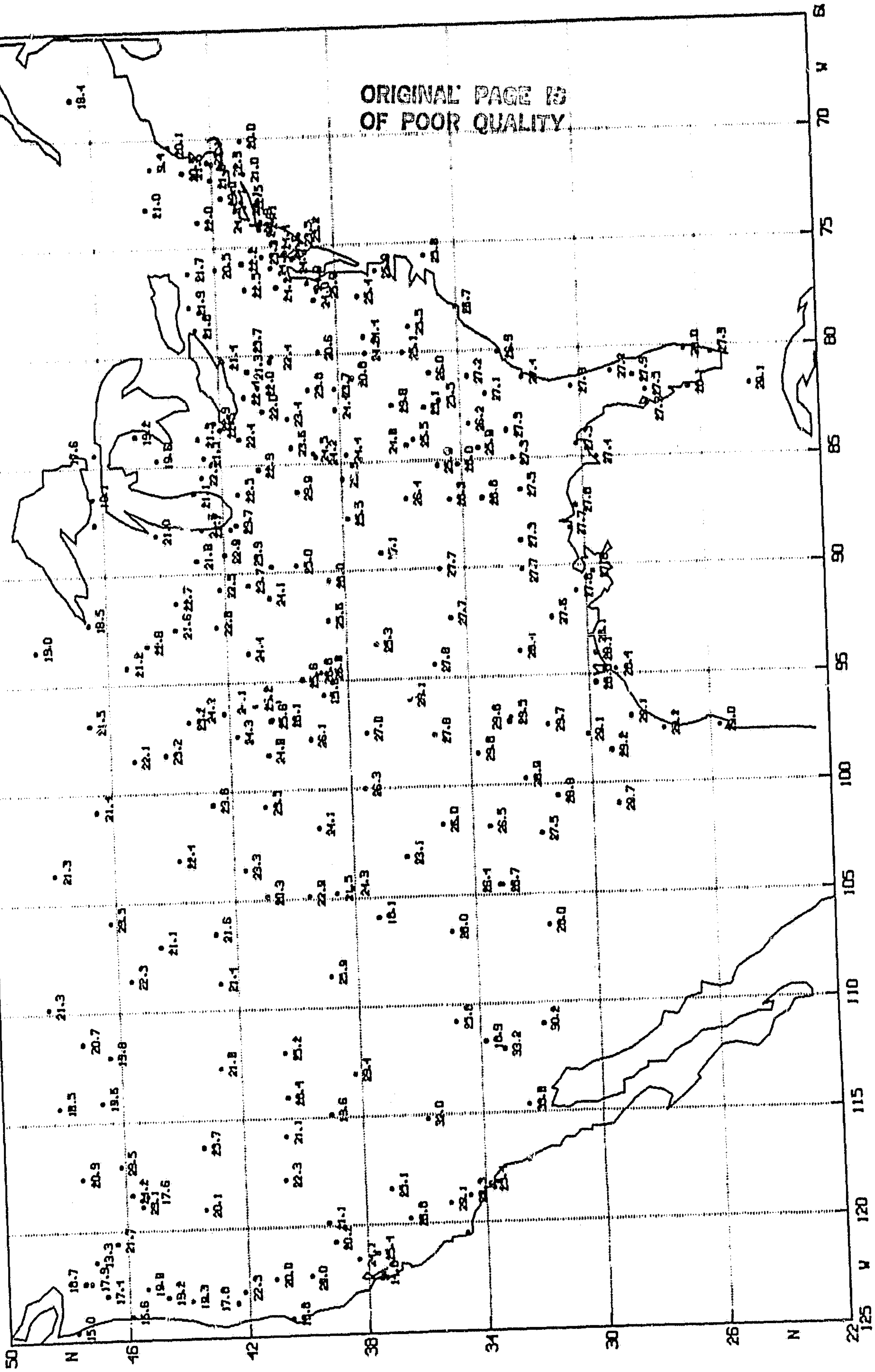


Fig. 3.a.8

AUGUST NCC LCD MEAN TEMFERATURE (DEG C)

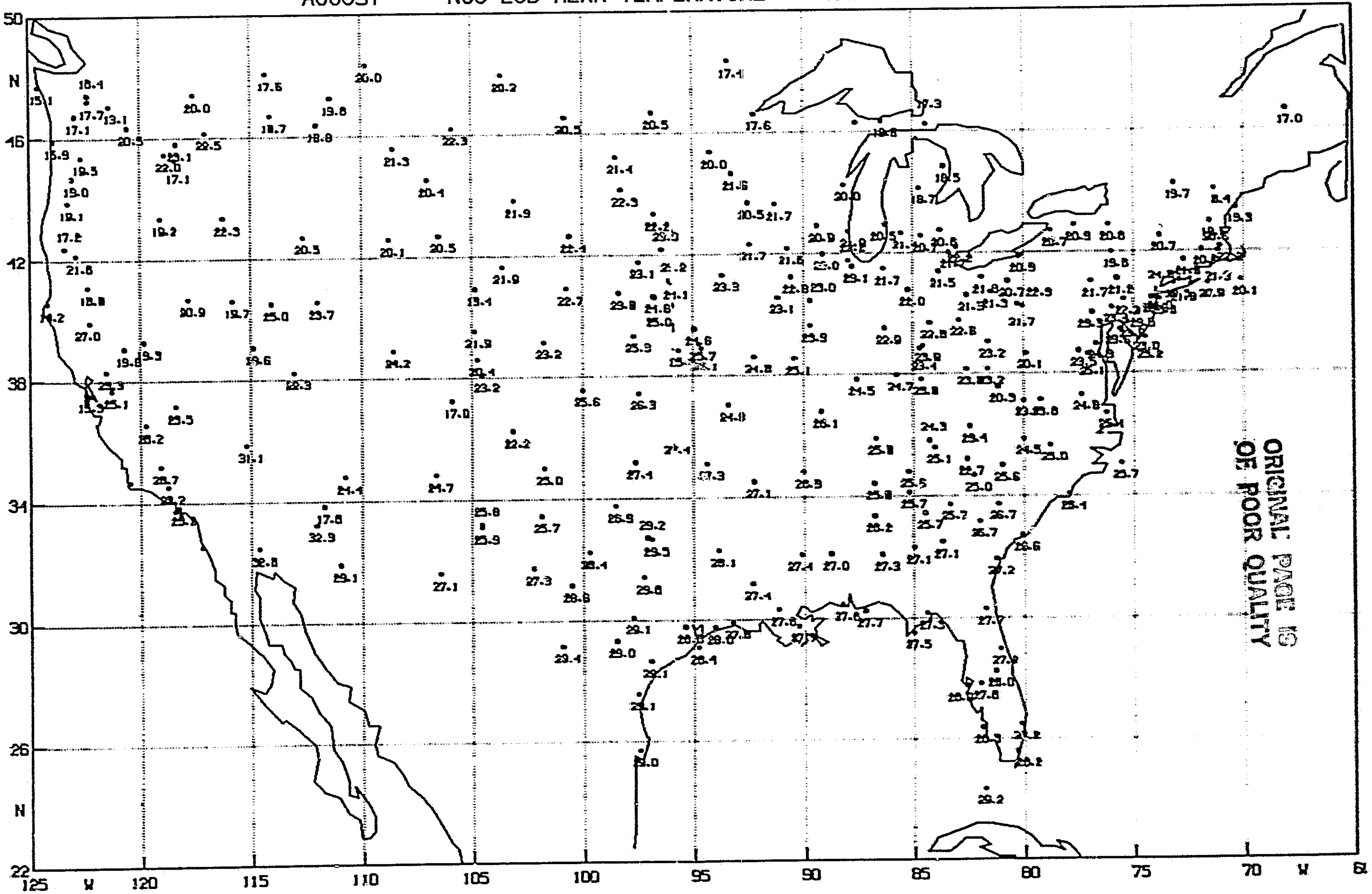


Fig. 3.a.9

SEPTMBER NCC LCD MEAN TEMFERATURE (DEG C)

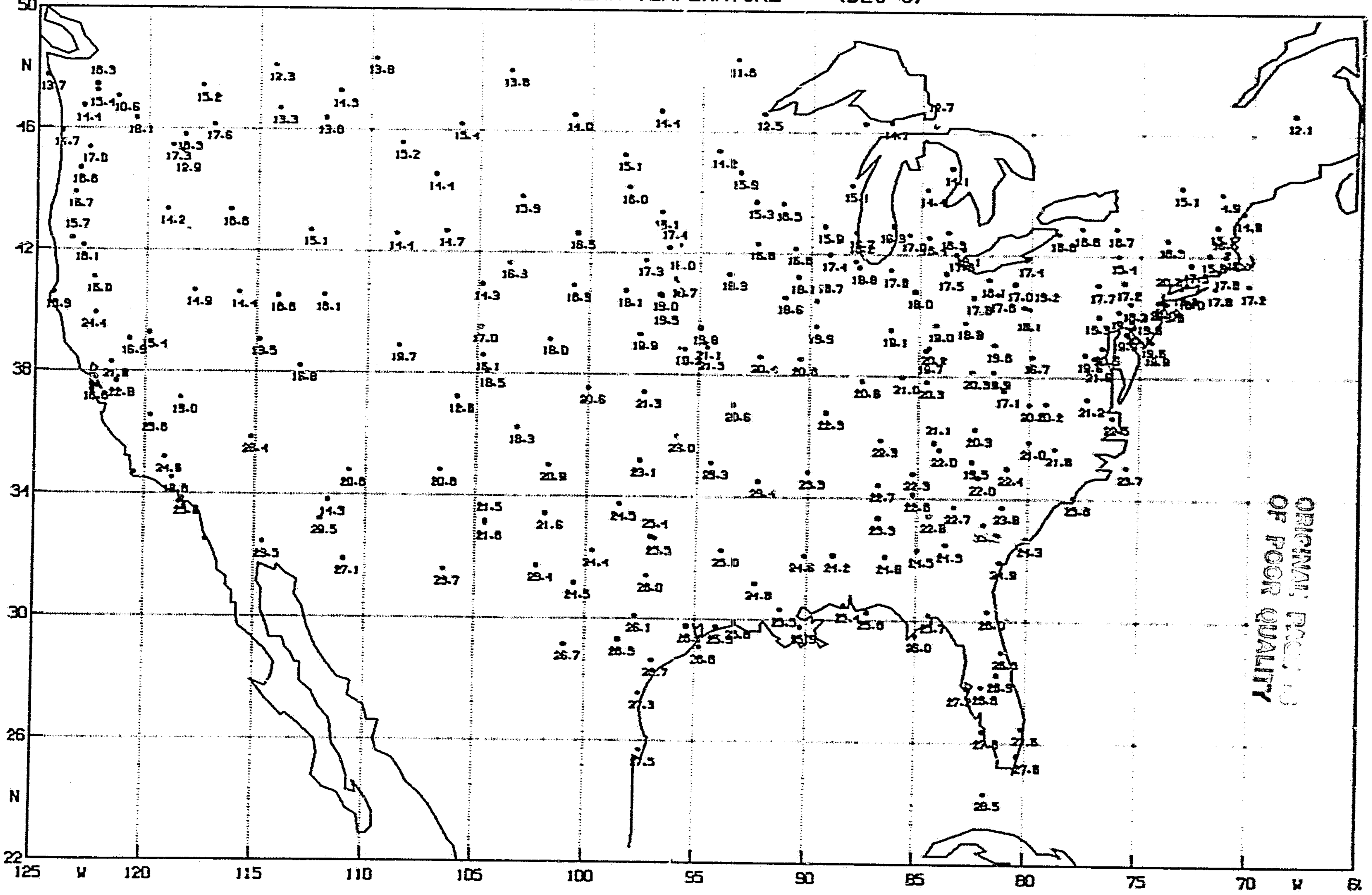


Fig. 3.a.10

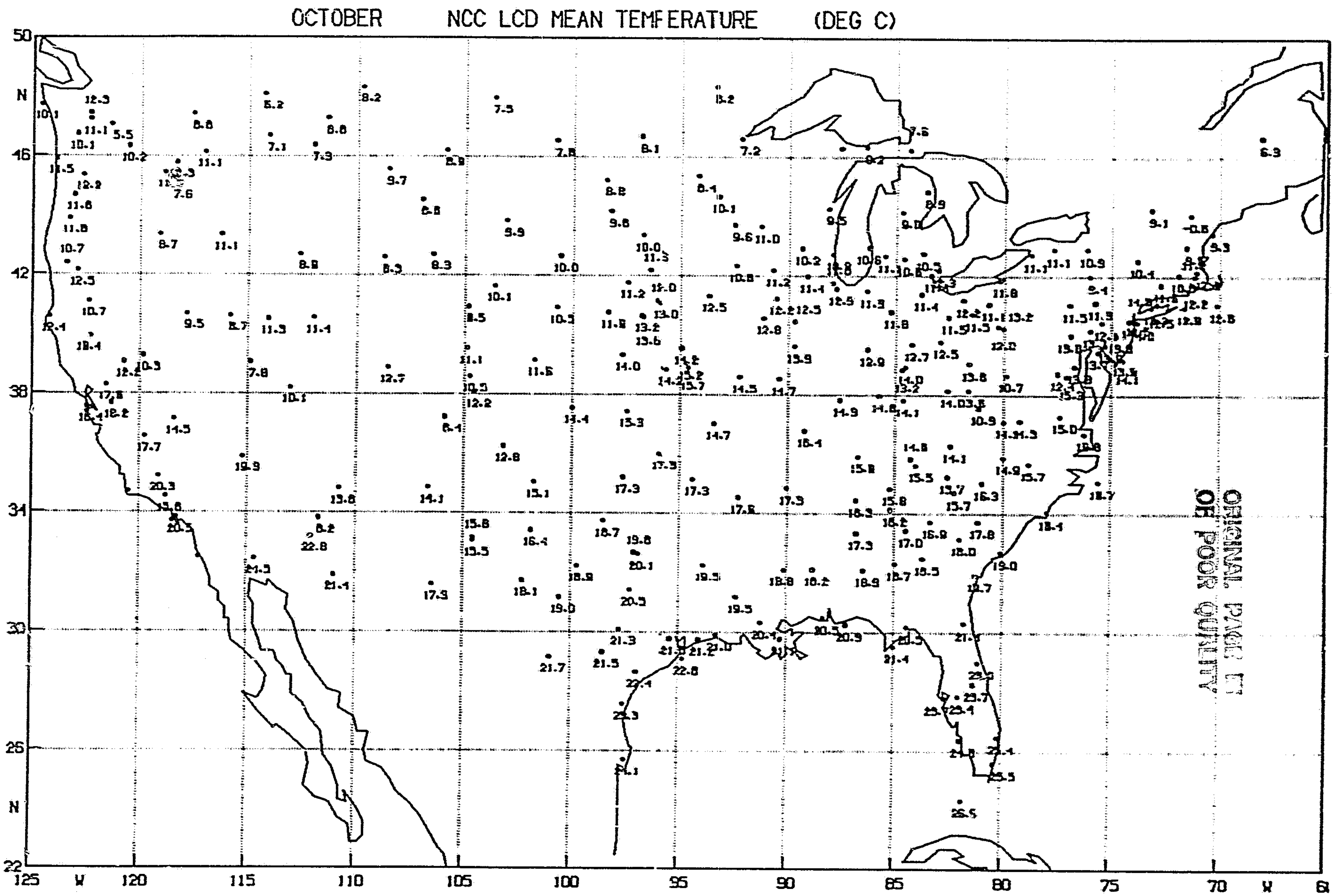

OCTOBER NCC LCD MEAN TEMFERATURE (DEG C)
50
N
46
42
38
34
30
26
N
22
125
W
120
115
110
105
100
95
90
85
80
75
70
W
61
ORIGINAL PAGE IS
OF POOR QUALITY

Fig. 3.a.11

NOVEMBER NCC LCD MEAN TEMFERATURE (DEG C)

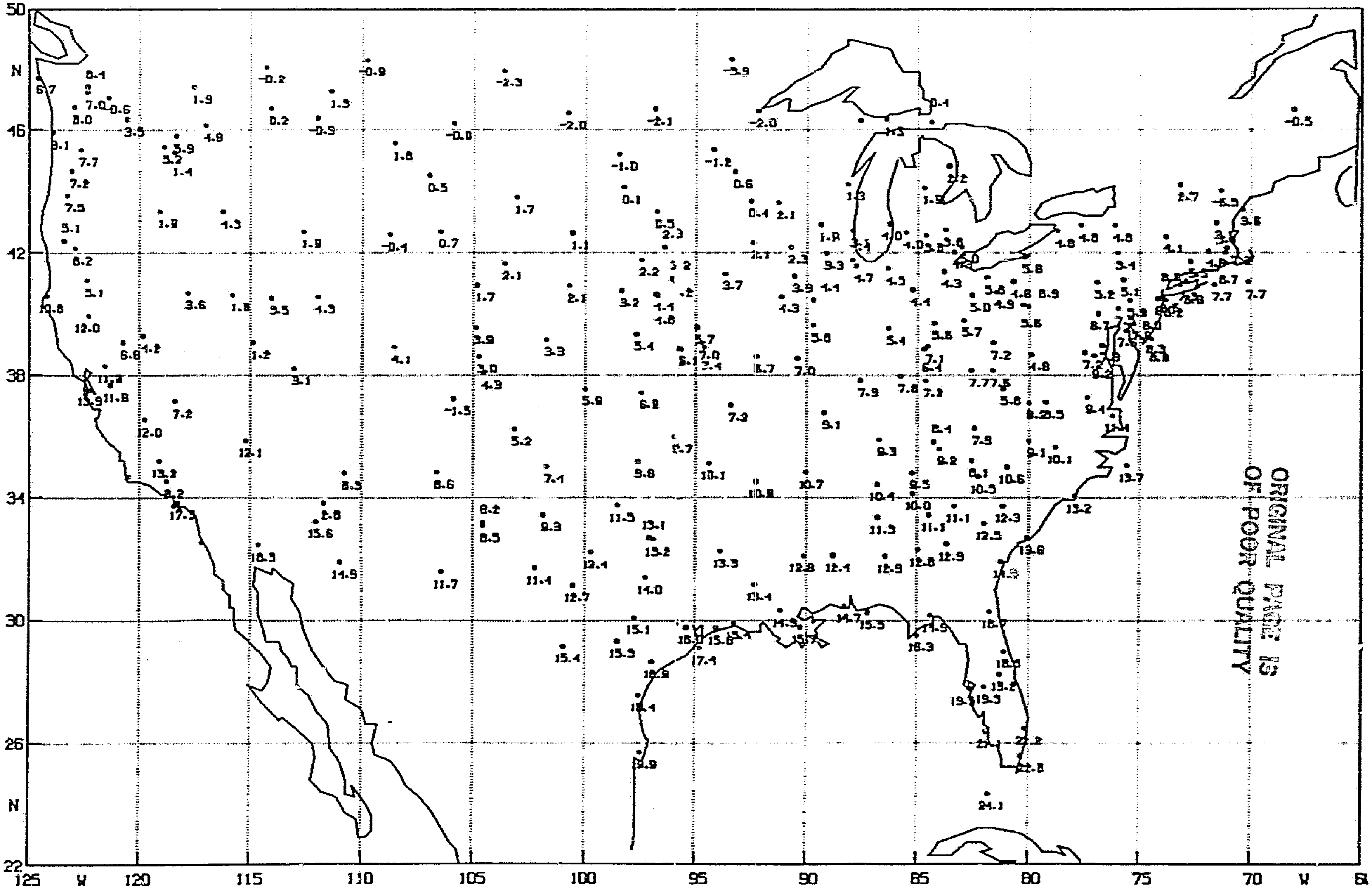


Fig. 3.a.12

DECEMBER NCC LCD MEAN TEMFERATURE (DEG C)

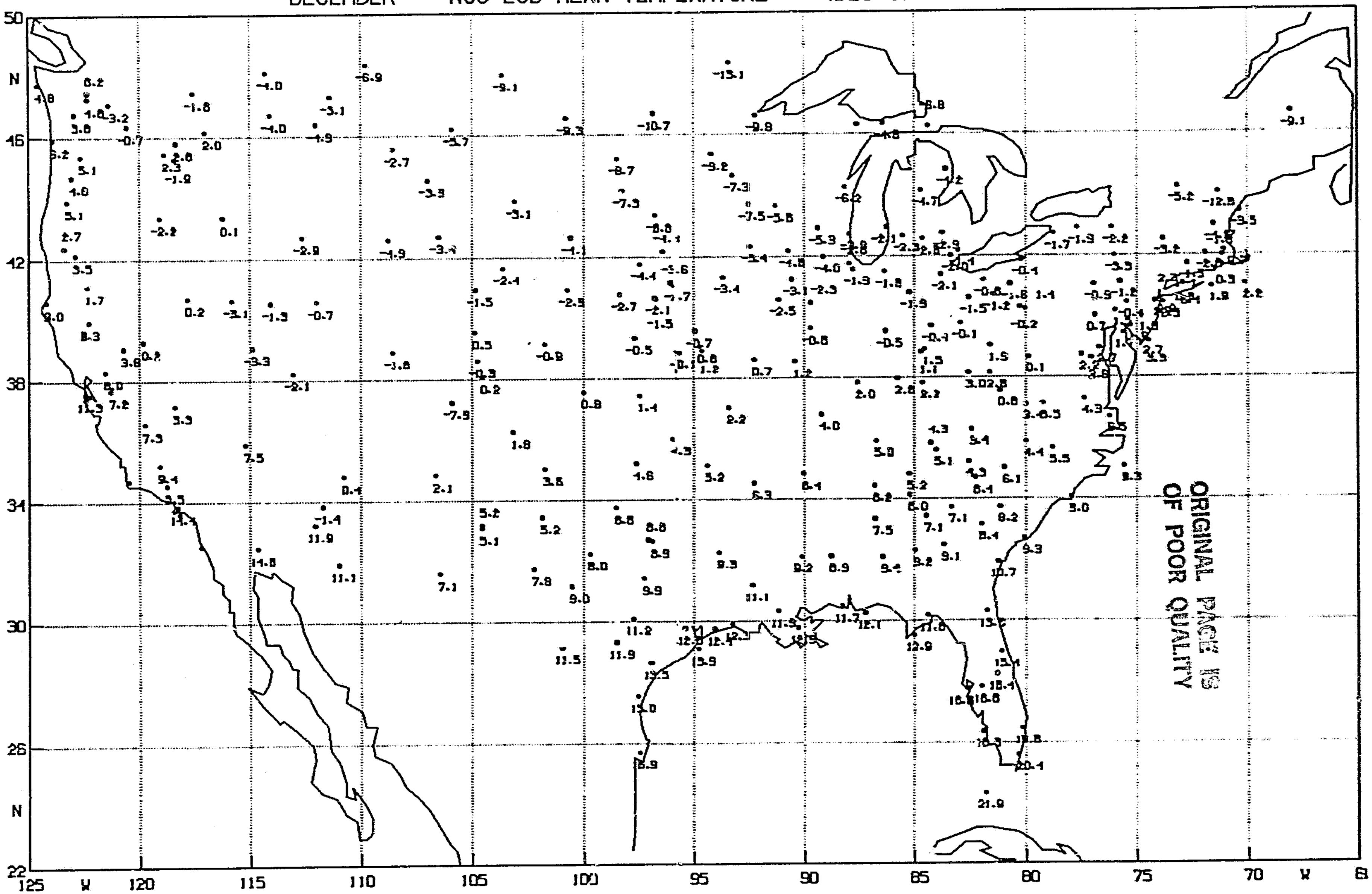


Fig. 3.b.1

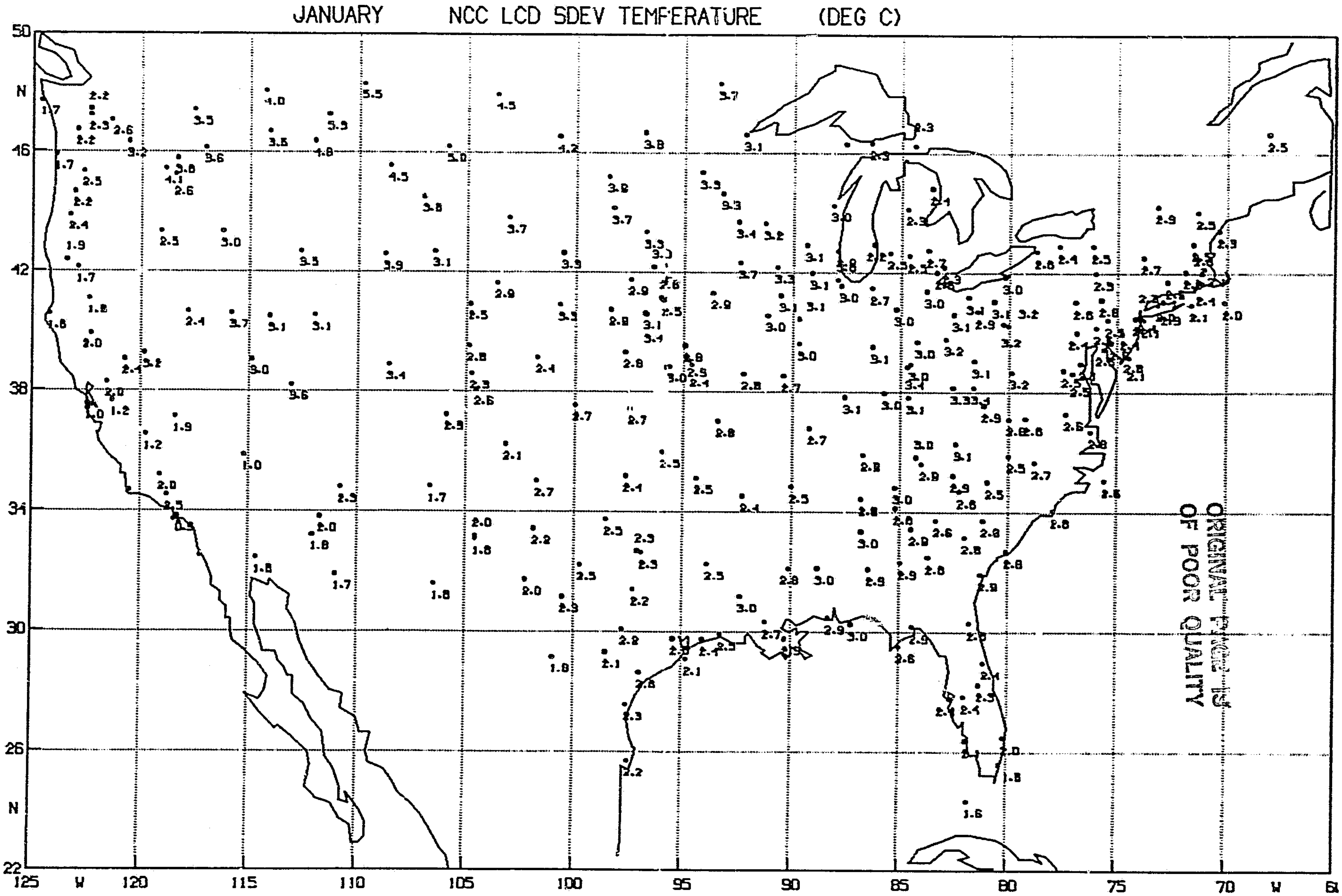
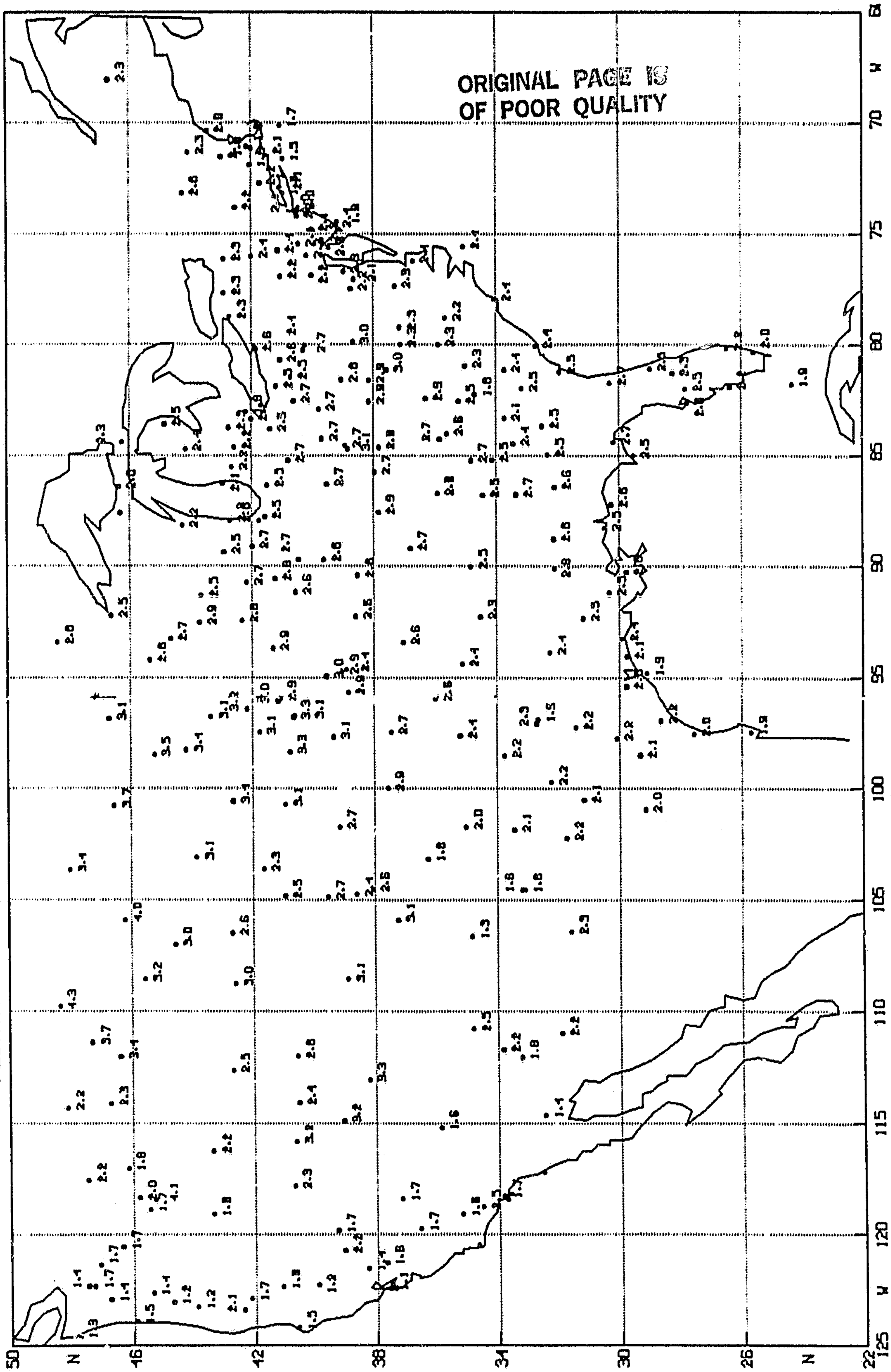

JANUARY NCC LCD SDEV TEMPERATURE (DEG C)
50
46
42
38
34
30
26
22
N
125 W 120 115 110 105 100 95 90 85 80 75 70 W 65

Fig. 3.b.2

FEBRUARY NCC LCD SDEV TEMPERATURE (DEG C)



MARCH NCC LCD SDEV TEMPERATURE (DEG C)

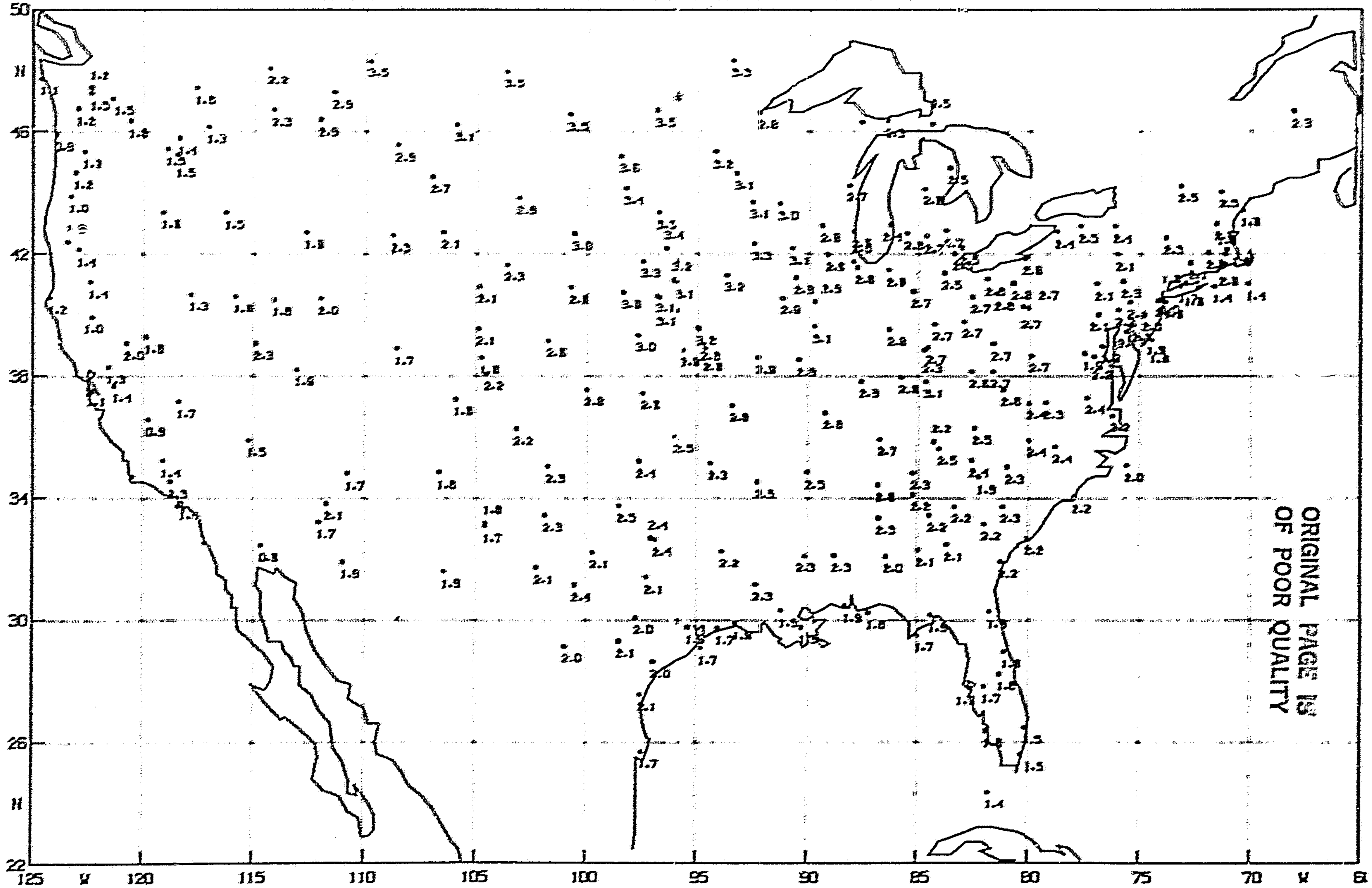


Fig. 3.b.4

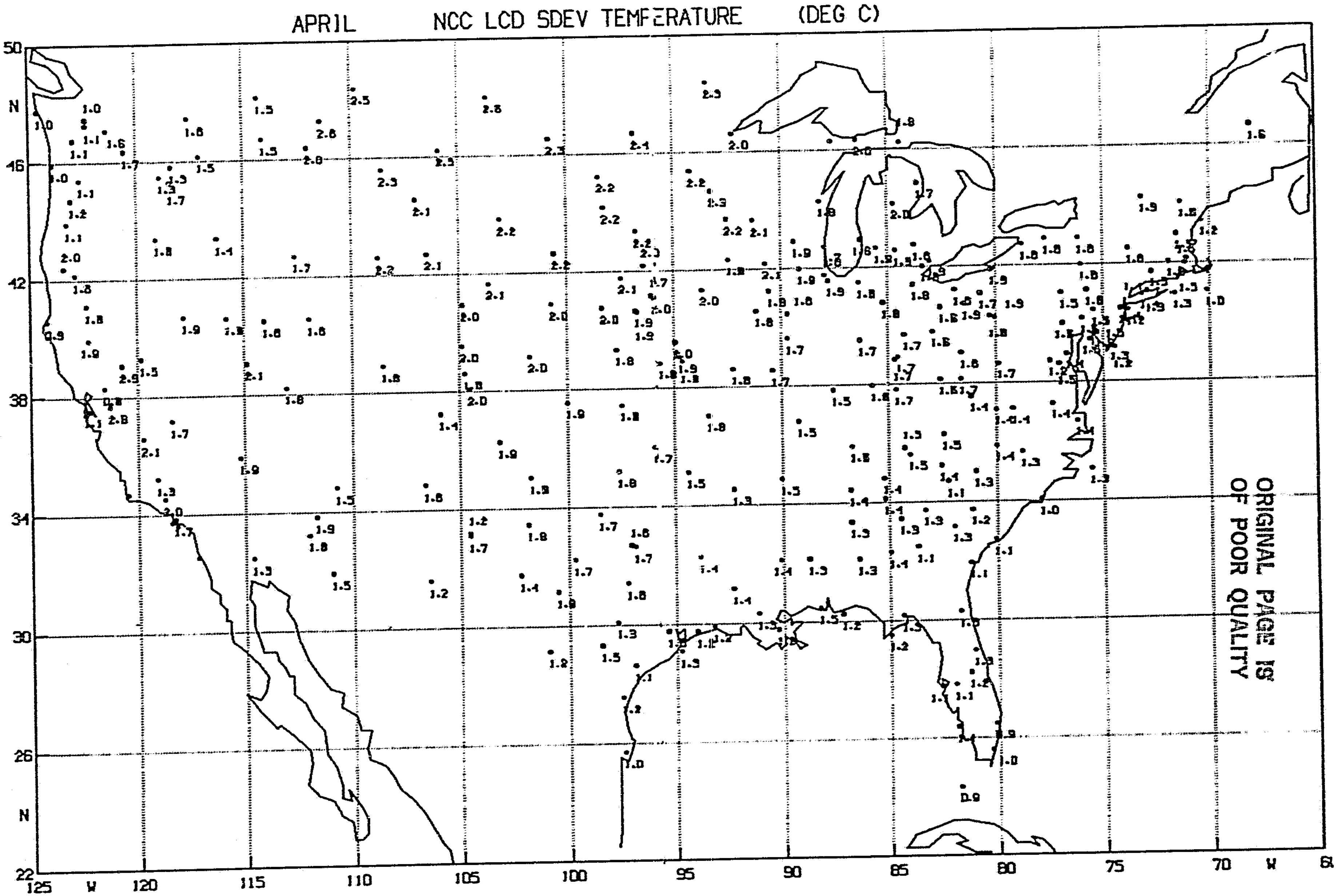

APRIL NCC LCD SDEV TEMPERATURE (DEG C)
ORIGINAL PAGE IS OF POOR QUALITY
50
N
46
42
38
34
30
26
N
22
125
W
120
115
110
105
100
95
90
85
80
75
70
W
65

Fig. 3.b.5

MAY NCC LCD SDEV TEMPERATURE (DEG C)

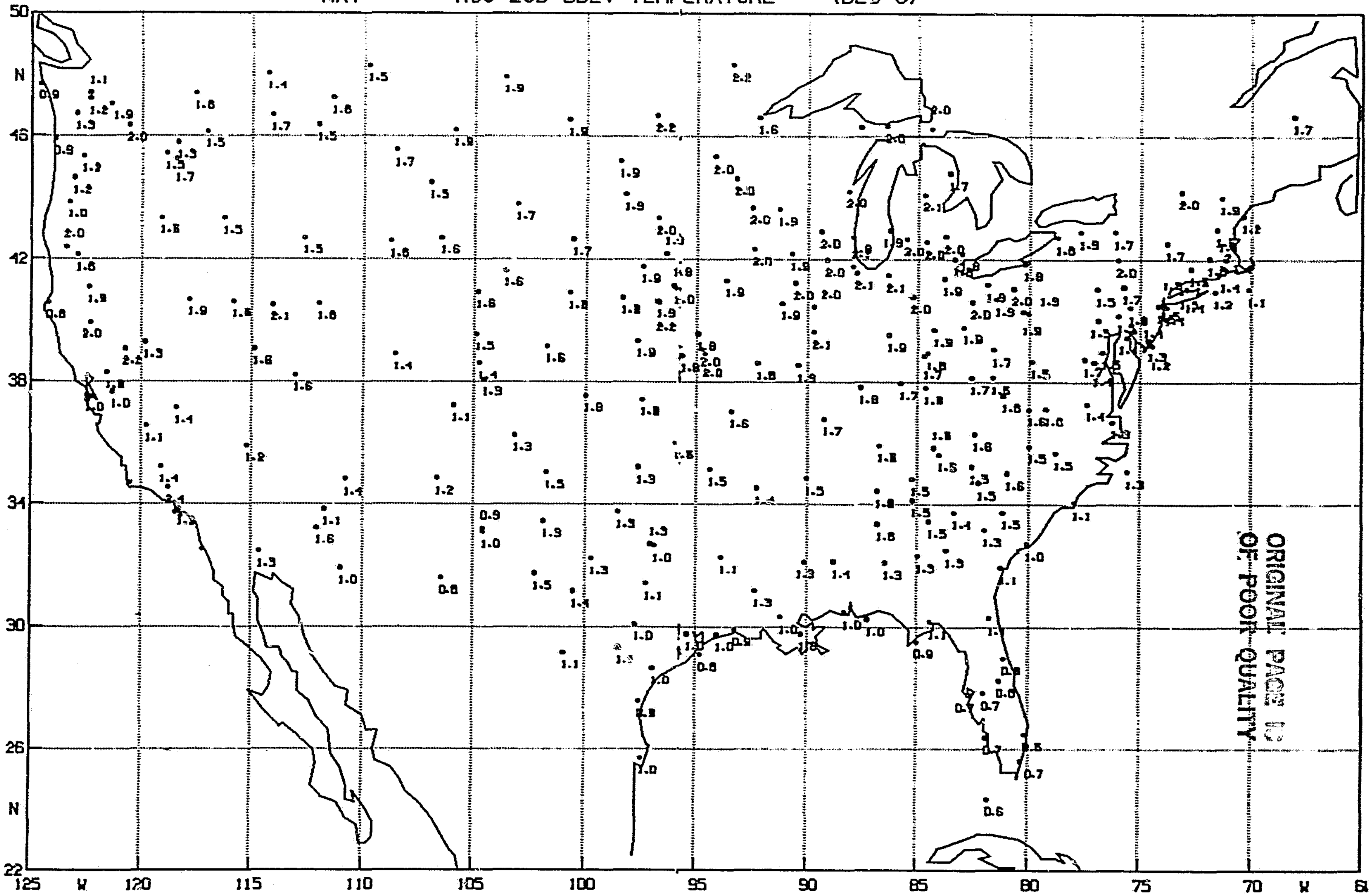
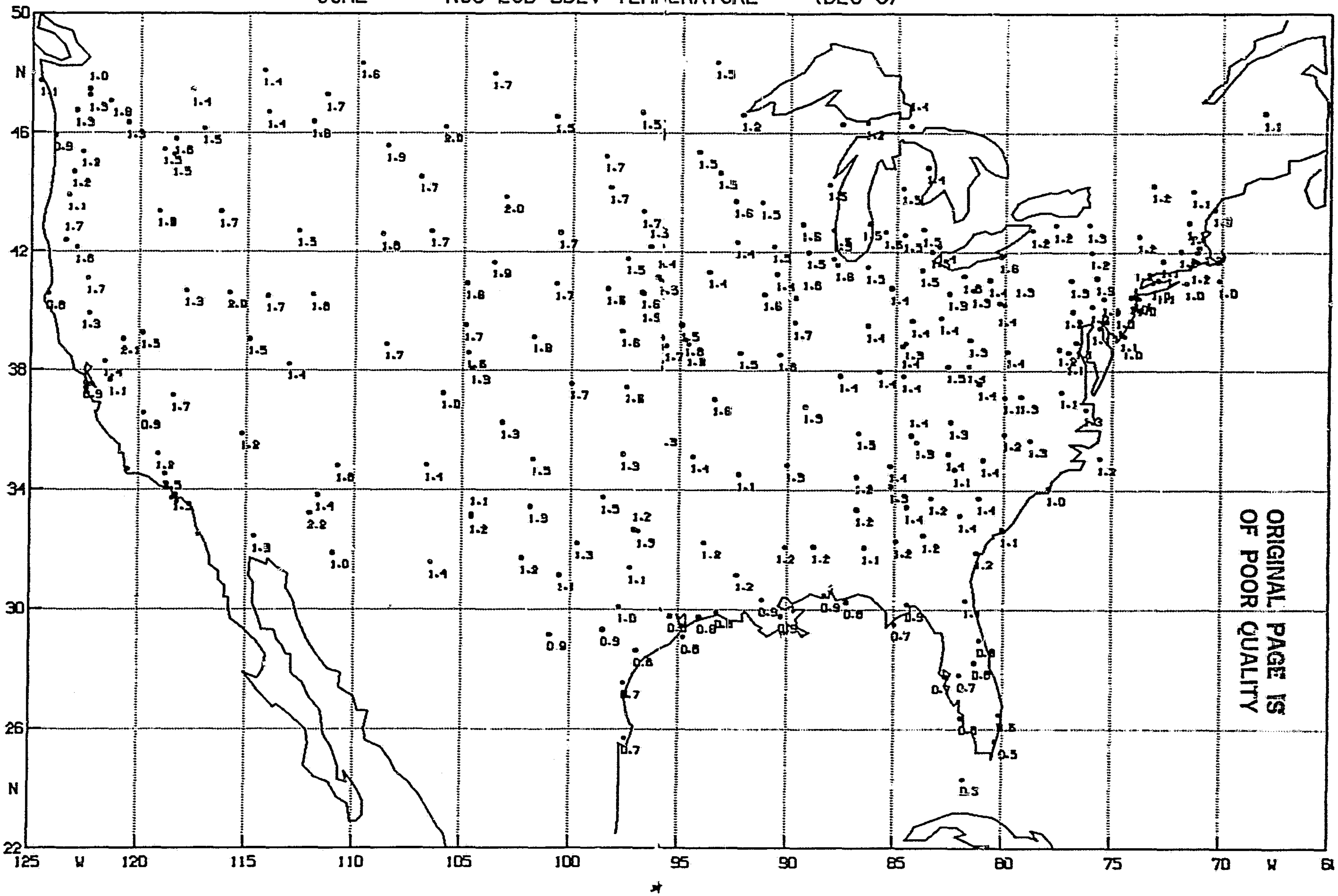


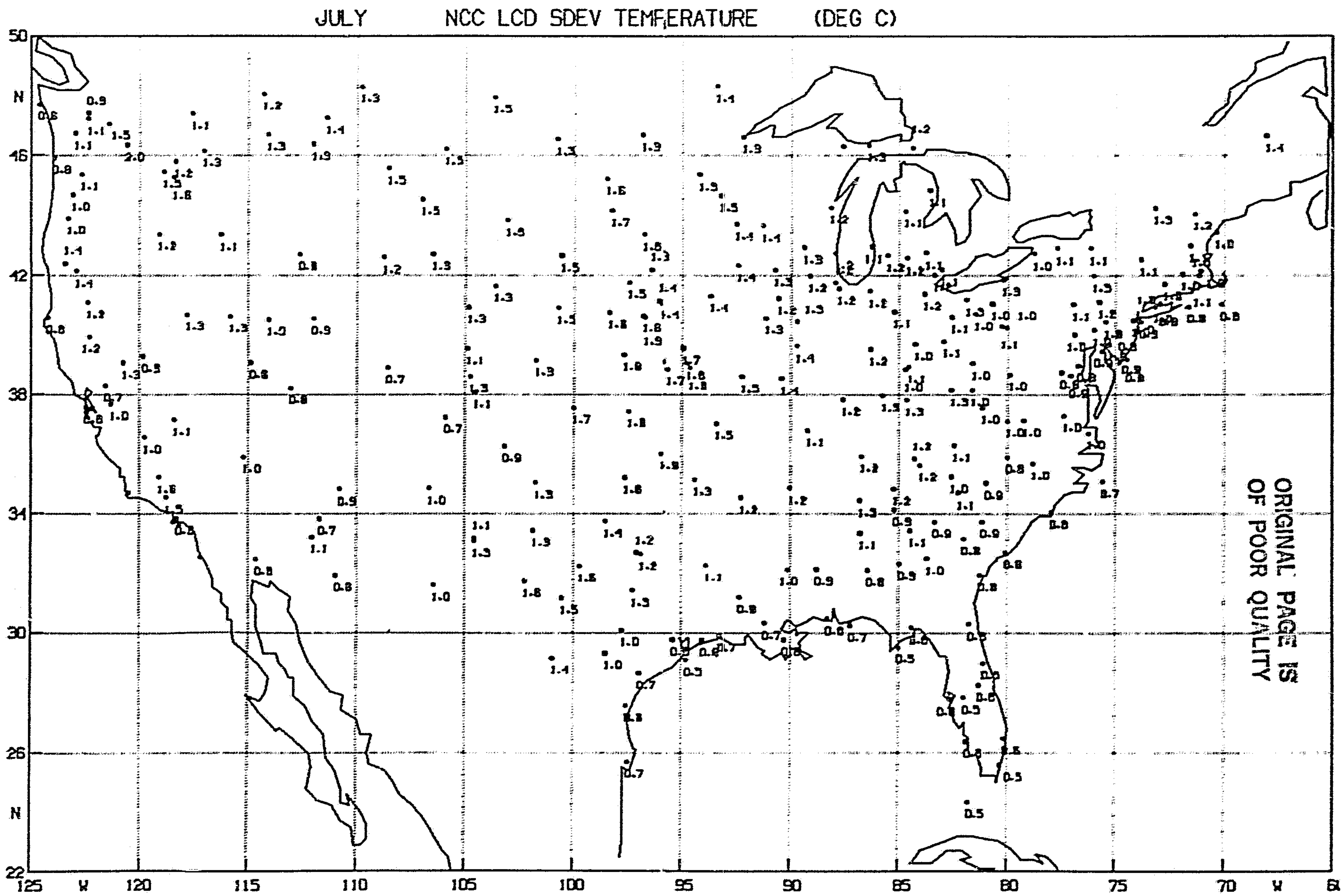
Fig. 3.b.6

JUNE NCC LCD SDEV TEMPERATURE (DEG C)



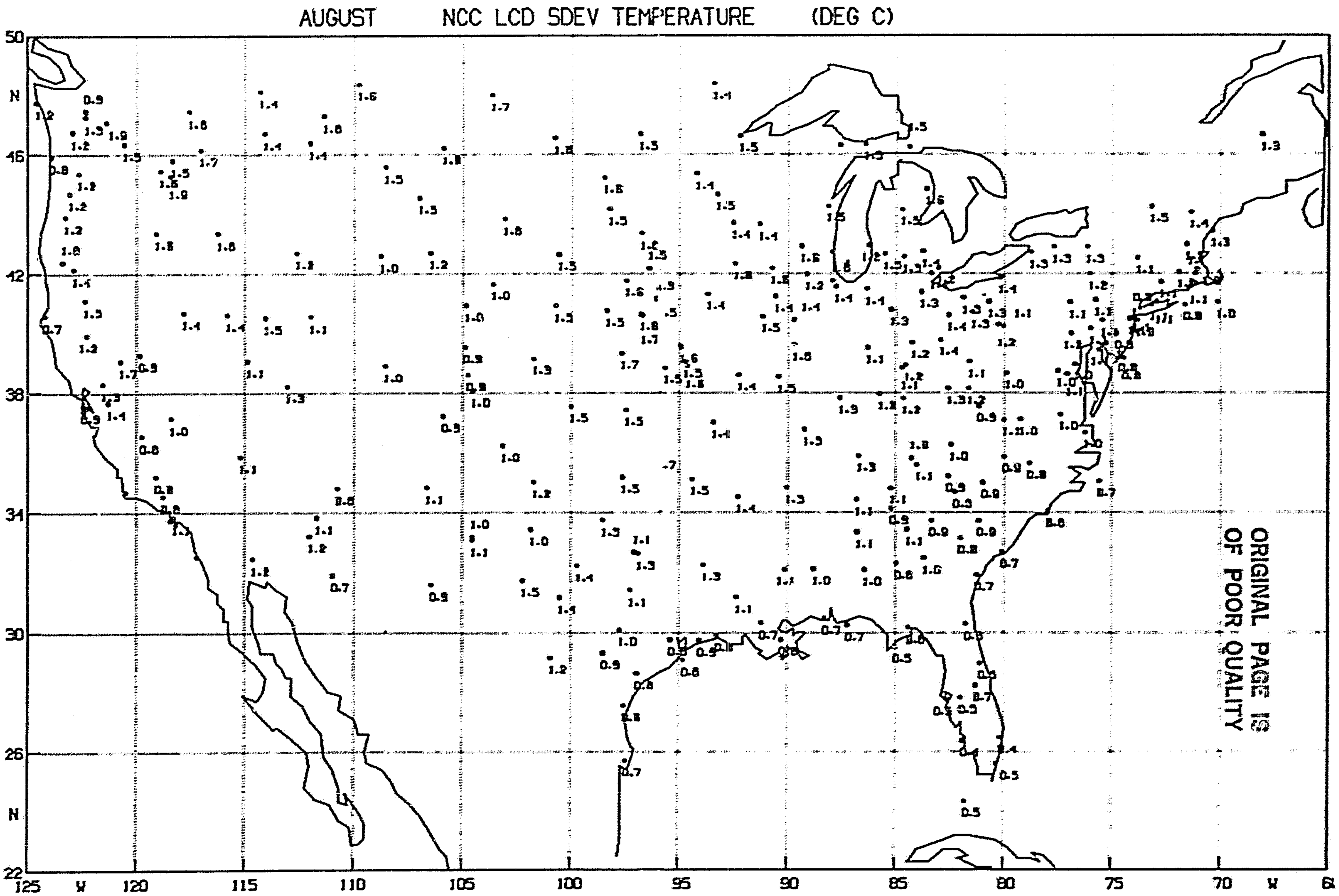
ORIGINAL PAGE IS OF POOR QUALITY

Fig. 3.b.7


JULY NCC LCD SDEV TEMPERATURE (DEG C)
50
N
46
42
38
34
30
26
N
22
125
W
120
115
110
105
100
95
90
85
80
75
70
W
61

896

Fig. 3.b.8


AUGUST NCC LCD SDEV TEMPERATURE (DEG C)
50
N
46
42
38
34
30
26
N
22
125
W
120
115
110
105
100
95
90
85
80
75
70
W
61
ORIGINAL PAGE IS OF POOR QUALITY

SEPTMBER NCC LCD SDEV TEMFERATURE (DEG C)

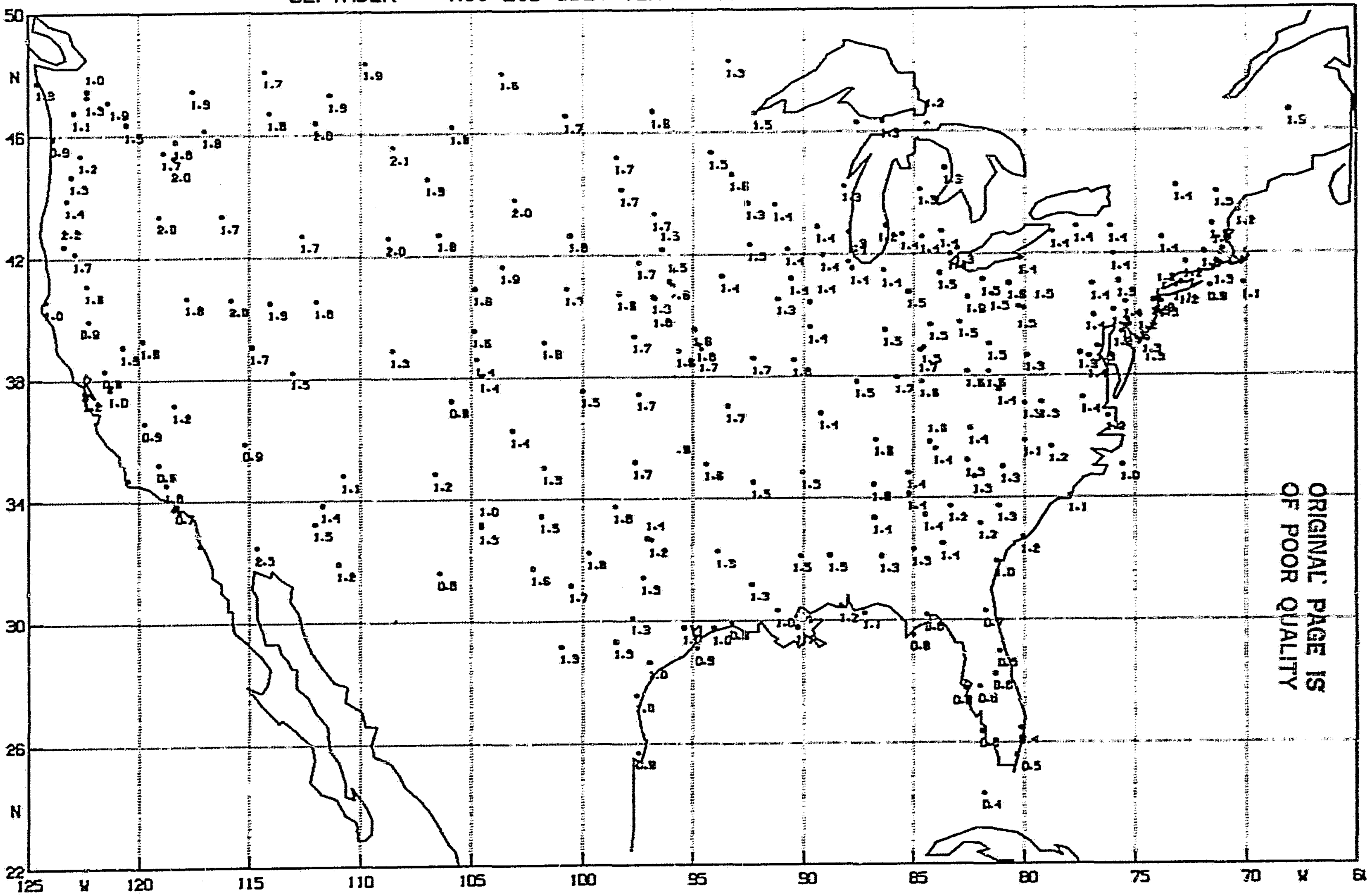


Fig. 3.b.10

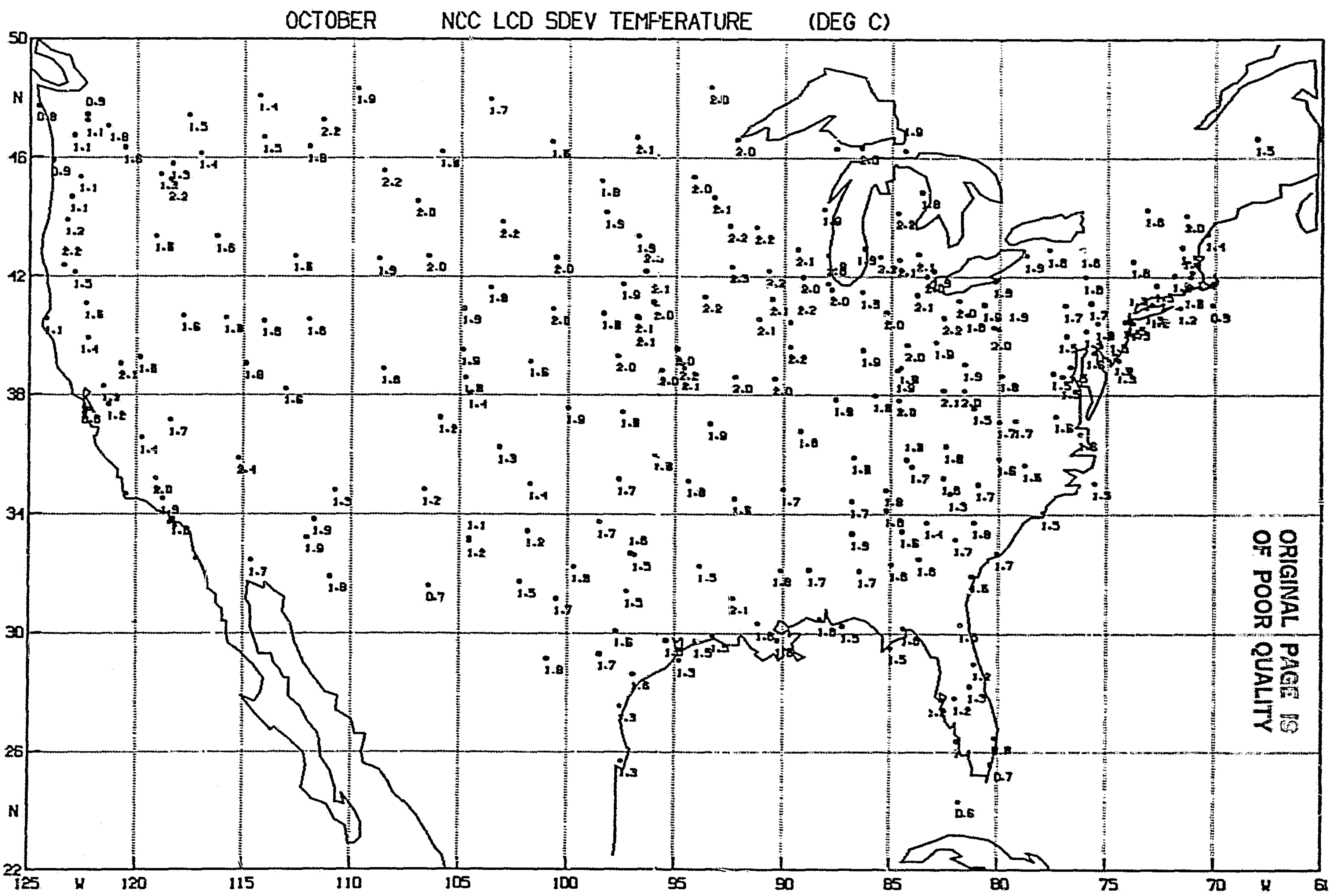

OCTOBER NCC LCD SDEV TEMPERATURE (DEG C)
50
N
46
42
38
34
30
26
N
22
125
W
120
115
110
105
100
95
90
85
80
75
70
W
61
ORIGINAL PAGE IS
OF POOR QUALITY

Fig. 3.b.11

NOVEMBER NCC LCD SDEV TEMPERATURE (DEG C)

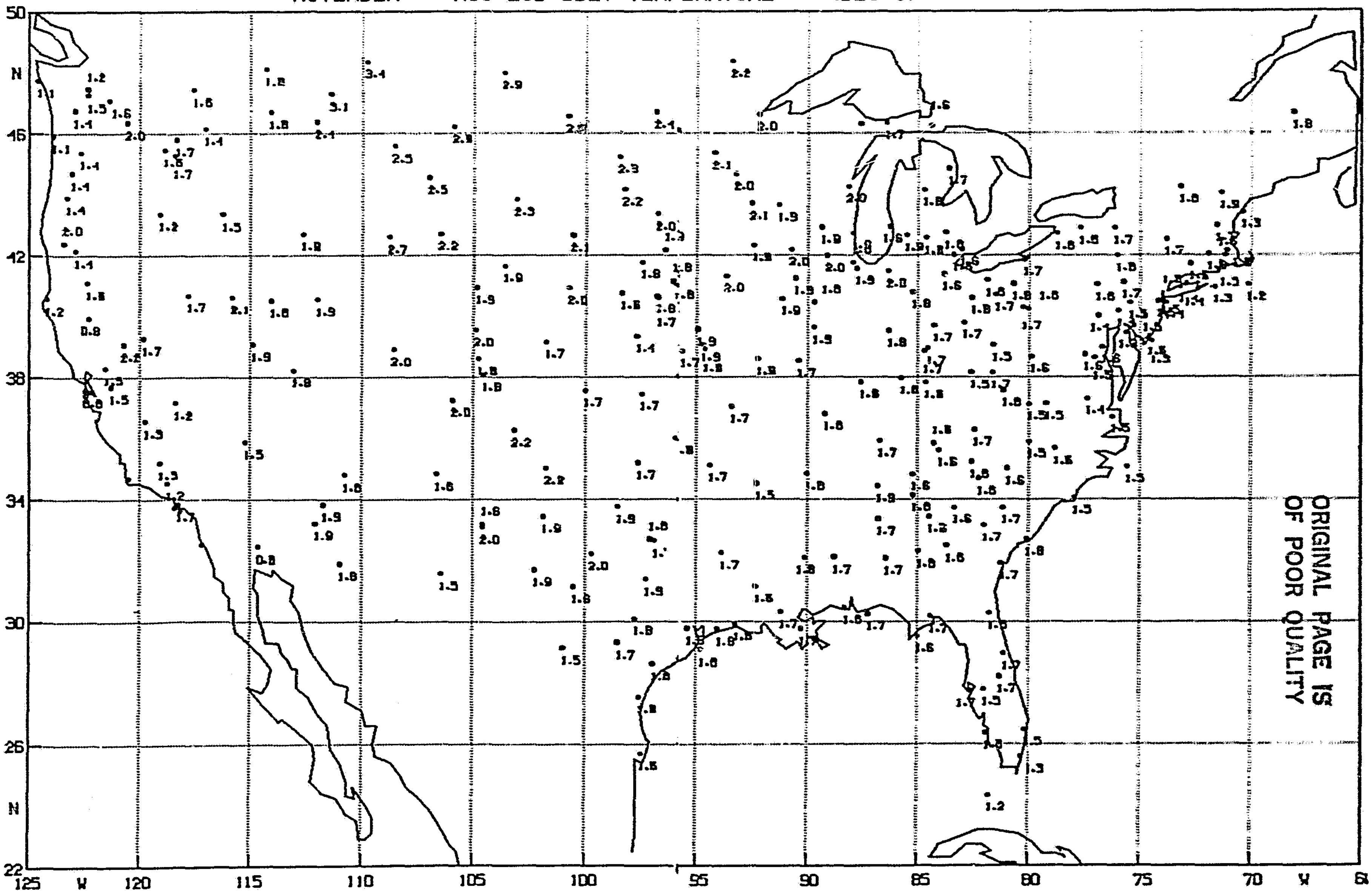
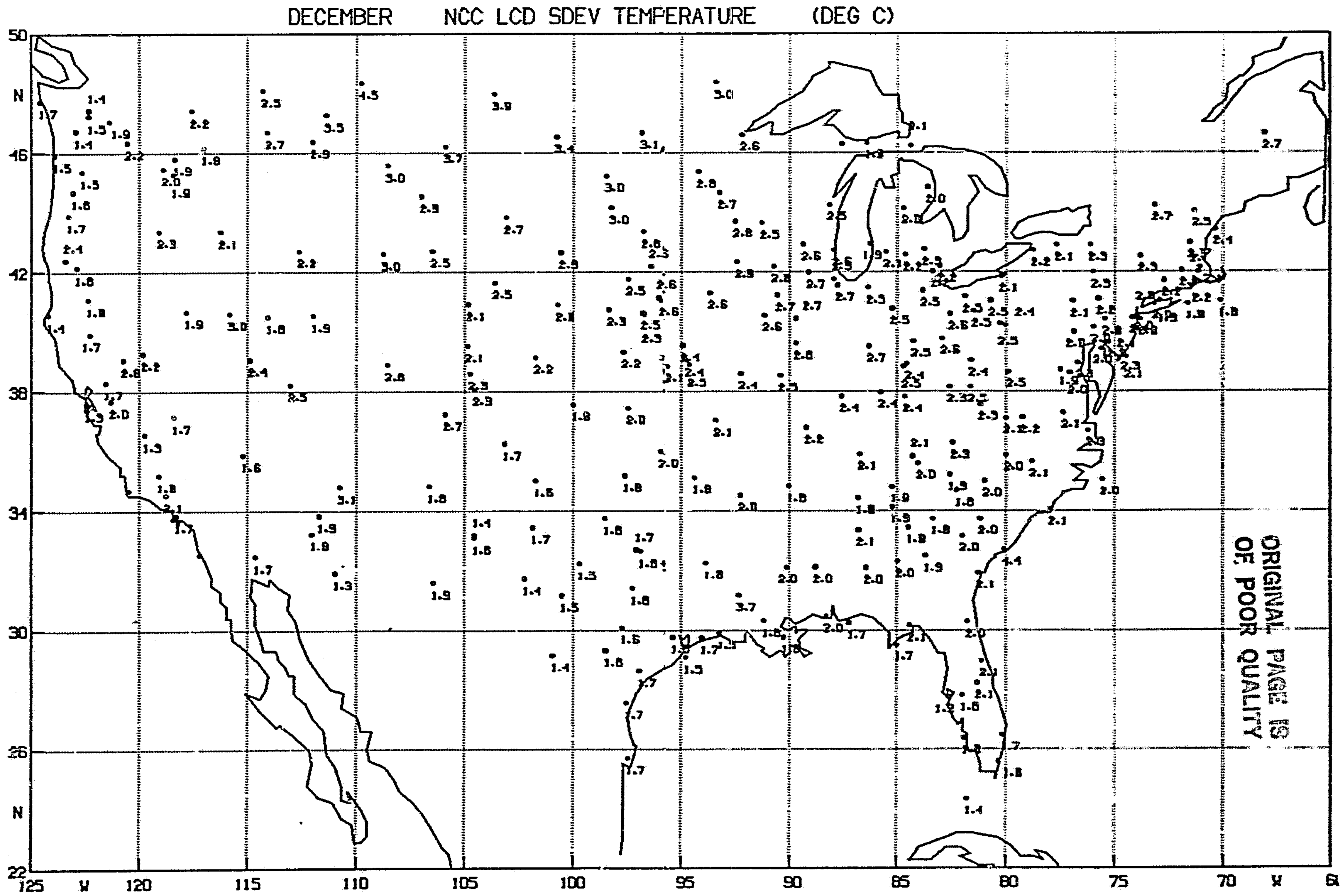


Fig. 3.b.12



ORIGINAL PAGE IS OF POOR QUALITY

Fig. 4.a.1

JANUARY NCC LCD MEAN PRECIPITATION (MM/MO)

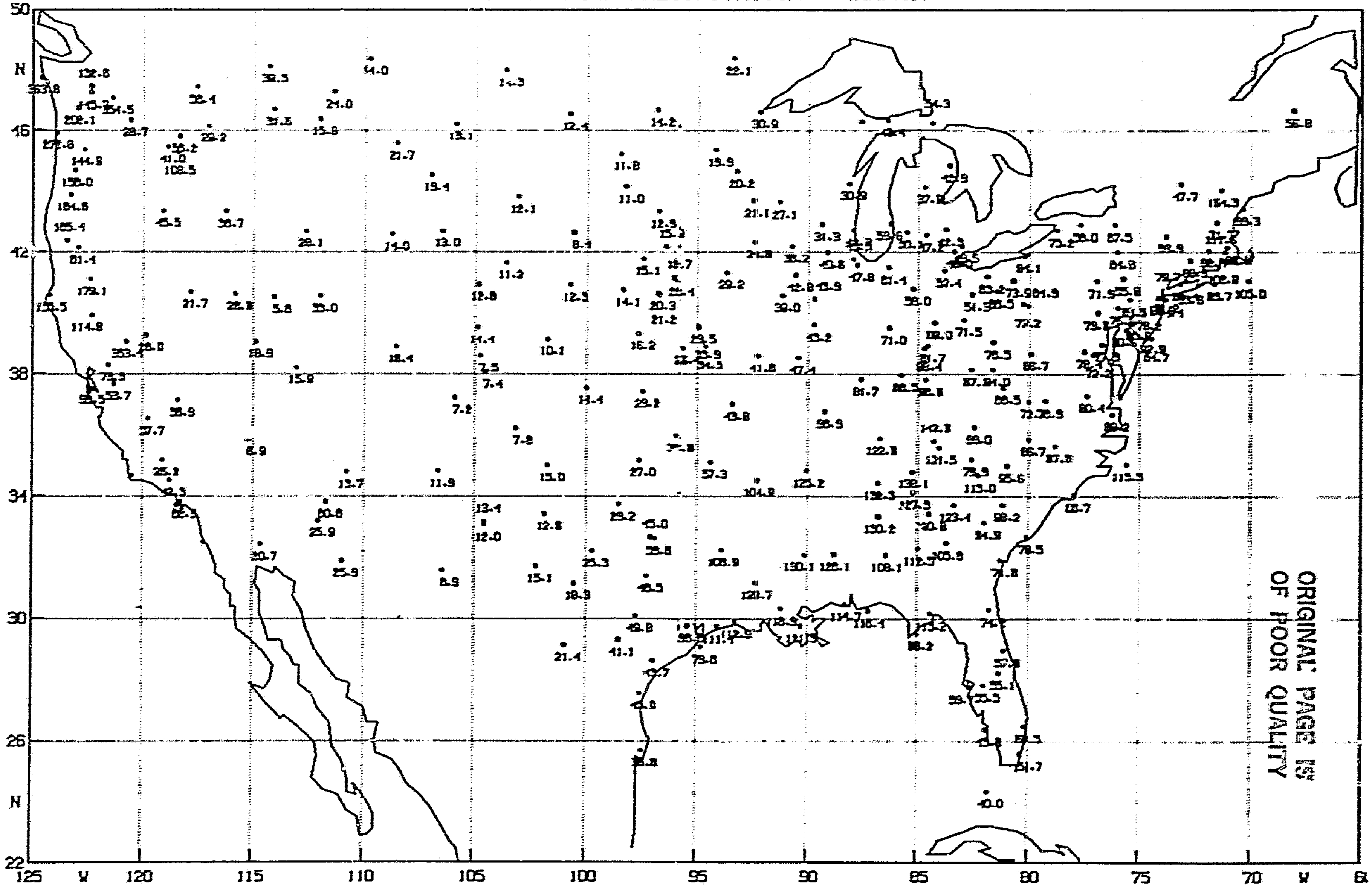
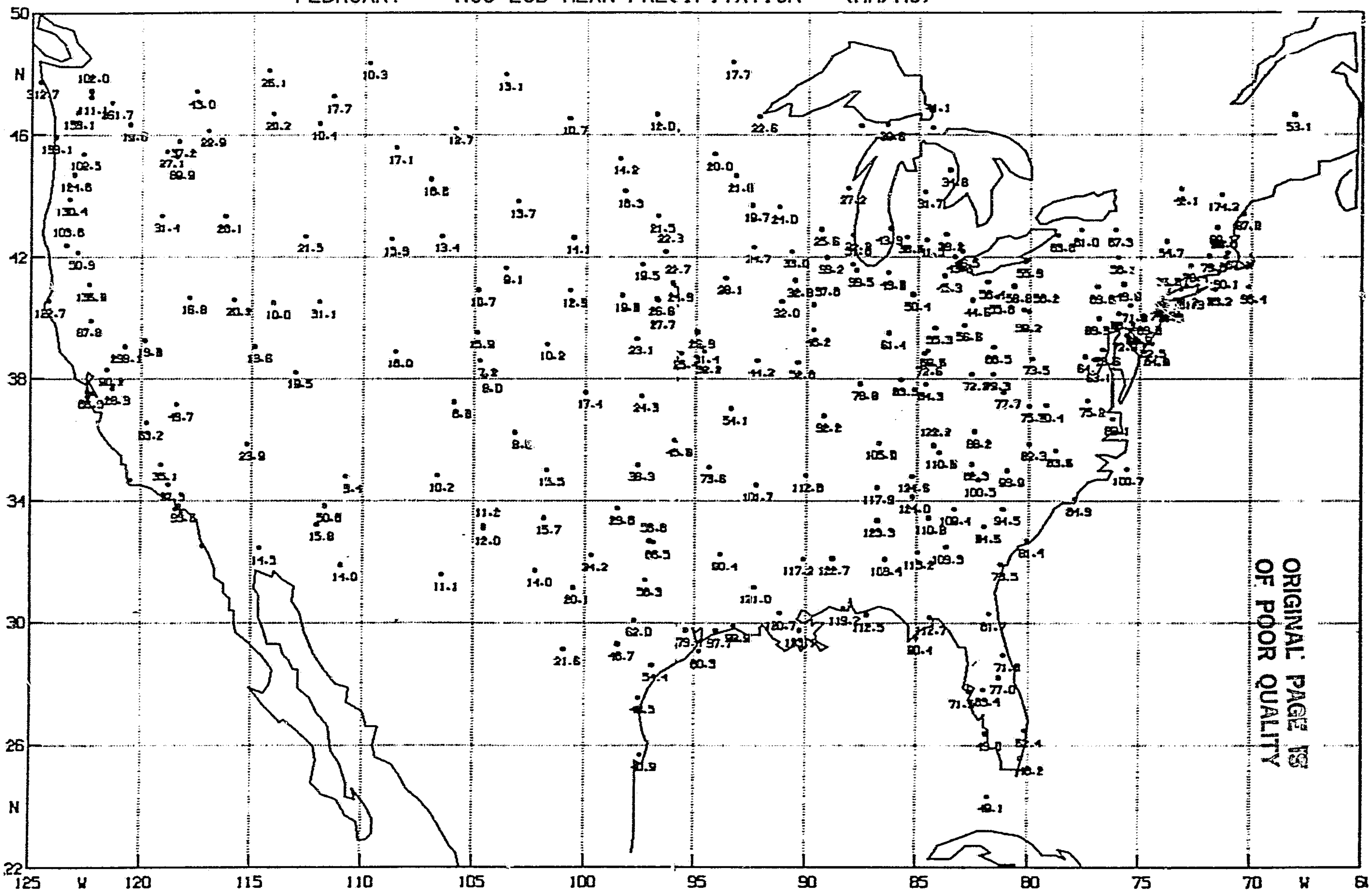


Fig. 4.a.2

FEBRUARY NCC LCD MEAN PRECIPITATION (MM/MO)



ORIGINAL PAGE IS OF POOR QUALITY

882 881

Fig. 4.a.3

MARCH NCC LCD MEAN PRECIPITATION (MM/MO)

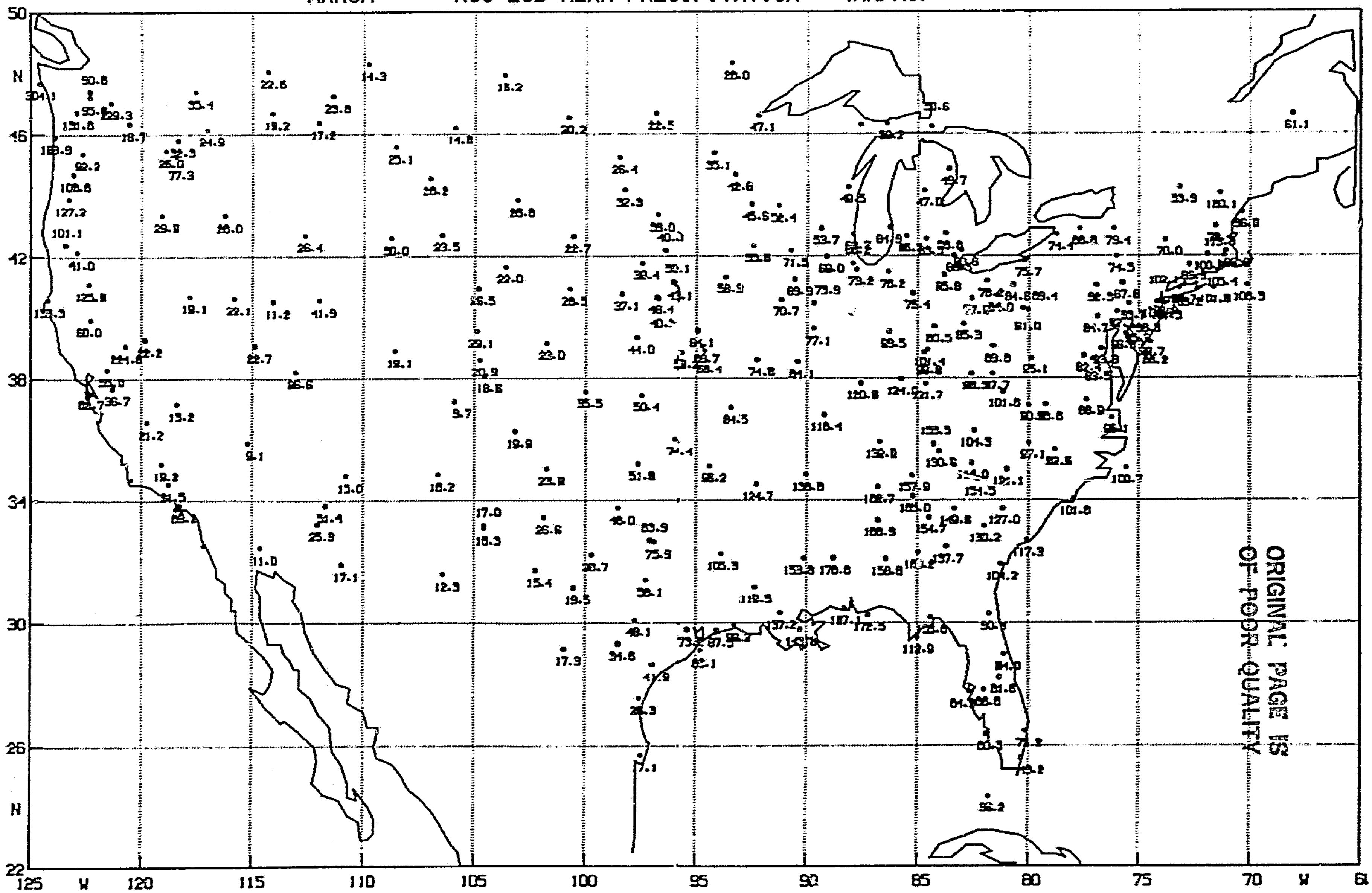


Fig. 4.a.4

APRIL NCC LCD MEAN PRECIPITATION (MM/MO)

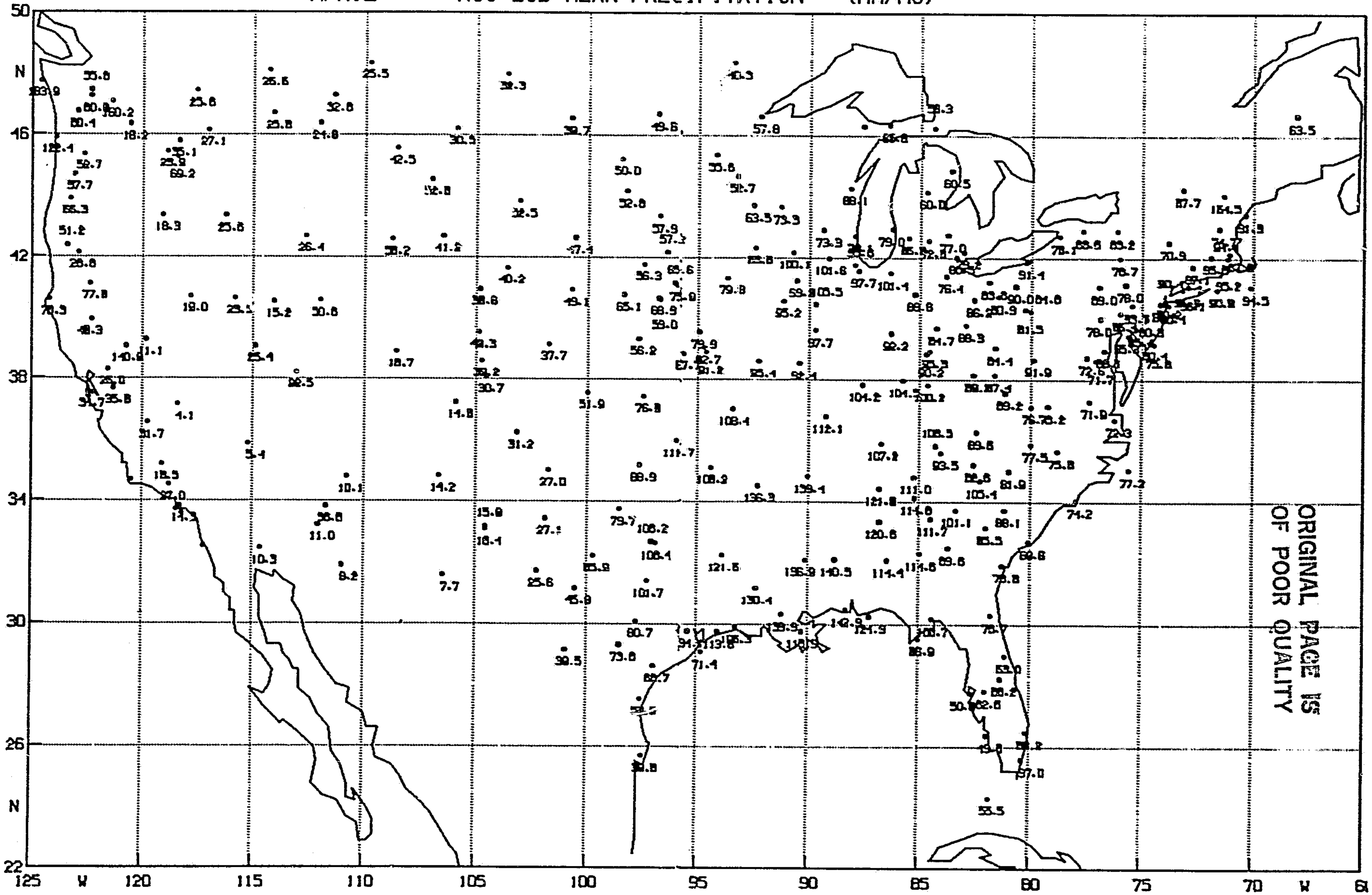
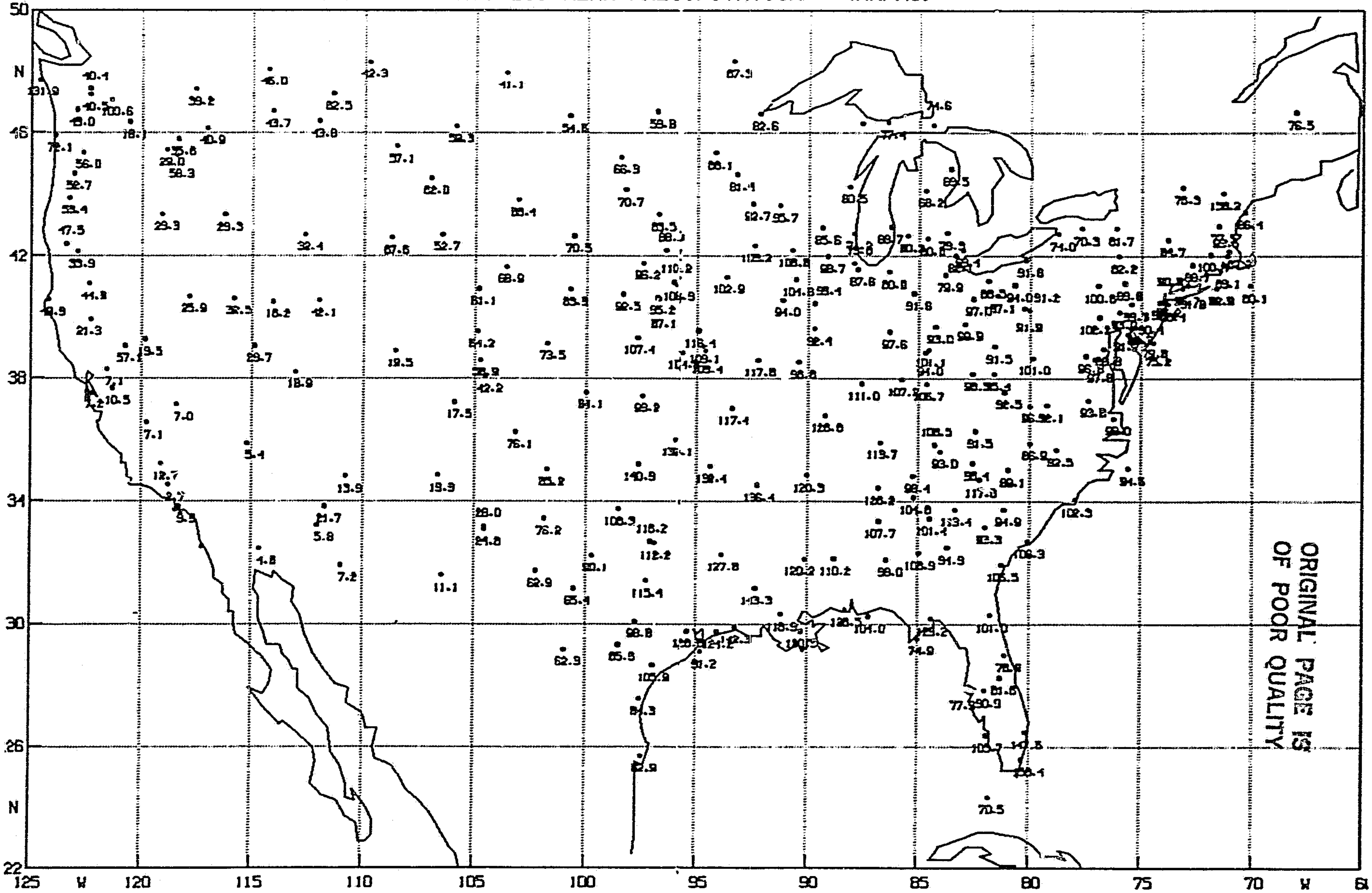


Fig. 4.a.5

MAY NCC LCD MEAN PRECIPITATION (MM/MO)



JUNE NCC LCD MEAN PRECIPITATION (MM/MO)

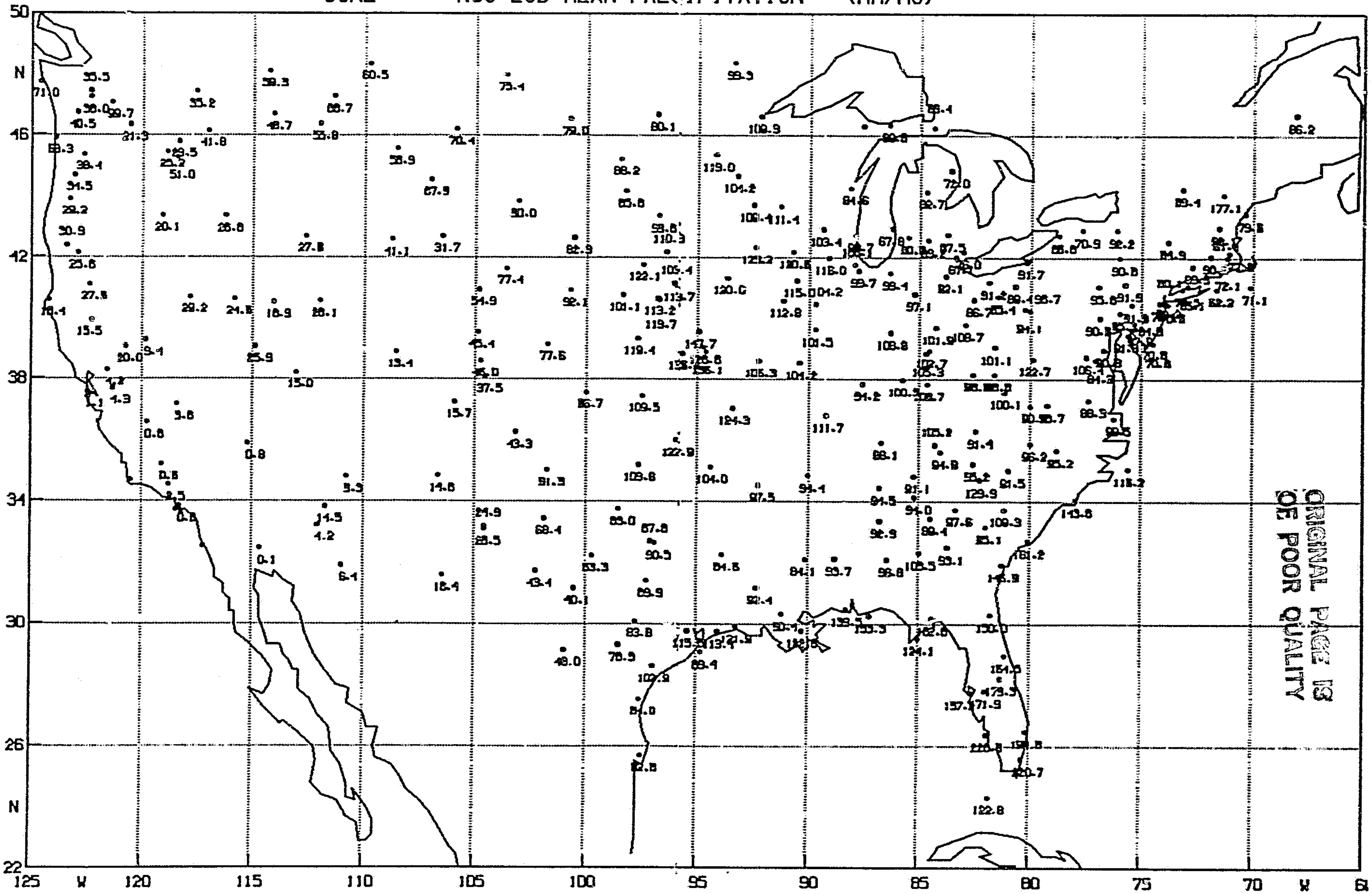
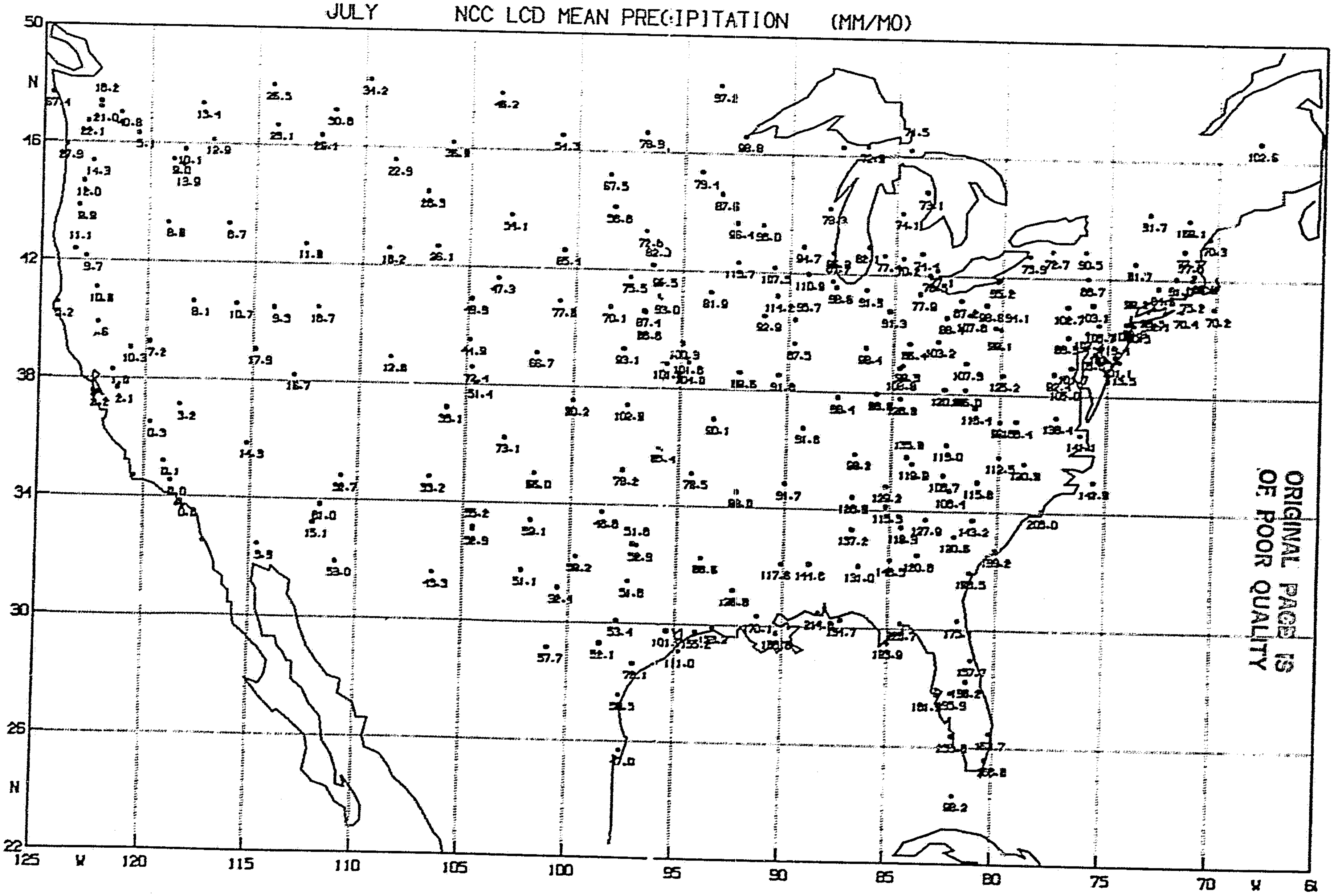


Fig. 4.a.7



JULY NCC LCD MEAN PRECIPITATION (MM/MO)
50
N
46
42
38
34
30
26
N
22
125
W
120
115
110
105
100
95
90
85
80
75
70
W
65
ORIGINAL PAGE IS
OF POOR QUALITY

Fig. 4.a.8

AUGUST NCC LCD MEAN PRECIPITATION (MM/MO)

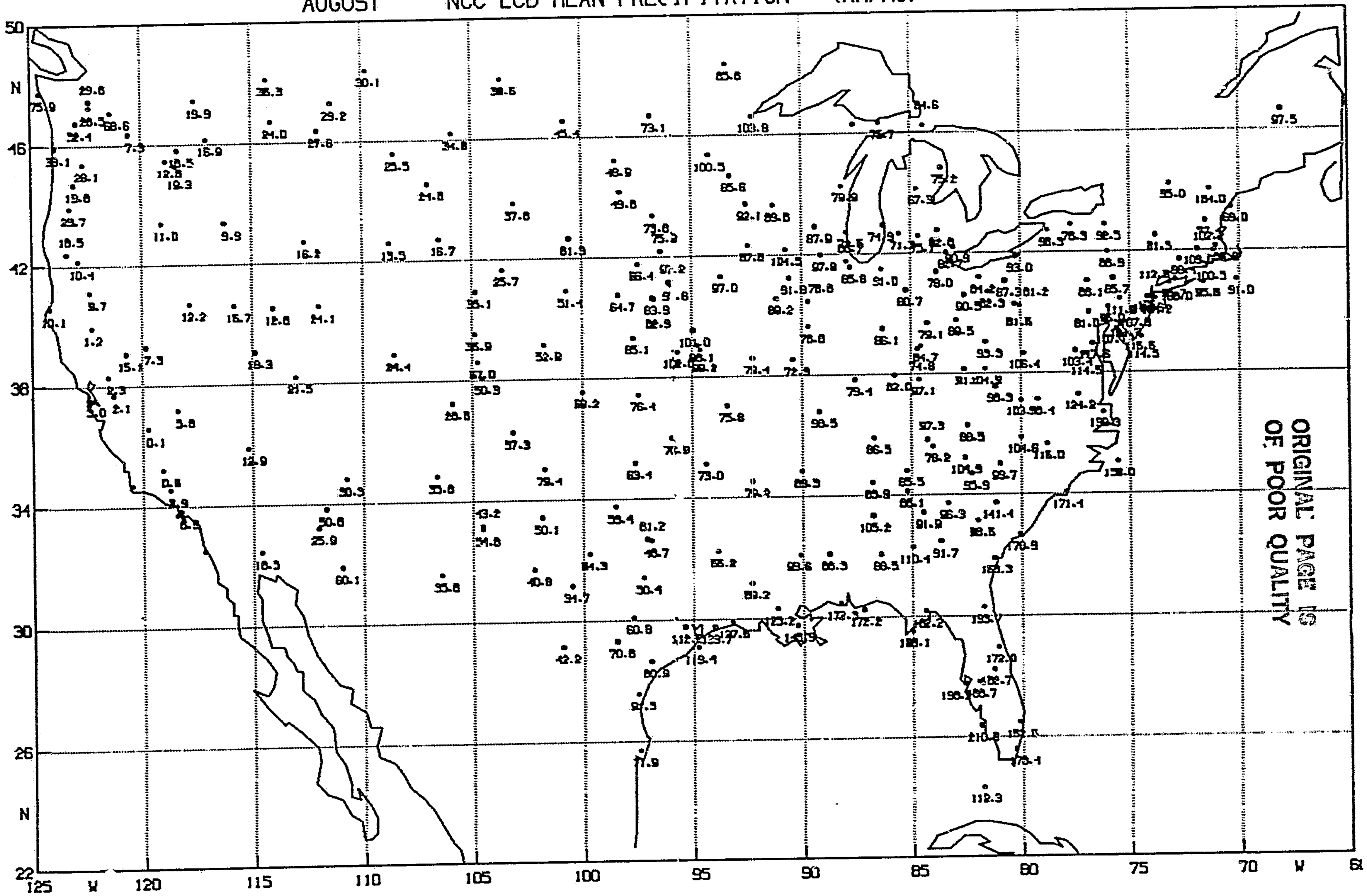


Fig. 4.a.9

SEPTMBER NCC LCD MEAN PRECIPITATION (MM/MO)

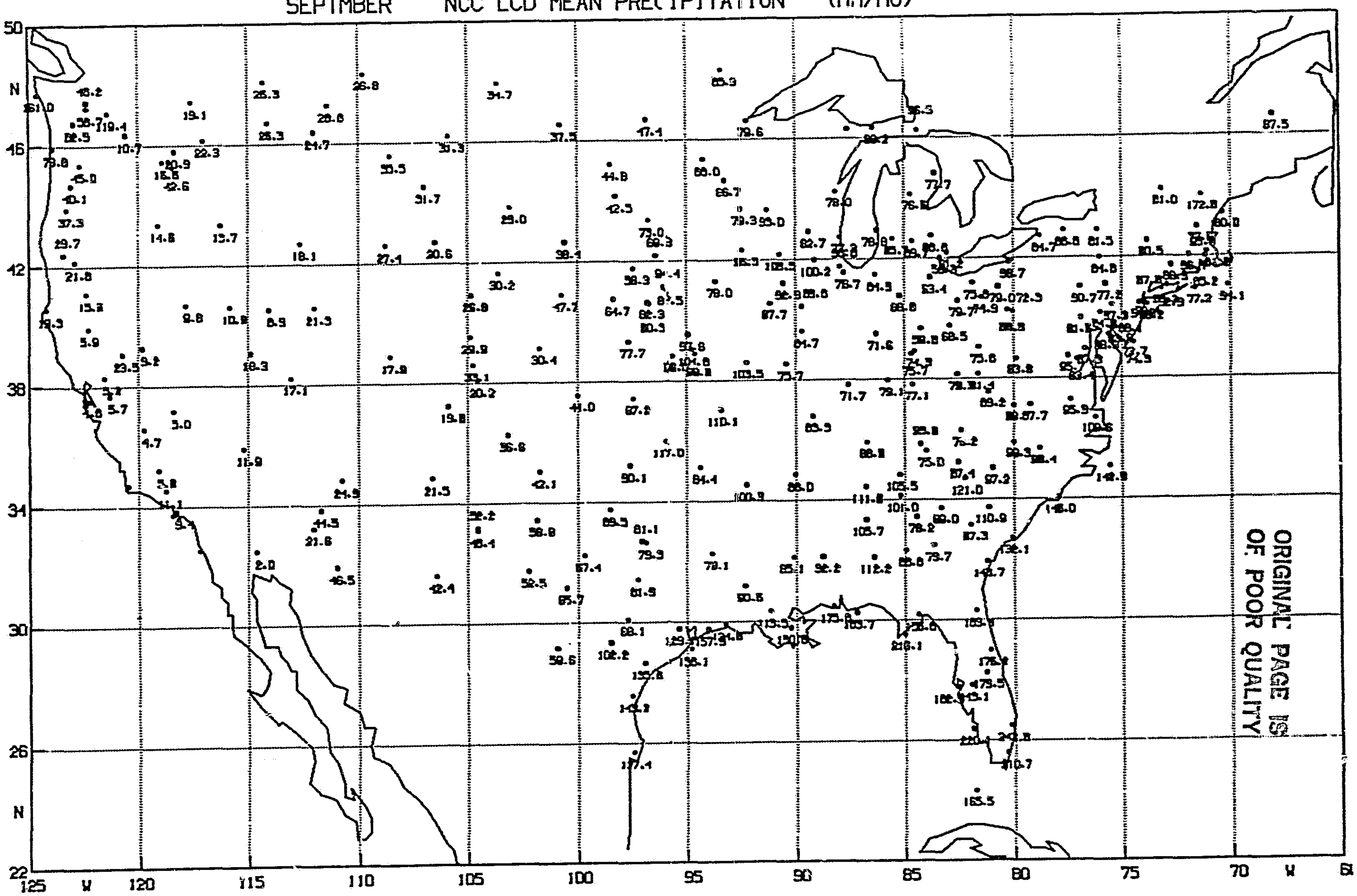


Fig. 4.a.10

OCTOBER NCC LCD MEAN PRECIPITATION (MM/MO)

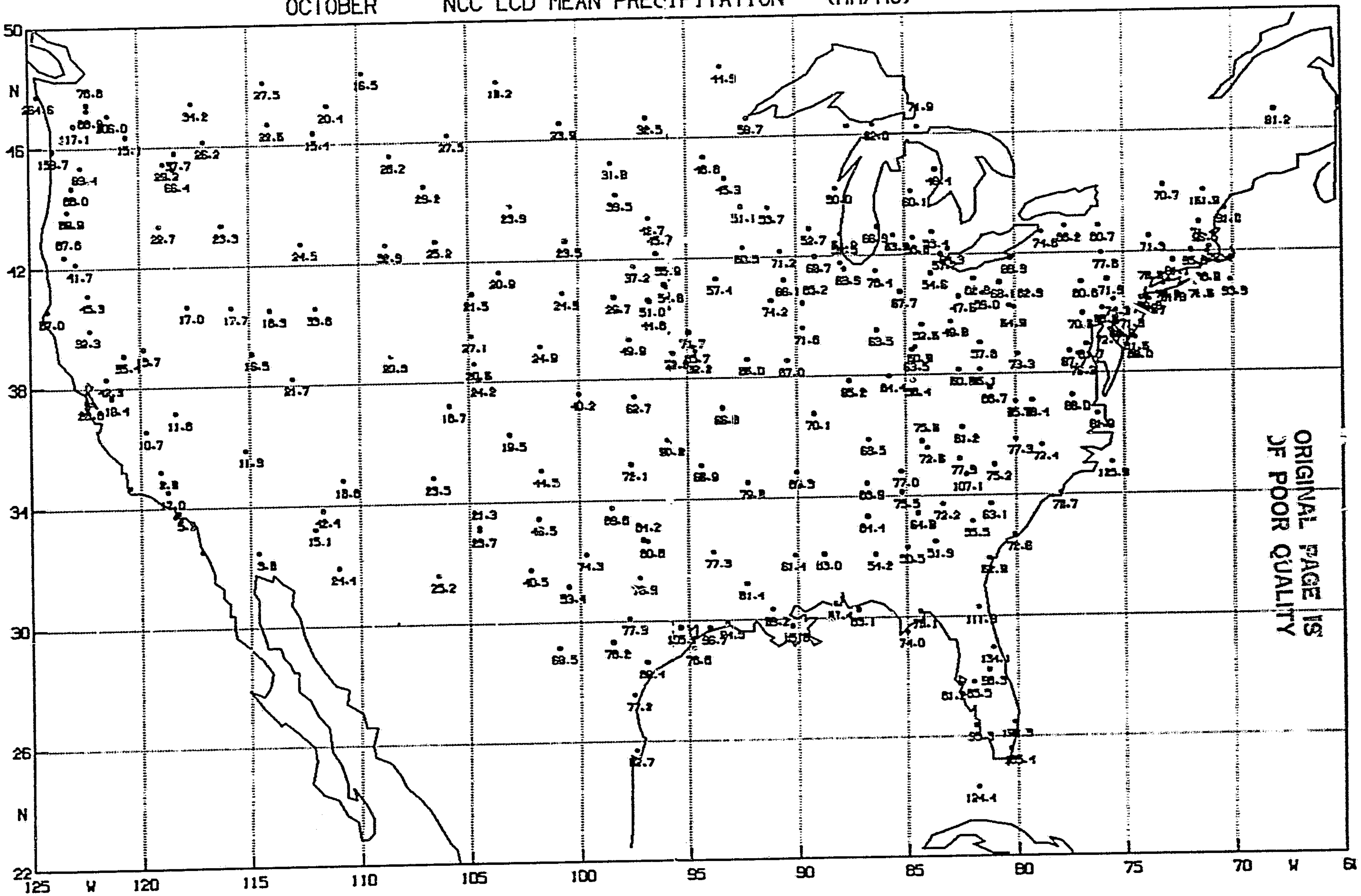
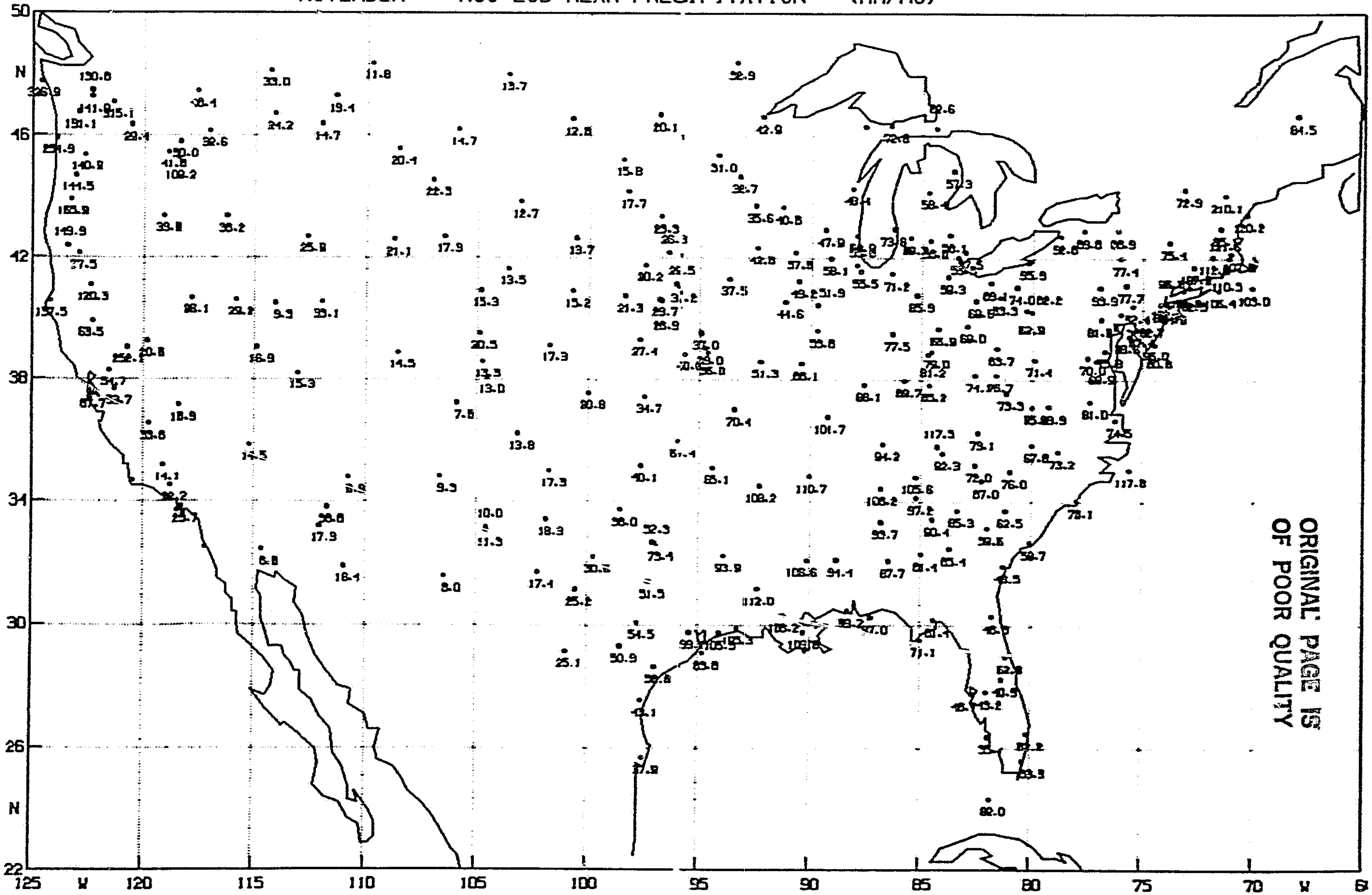


Fig. 4.a.11

NOVEMBER NCC LCD MEAN PRECIPITATION (MM/MO)



ORIGINAL PAGE IS
OF POOR QUALITY

Fig. 4.a.12

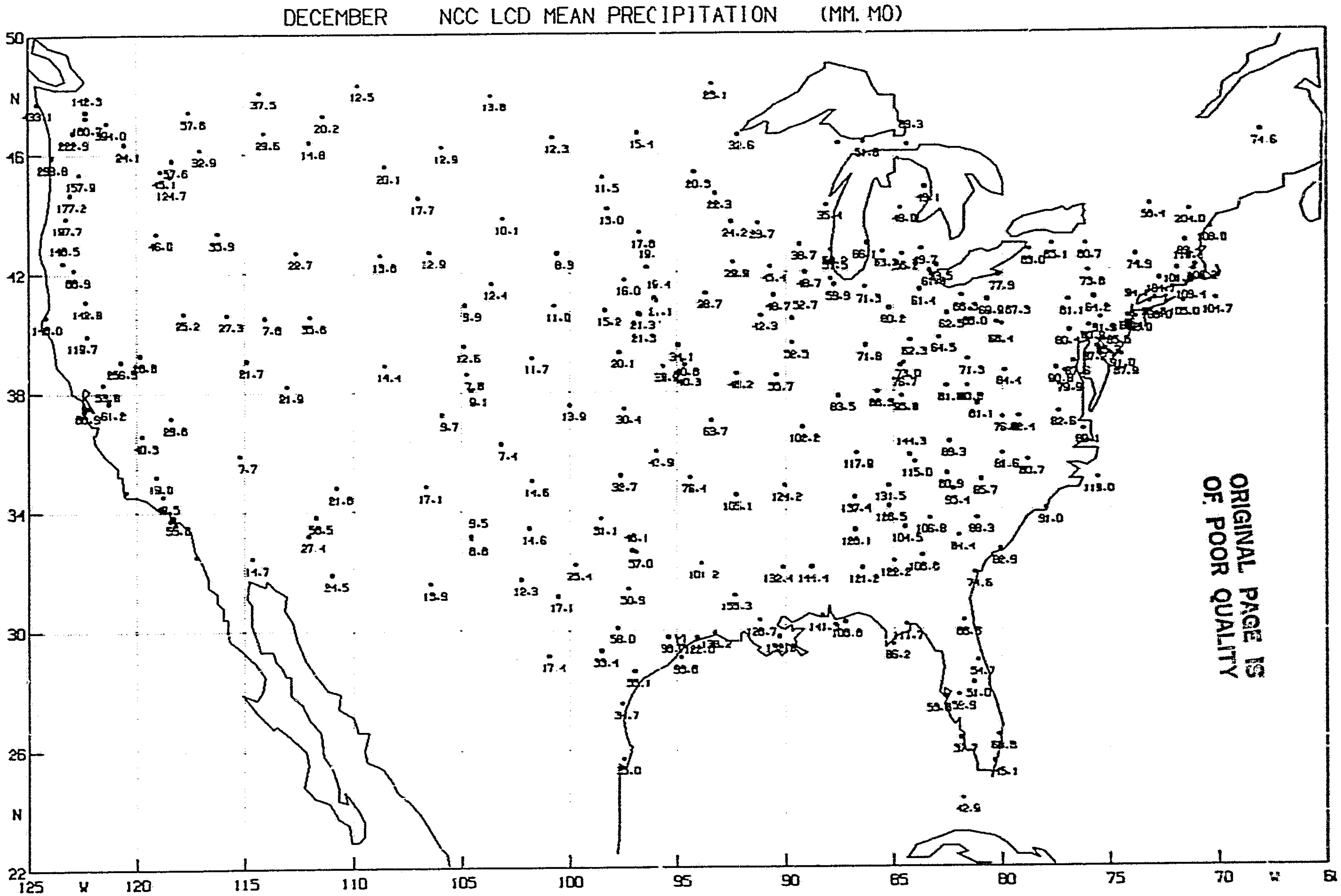

DECEMBER NCC LCD MEAN PRECIPITATION (MM. MO)
50
N
46
42
38
34
30
26
N
22
125
W
120
115
110
105
100
95
90
85
80
75
70
W
65

Fig. 4.b.1

JANUARY NCC LCD SDEV PRECIPITATION (MM/MO)

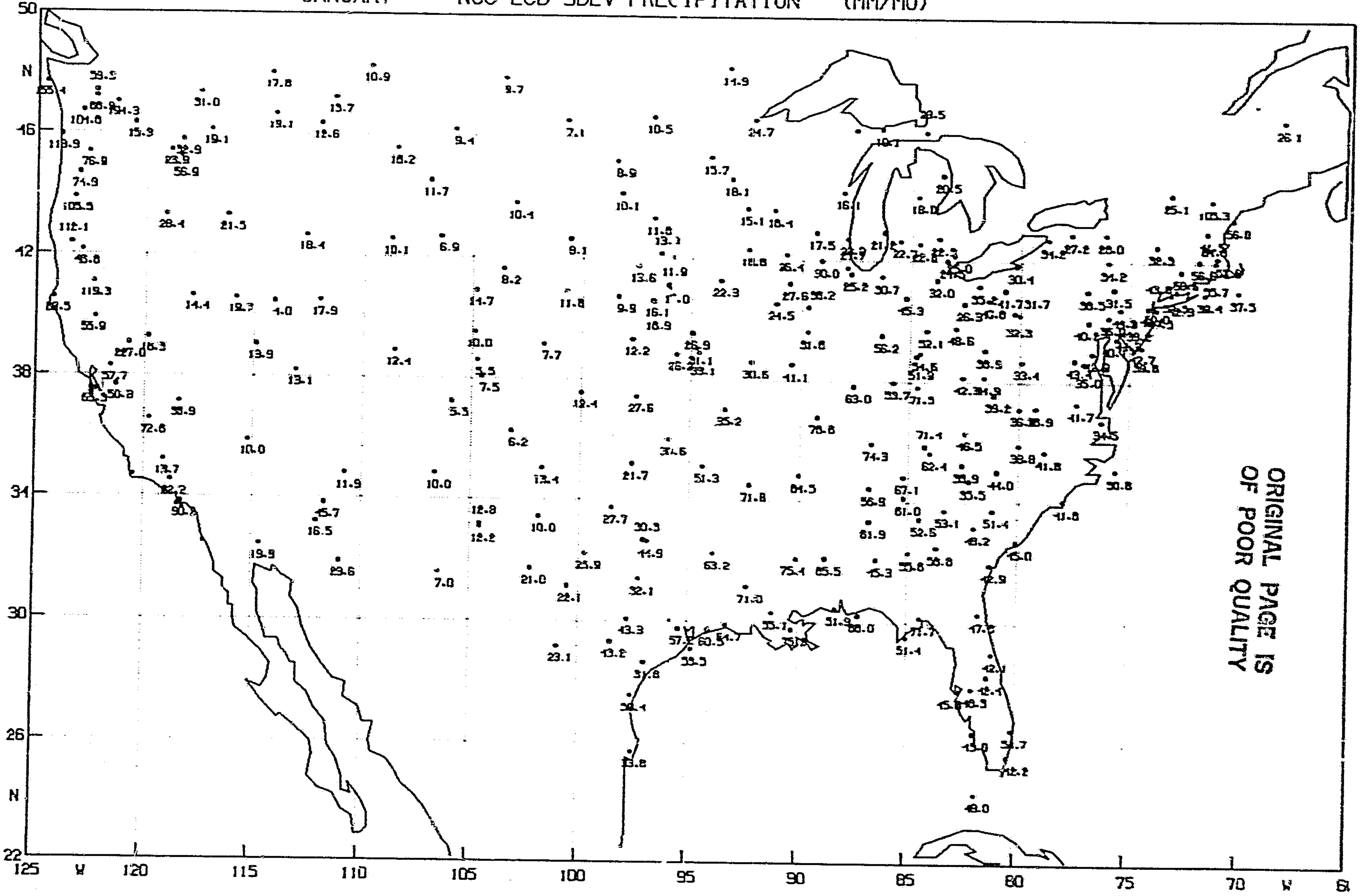


Fig. 4.b.2

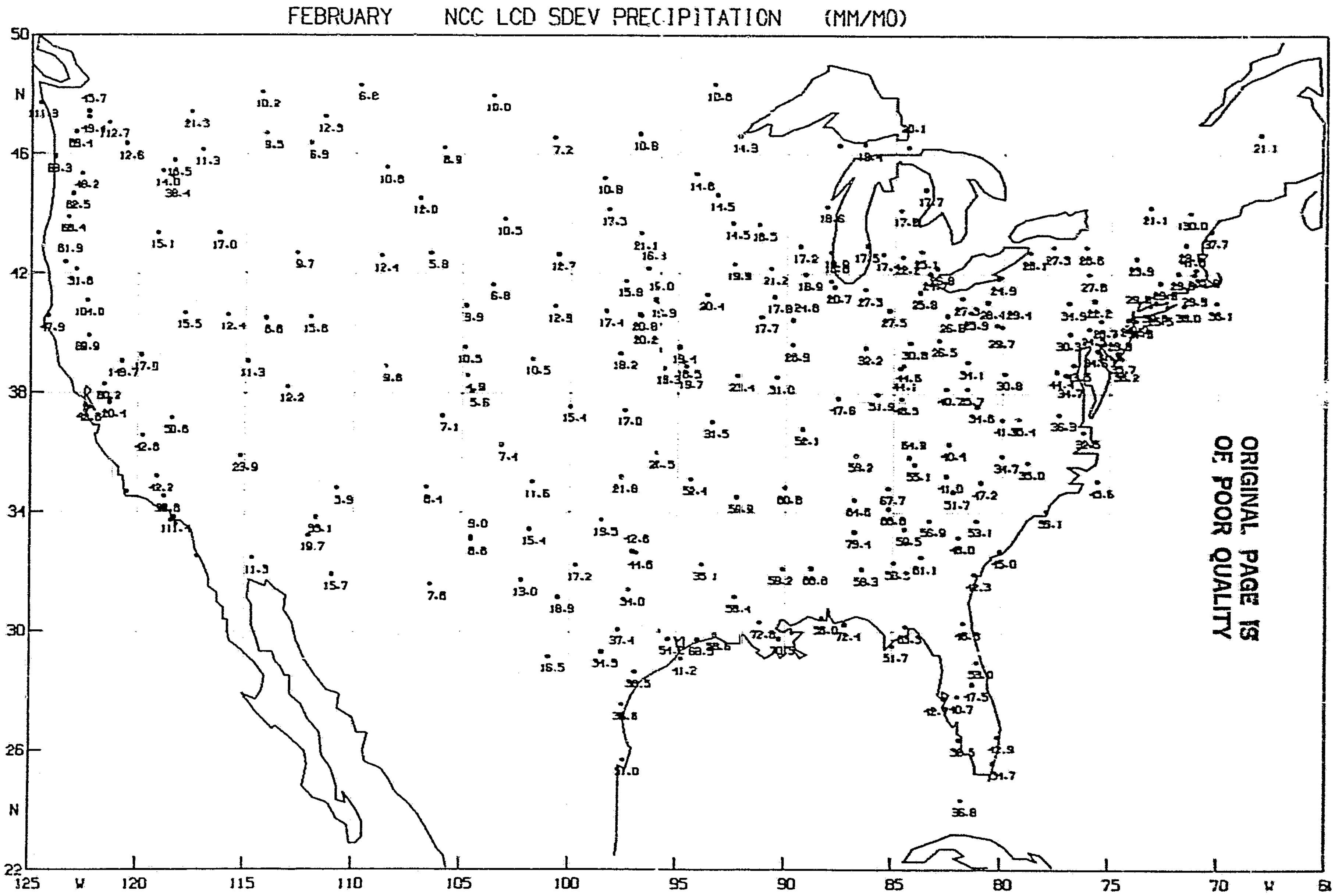

FEBRUARY NCC LCD SDEV PRECIPITATION (MM/MO)
50
N
46
42
38
34
30
26
N
22
125
W
120
115
110
105
100
95
90
85
80
75
70
W
65

Fig. 4.b.3

MARCH NCC LCD SDEV PRECIPITATION (MM/MO)

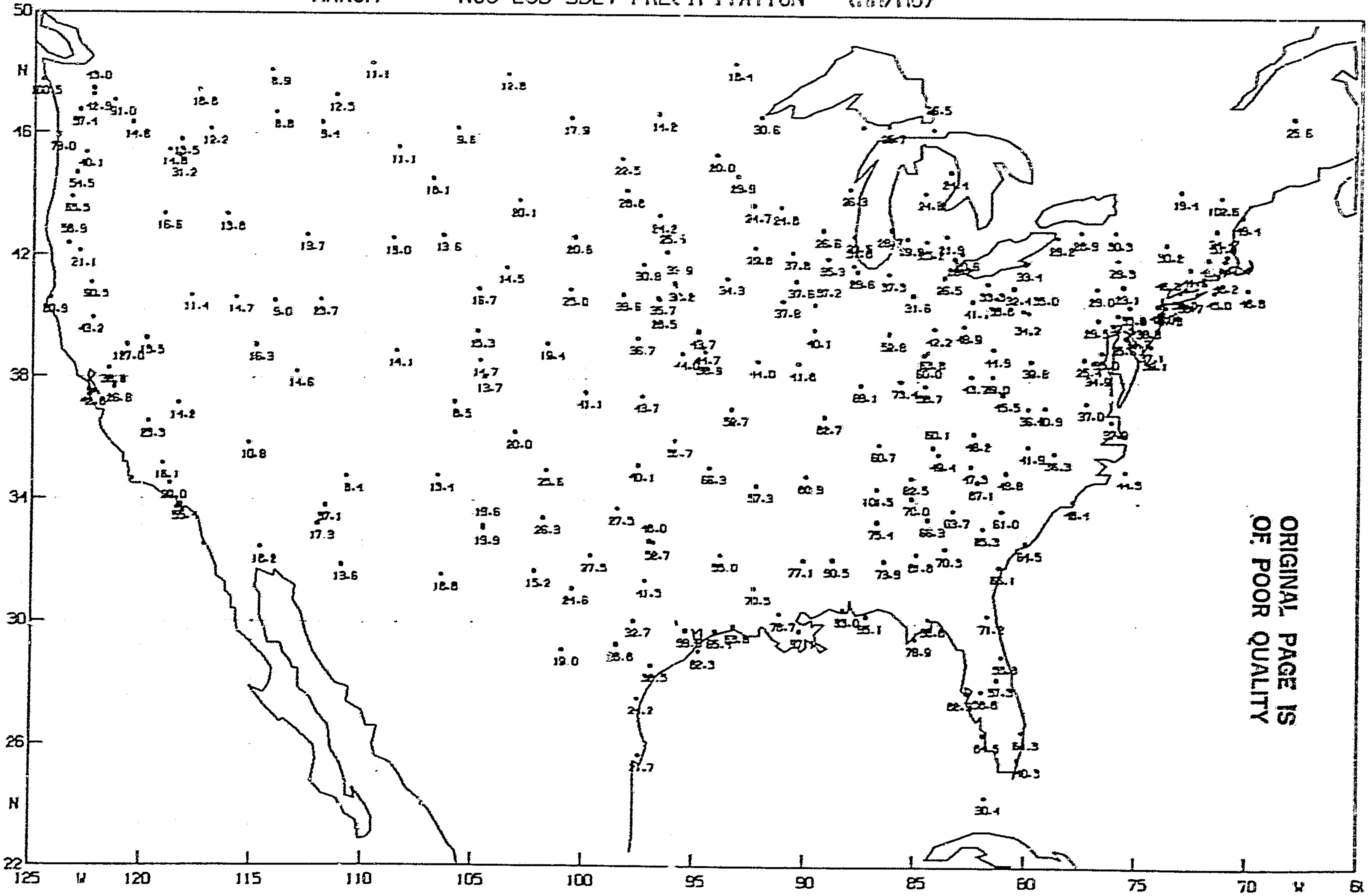


Fig. 4.b.4

APRIL NCC LCD SDEV PRECIPITATION (MM/MO)

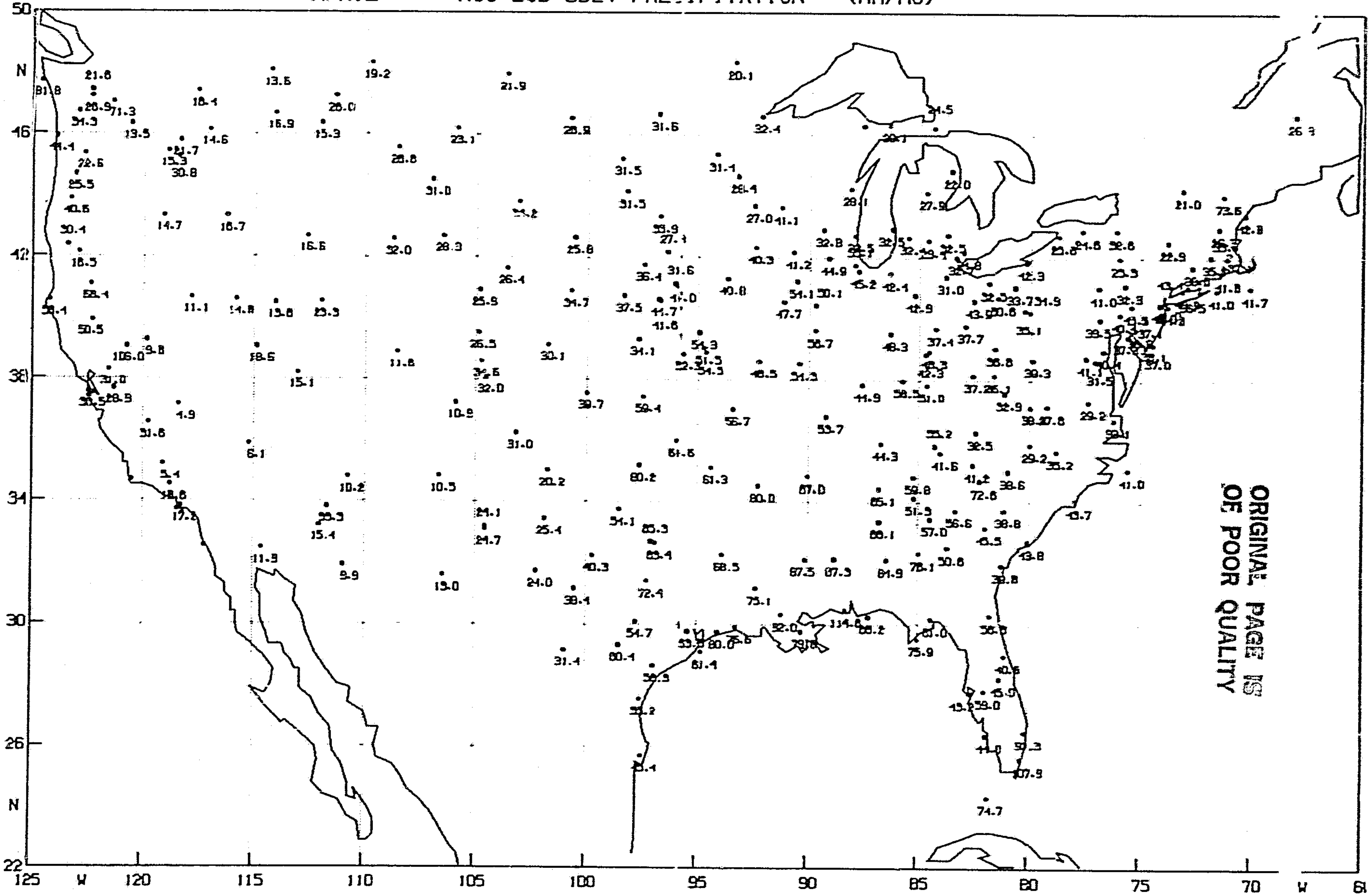


Fig. 4.b.5

MAY NCC LCD SDEV PRECIPITATION (MM/MO)

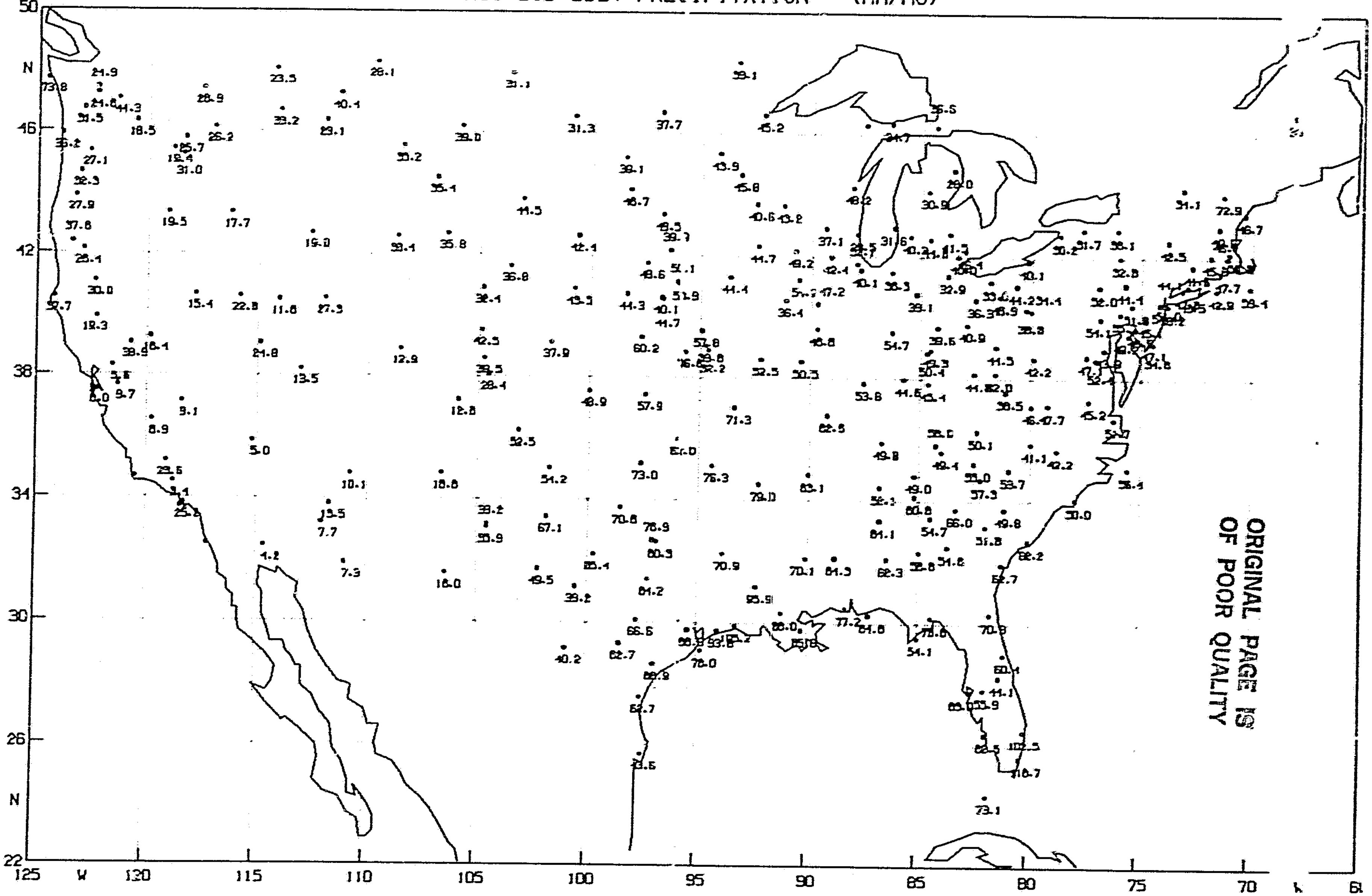
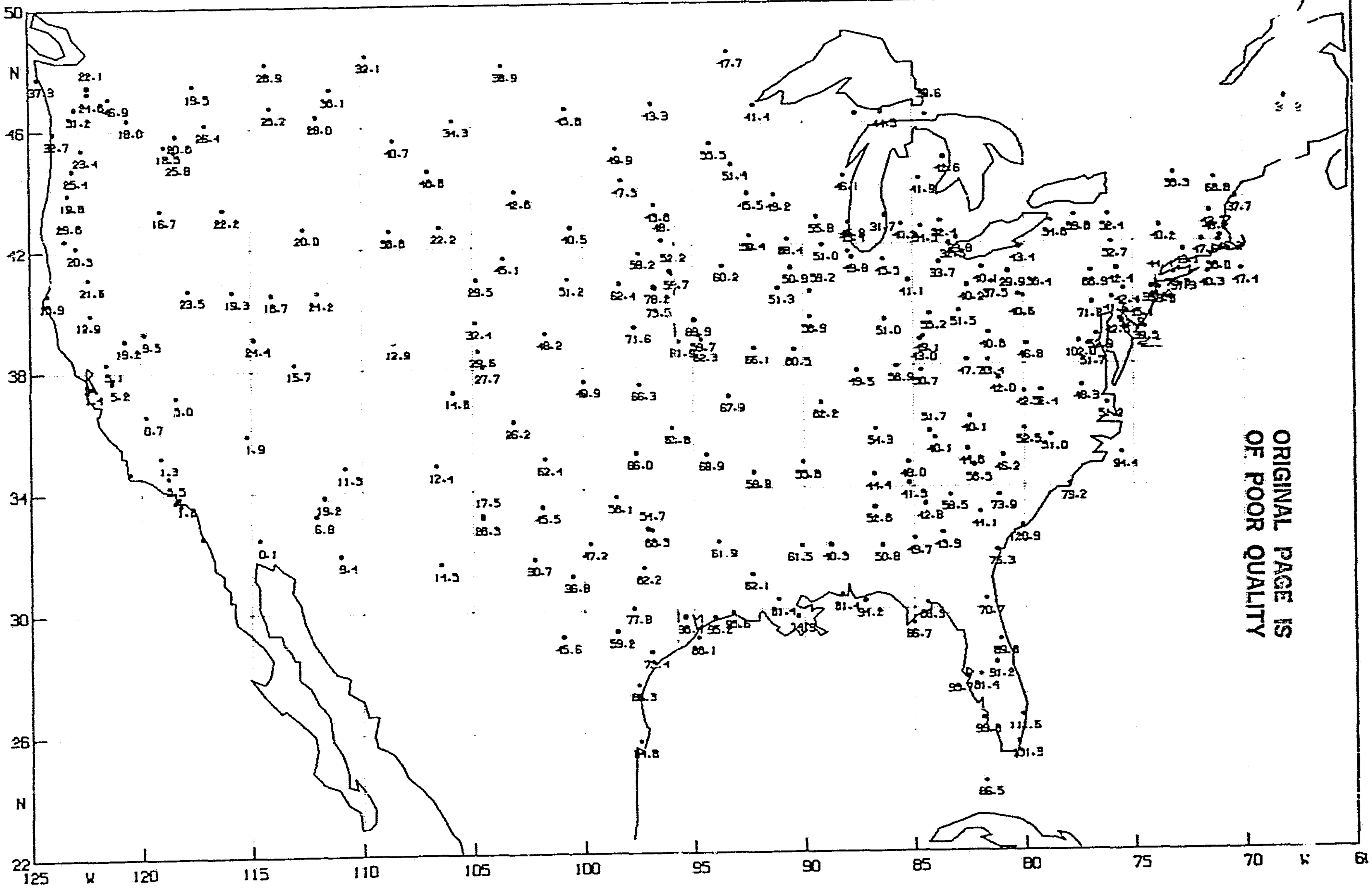


Fig. 4.b.6

JUNE NCC LCD SDEV PRECIPITATION (MM/MO)



ORIGINAL PAGE IS
OF POOR QUALITY

Fig. 4.b.7

JULY NCC LCD SDEV PRECIPITATION (MM/MO)

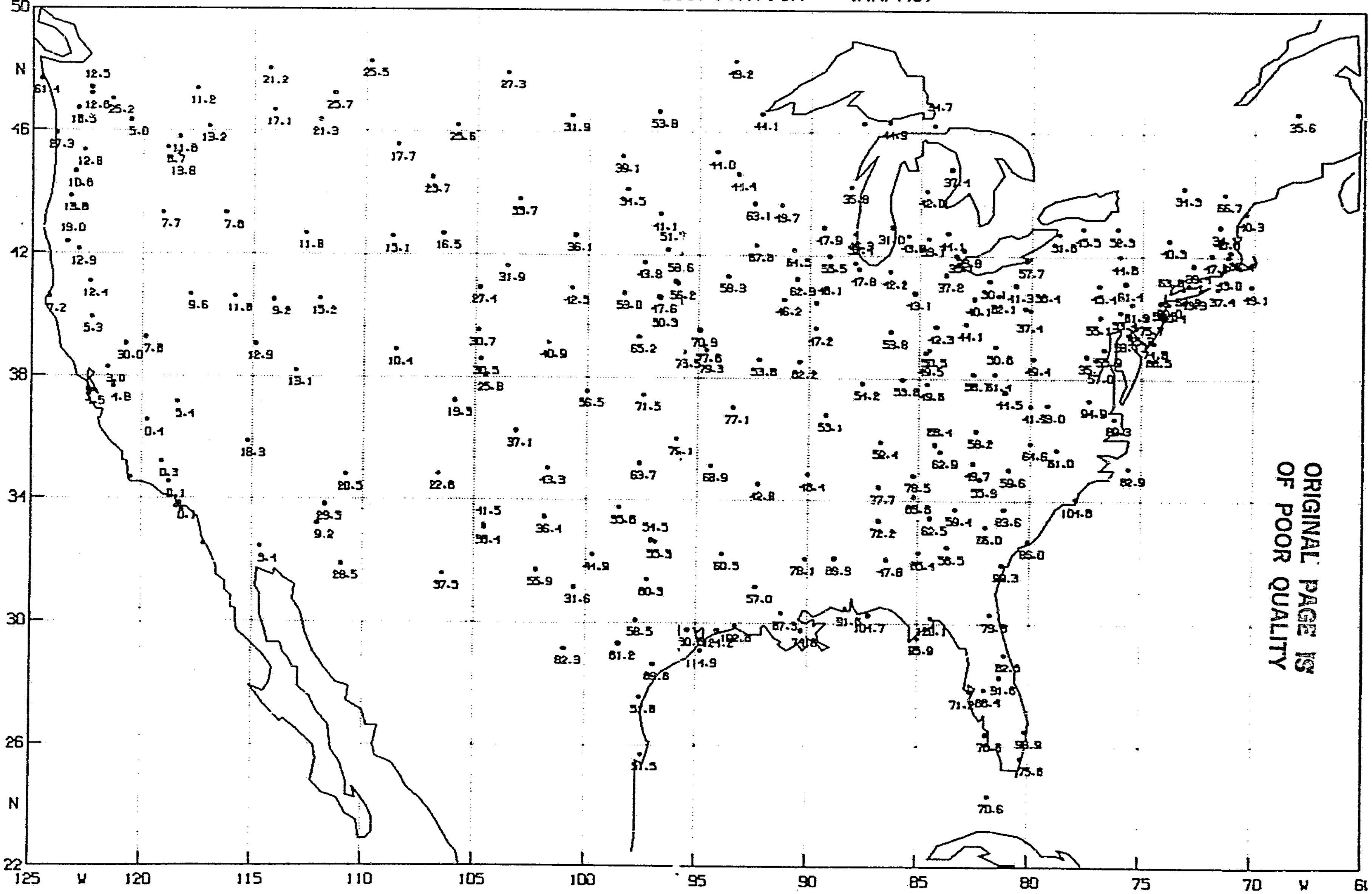


Fig. 4.b.8

AUGUST NCC LCD SDEV PRECIPITATION (MM/MO)

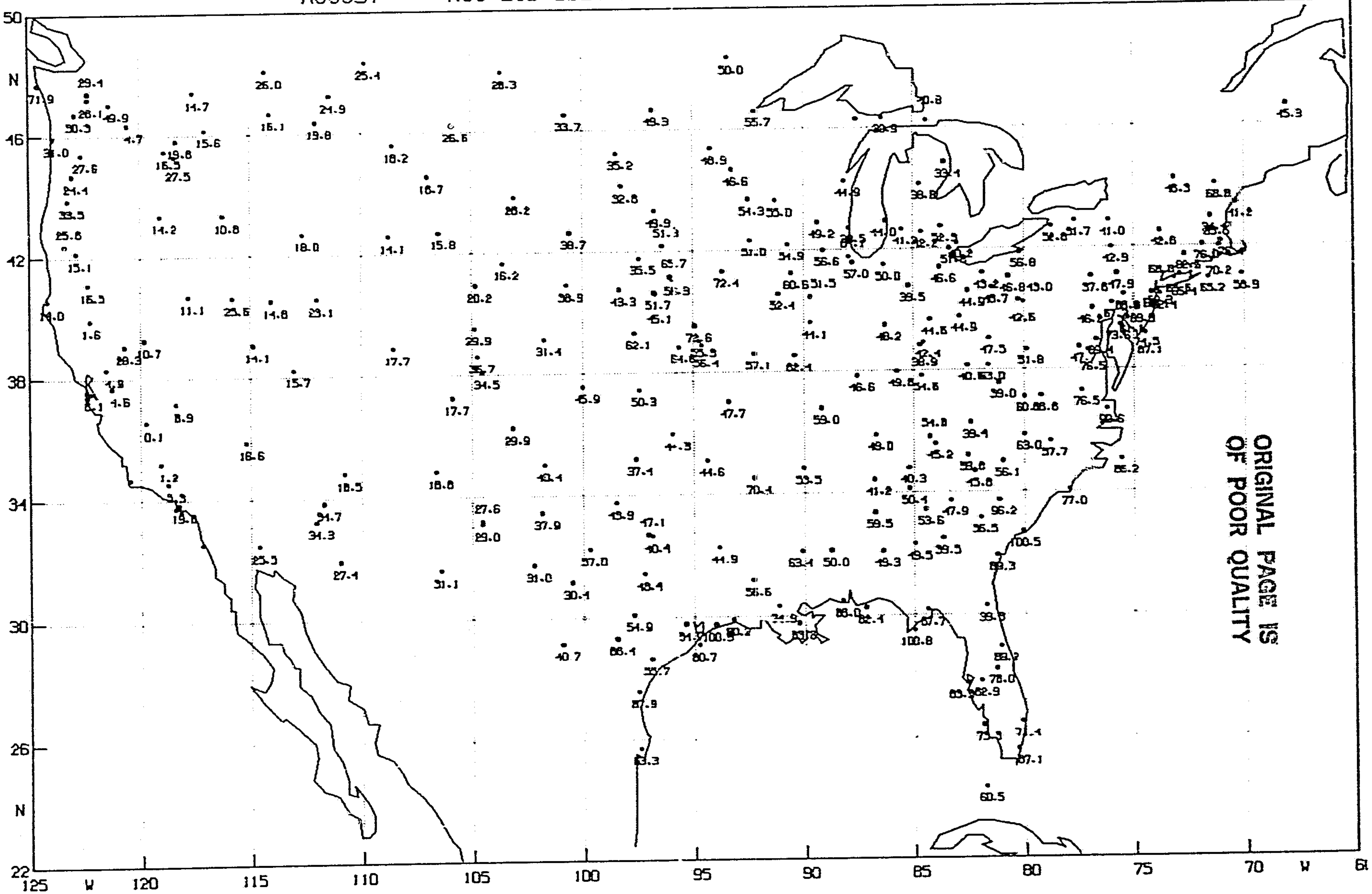


Fig. 4.b.9

SEPTMBER NCC LCD SDEV PRECIPITATION (MM/MO)

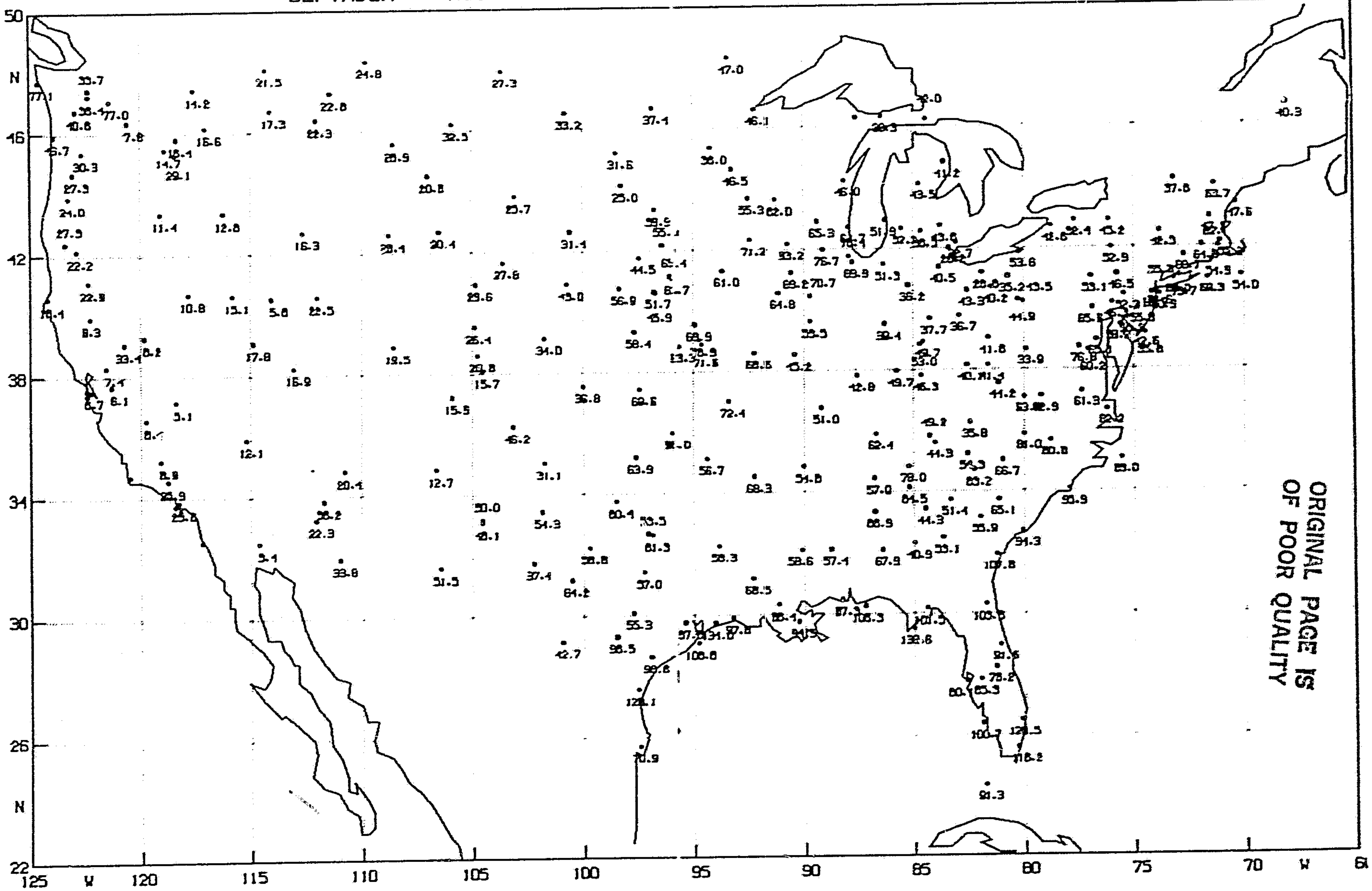


Fig. 4.b.10

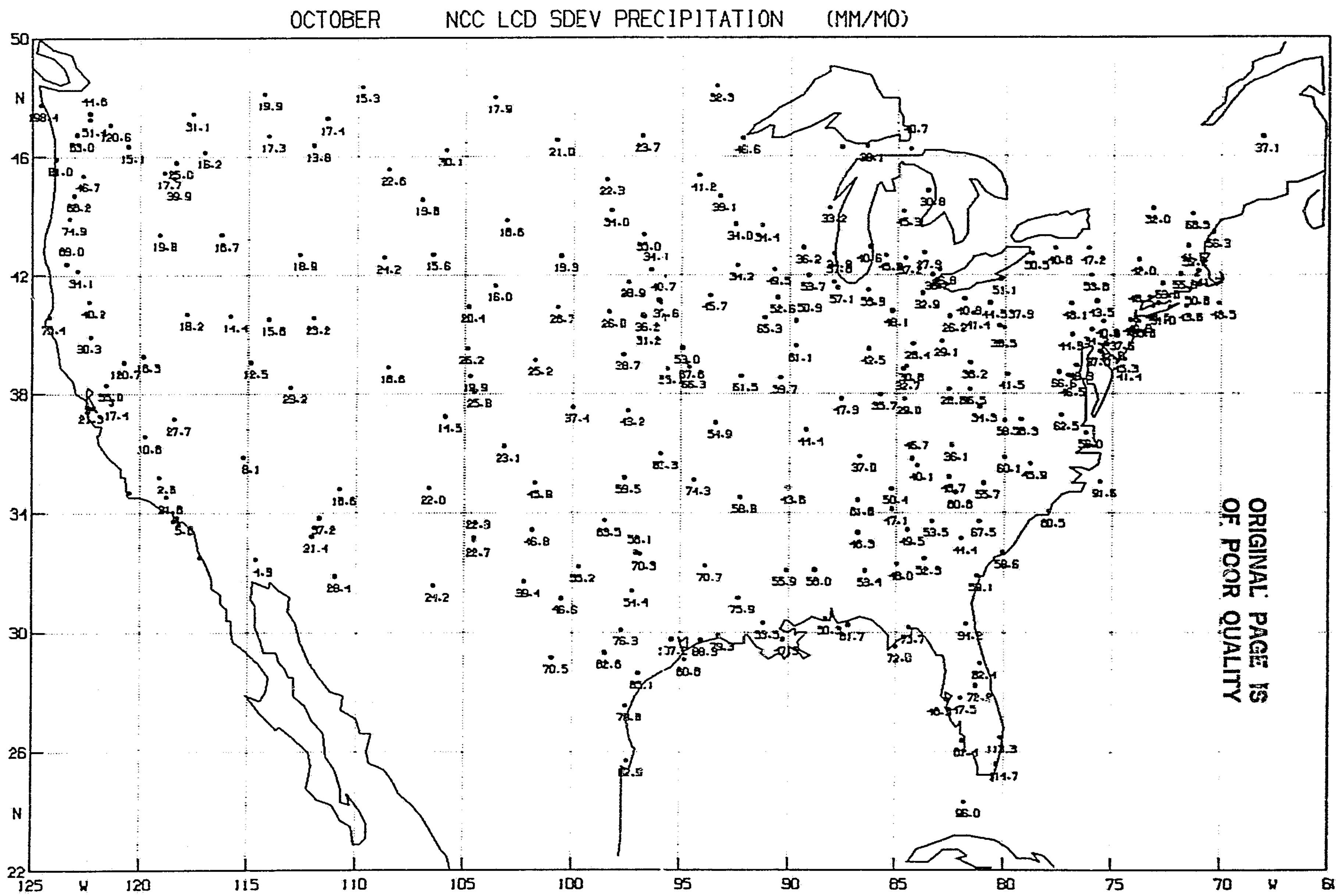

OCTOBER NCC LCD SDEV PRECIPITATION (MM/MO)
50
N
46
42
38
34
30
26
N
22
125
W
120
115
110
105
100
95
90
85
80
75
70
W
ORIGINAL PAGE IS
OF POOR QUALITY

Fig. 4.b.11

NOVEMBER NCC LCD SDEV PRE(IPITATION (MM/MO)

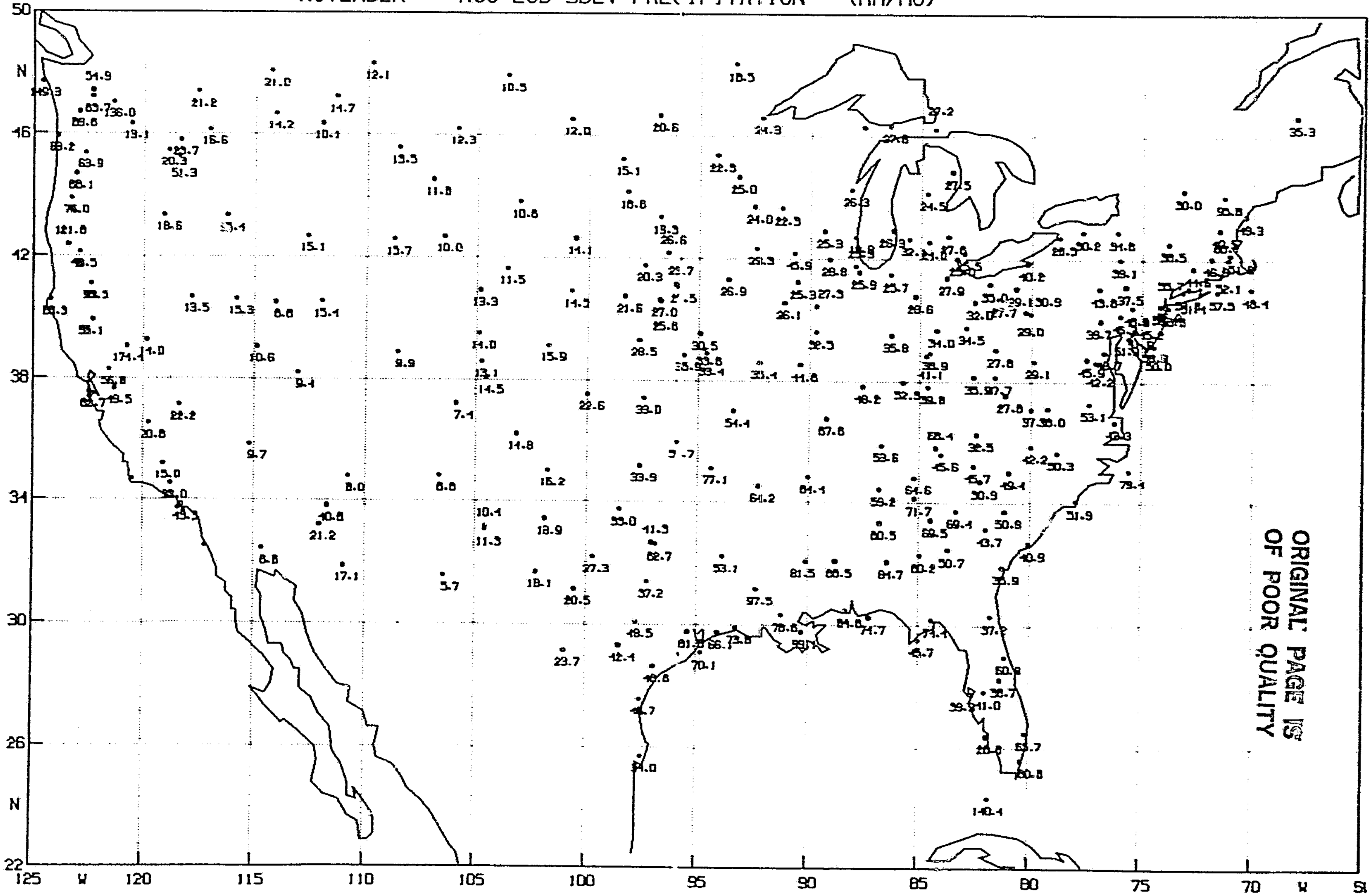


Fig. 4.b.12

DECEMBER NCC LCC SDEV PRECIPITATION (MM/MO)

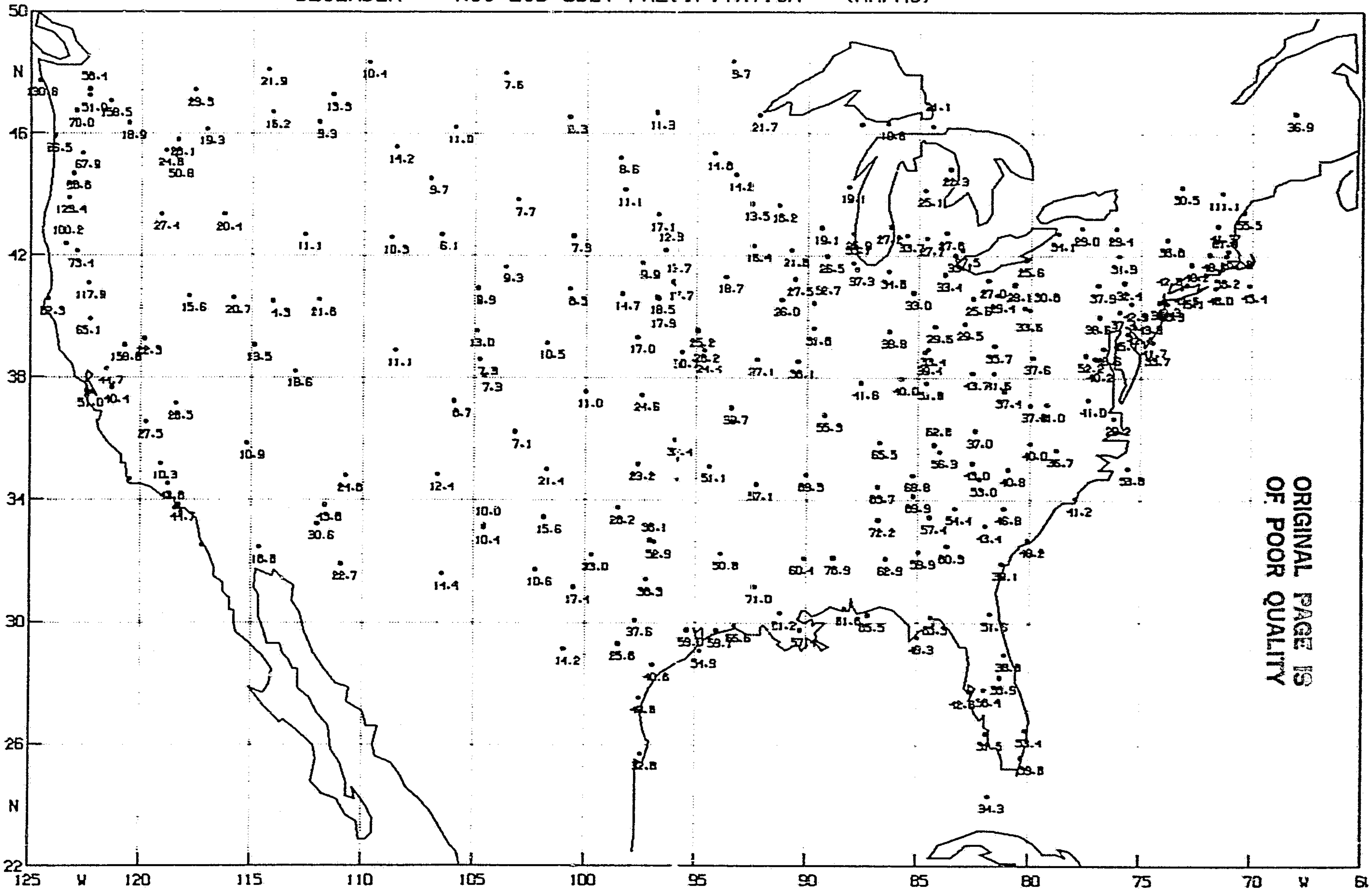


Fig. 5.a.1

JANUARY NCC LCD MEAN SOIL MOISTURE FRACTION

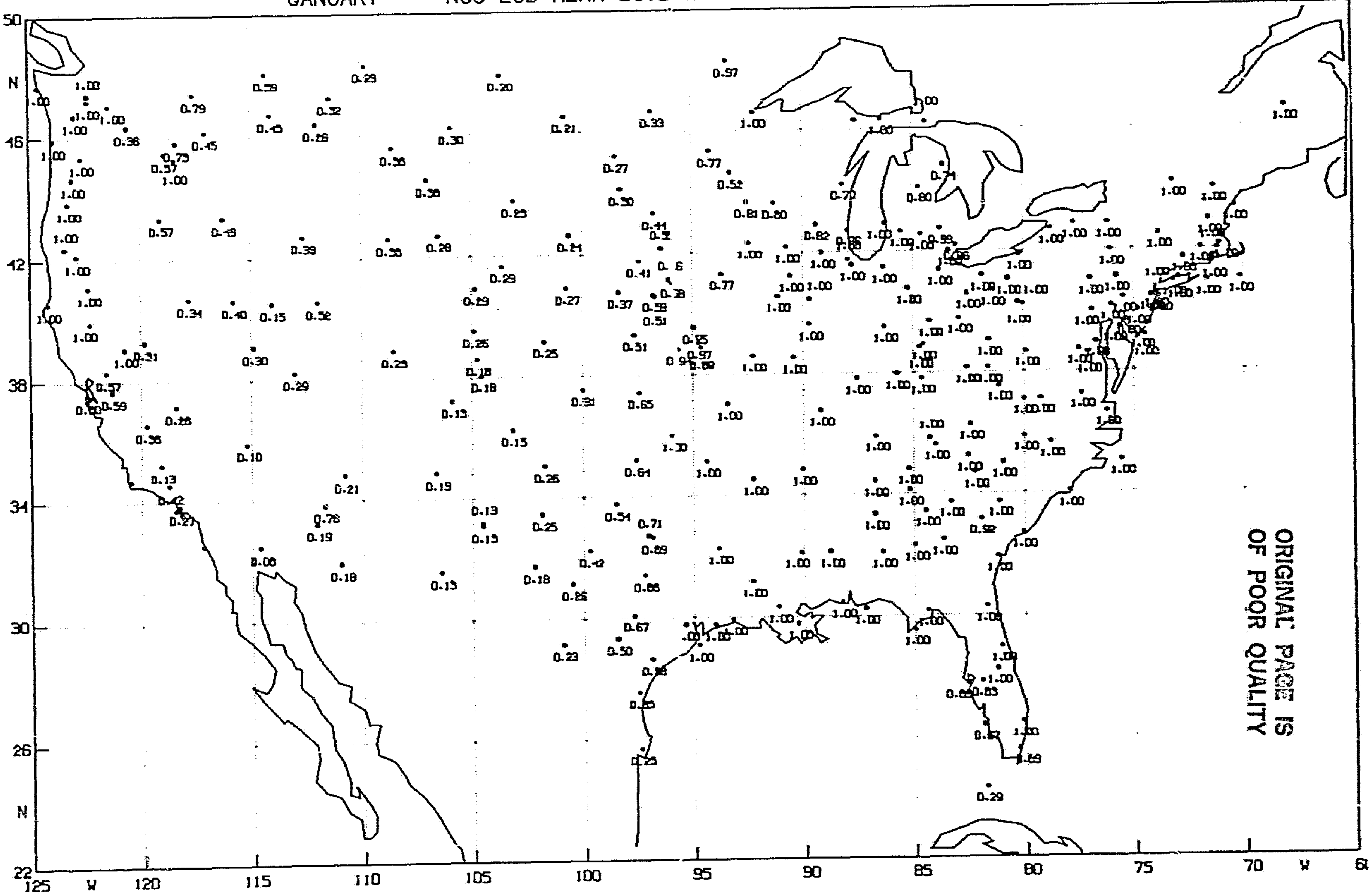


Fig. 5.a.2

FEBRUARY NCC LCD MEAN SOIL MOISTURE FRACTION

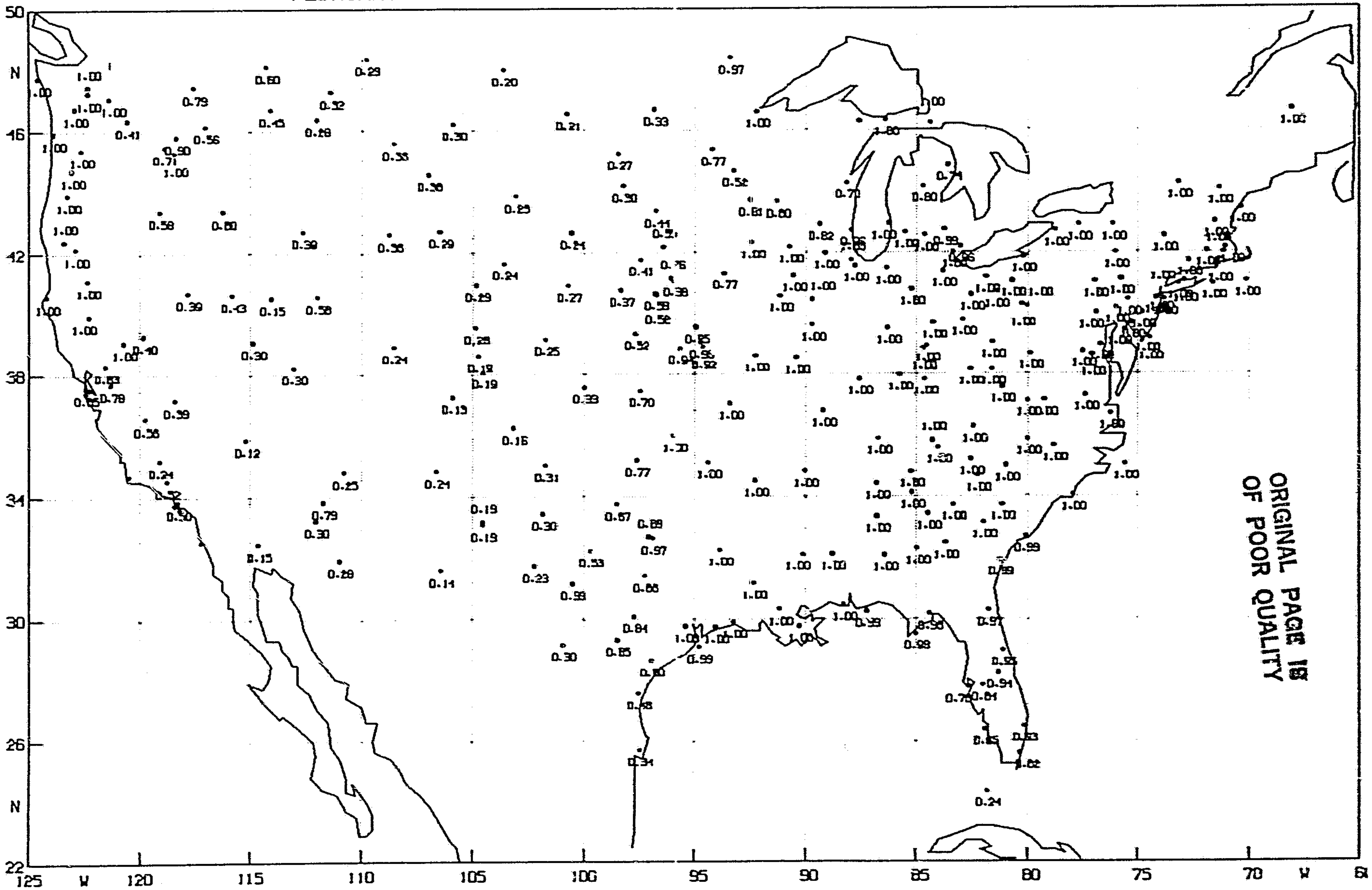
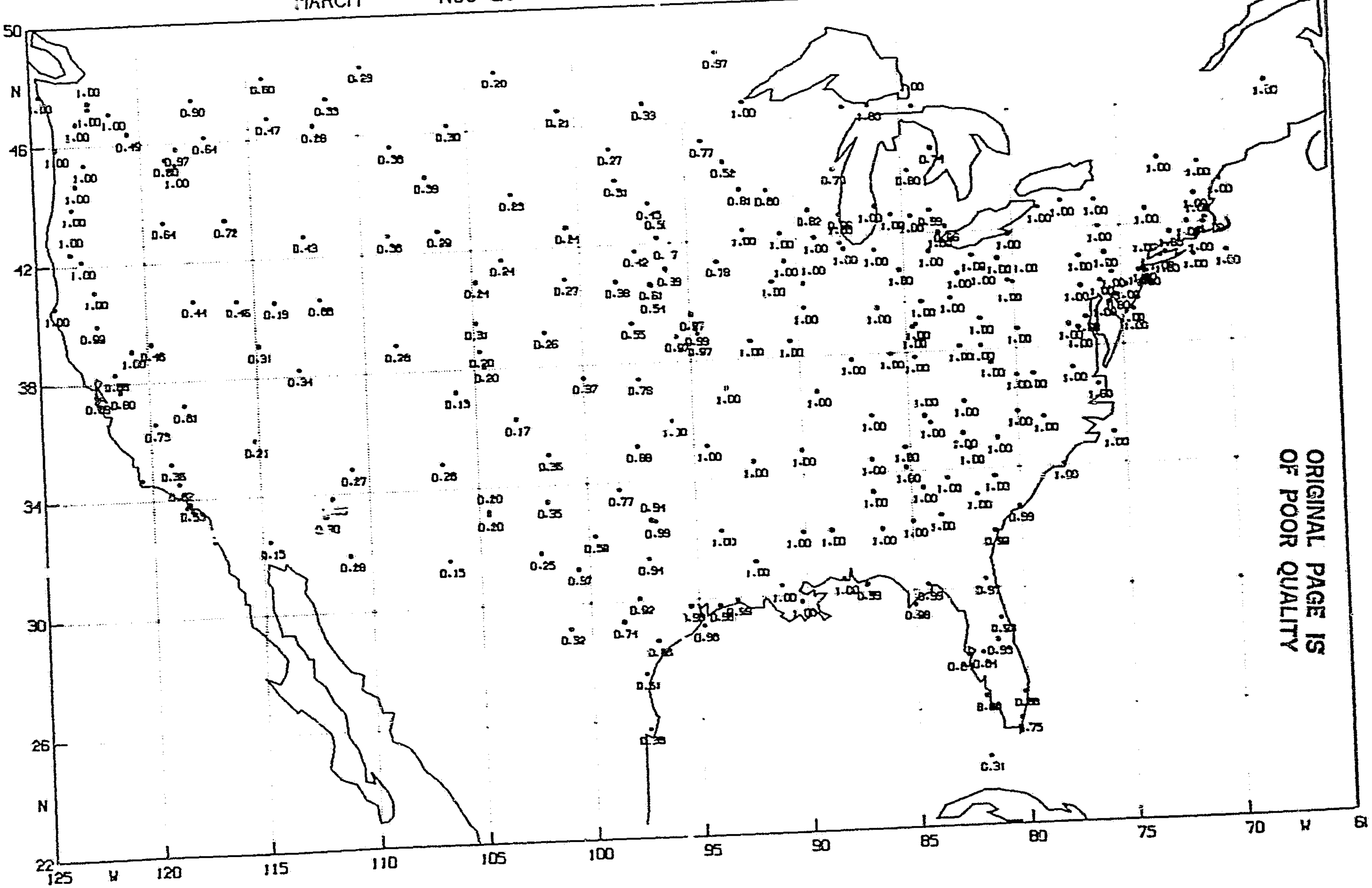


Fig. 5.a.3



MARCH NCC LCD MEAN SOIL MOISTURE FRACTION

Fig. 5.a.4

APRIL NCC LCD MEAN SOIL MOISTURE FRACTION

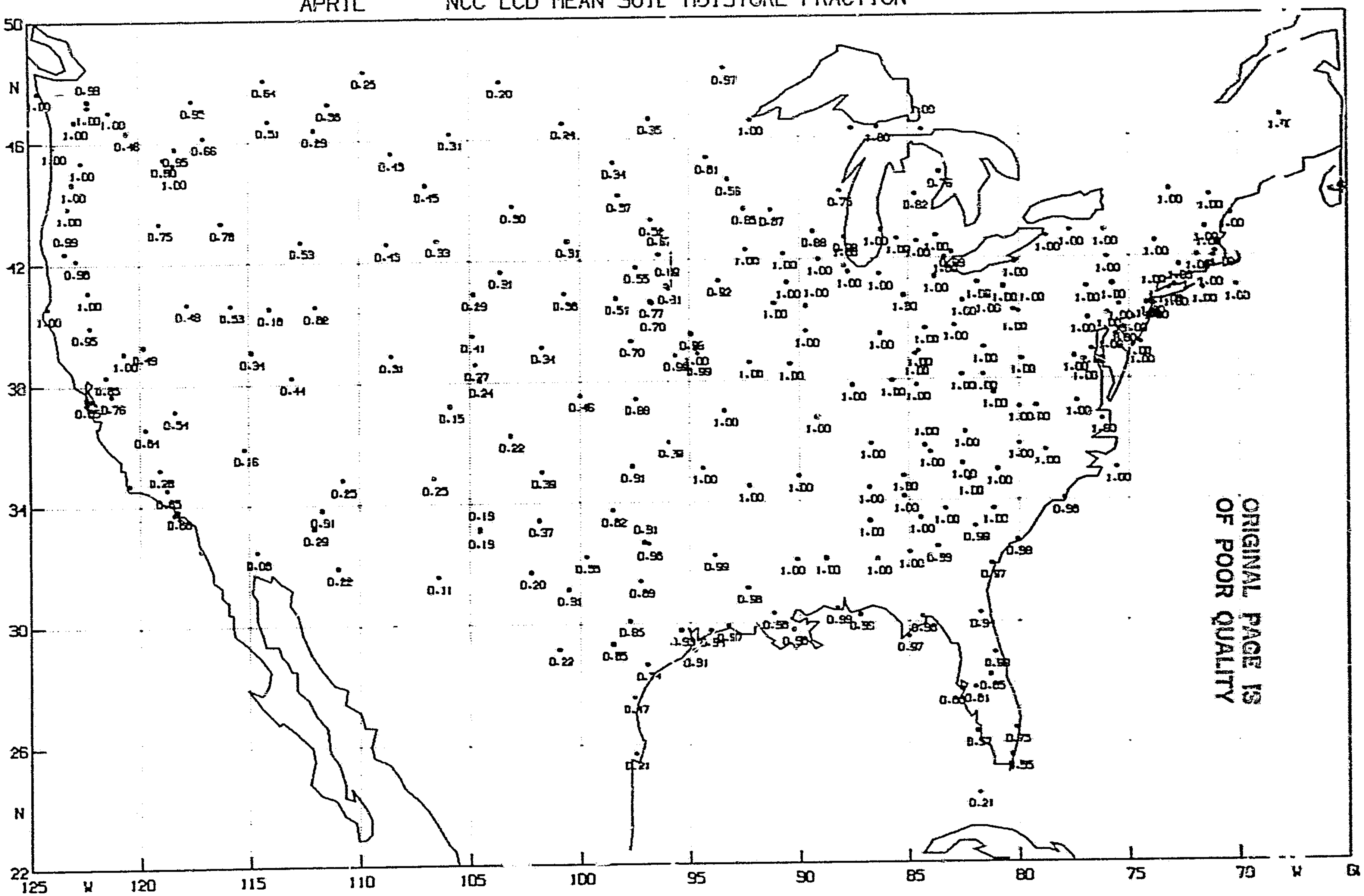


Fig. 5.a.5

MAY NCC LCD MEAN SOIL MOISTURE FRACTION

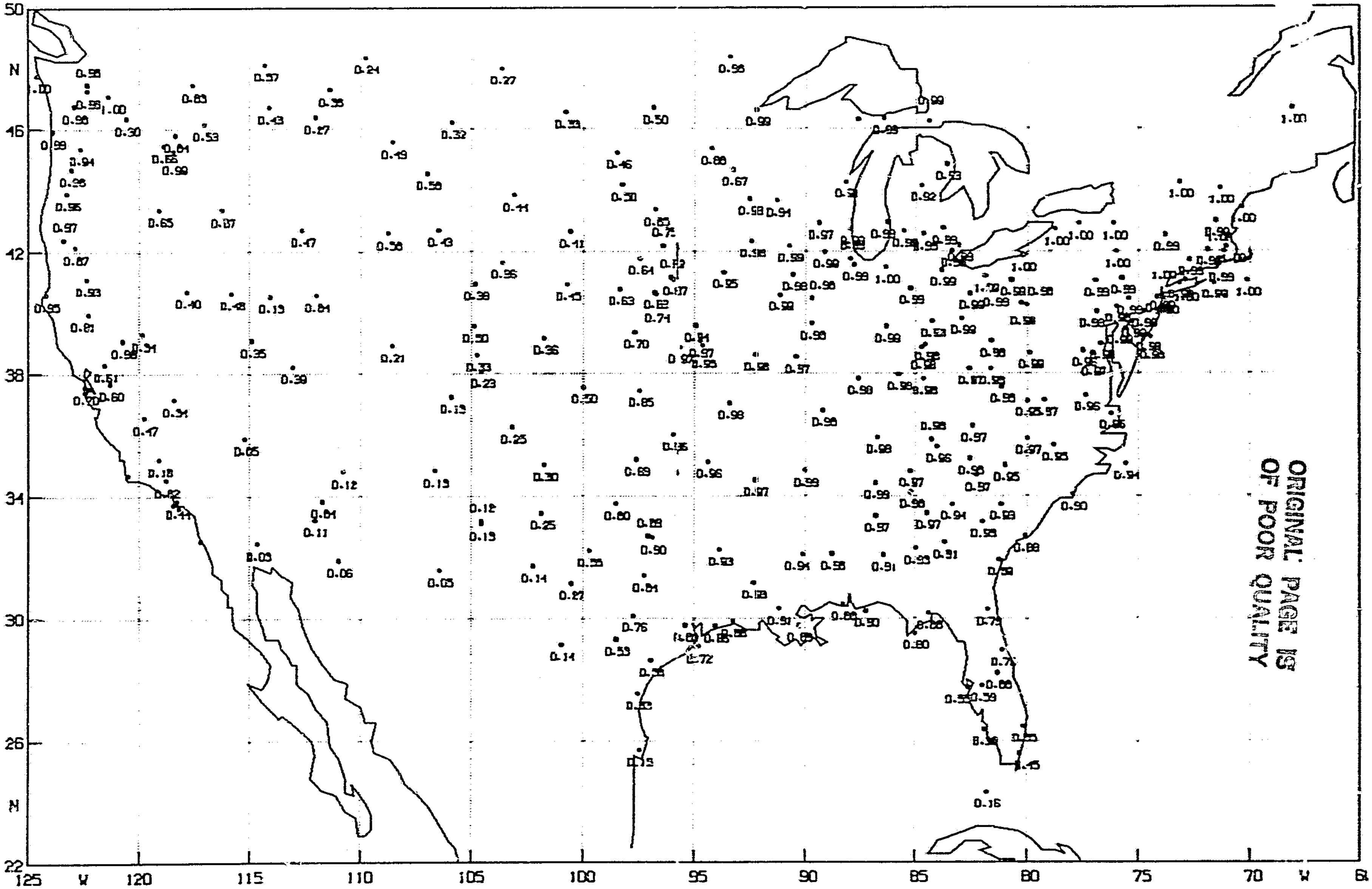


Fig. 5.a.6

JUNE NCC LCD MEAN SOIL MOISTURE FRACTION

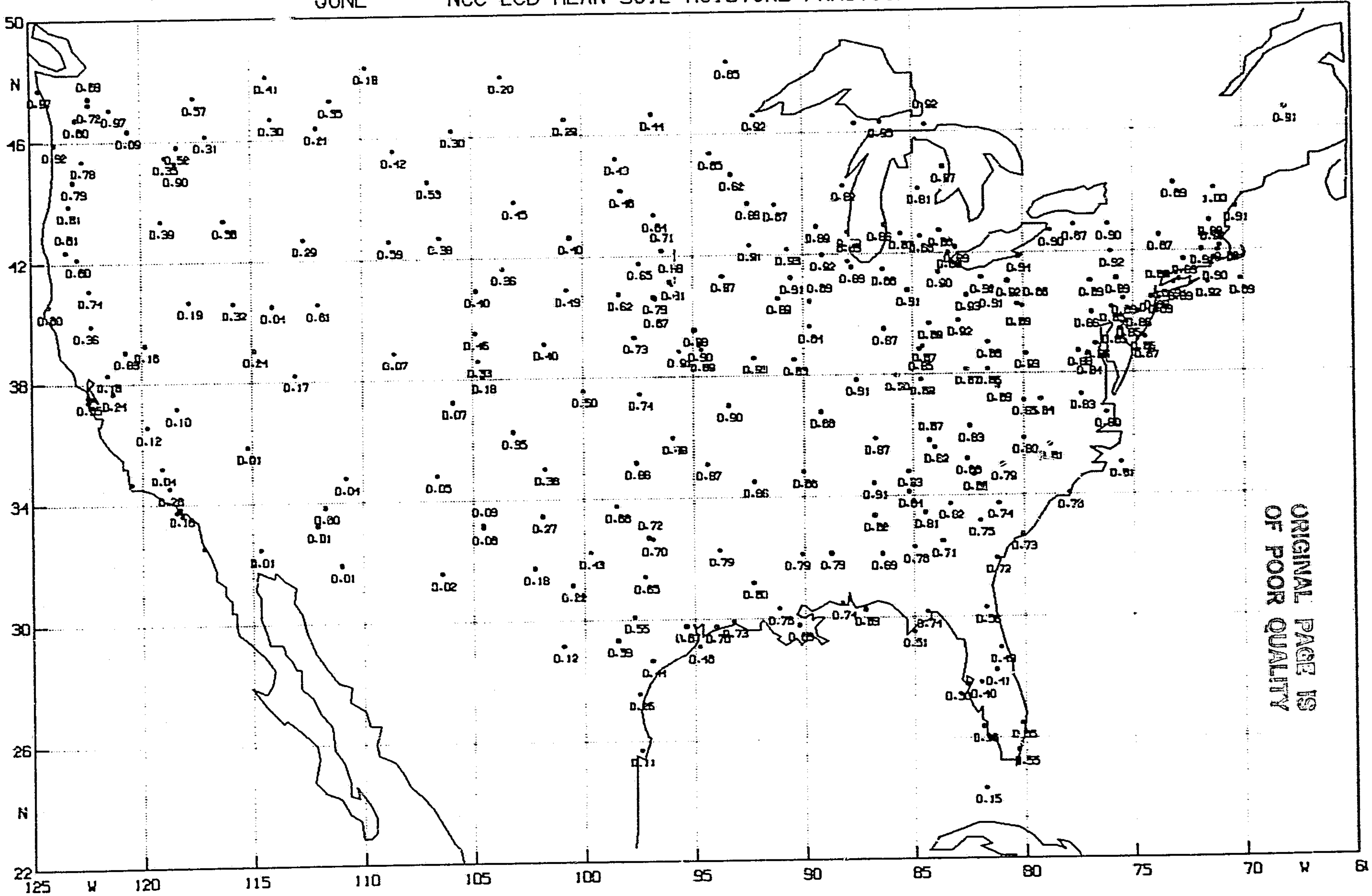


Fig. 5.a.7

JULY NCC LCD MEAN SOIL MOISTURE FRACTION

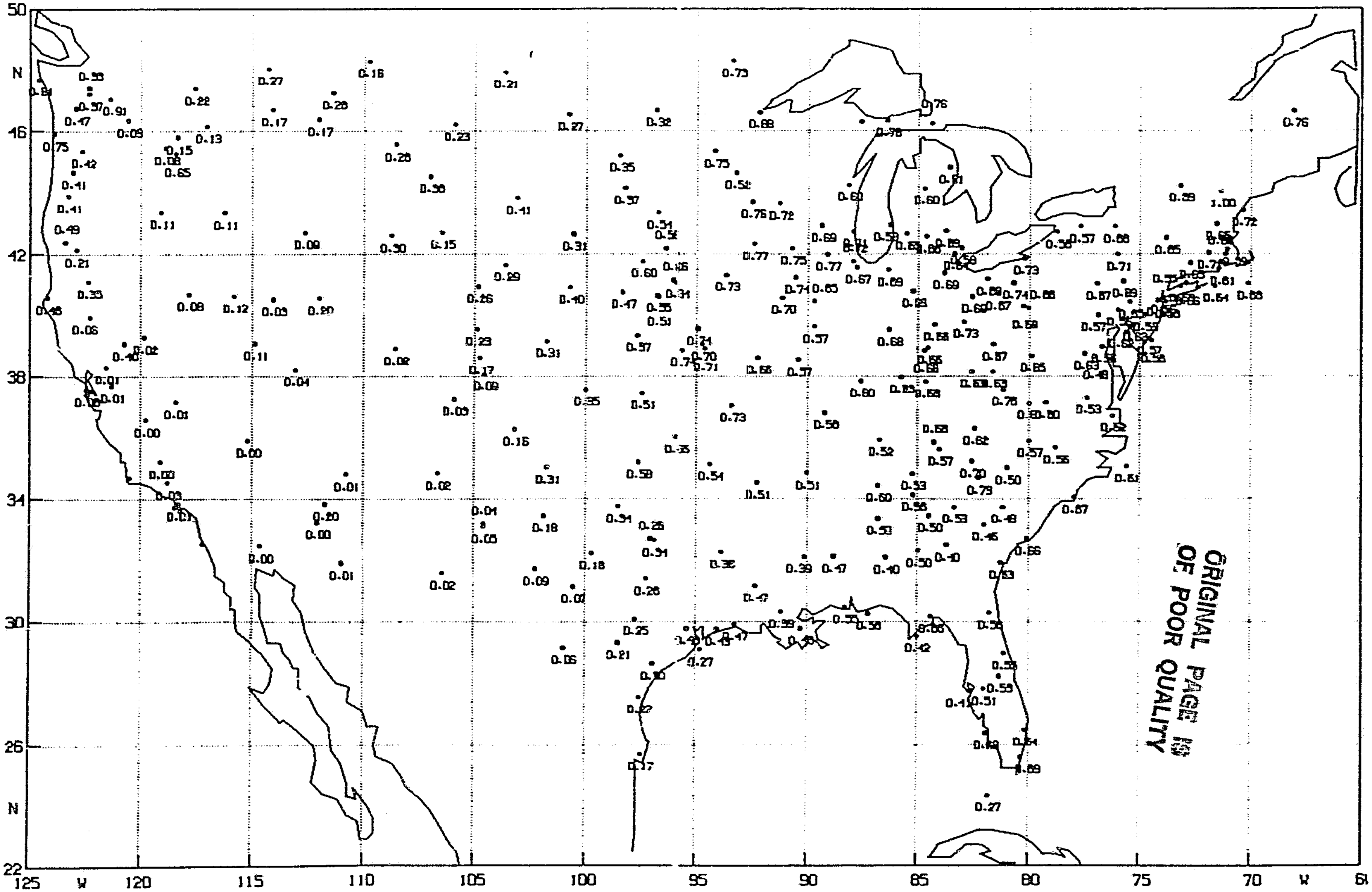


Fig. 5.a.8

AUGUST NCC LCD MEAN SOIL MOISTURE FRACTION

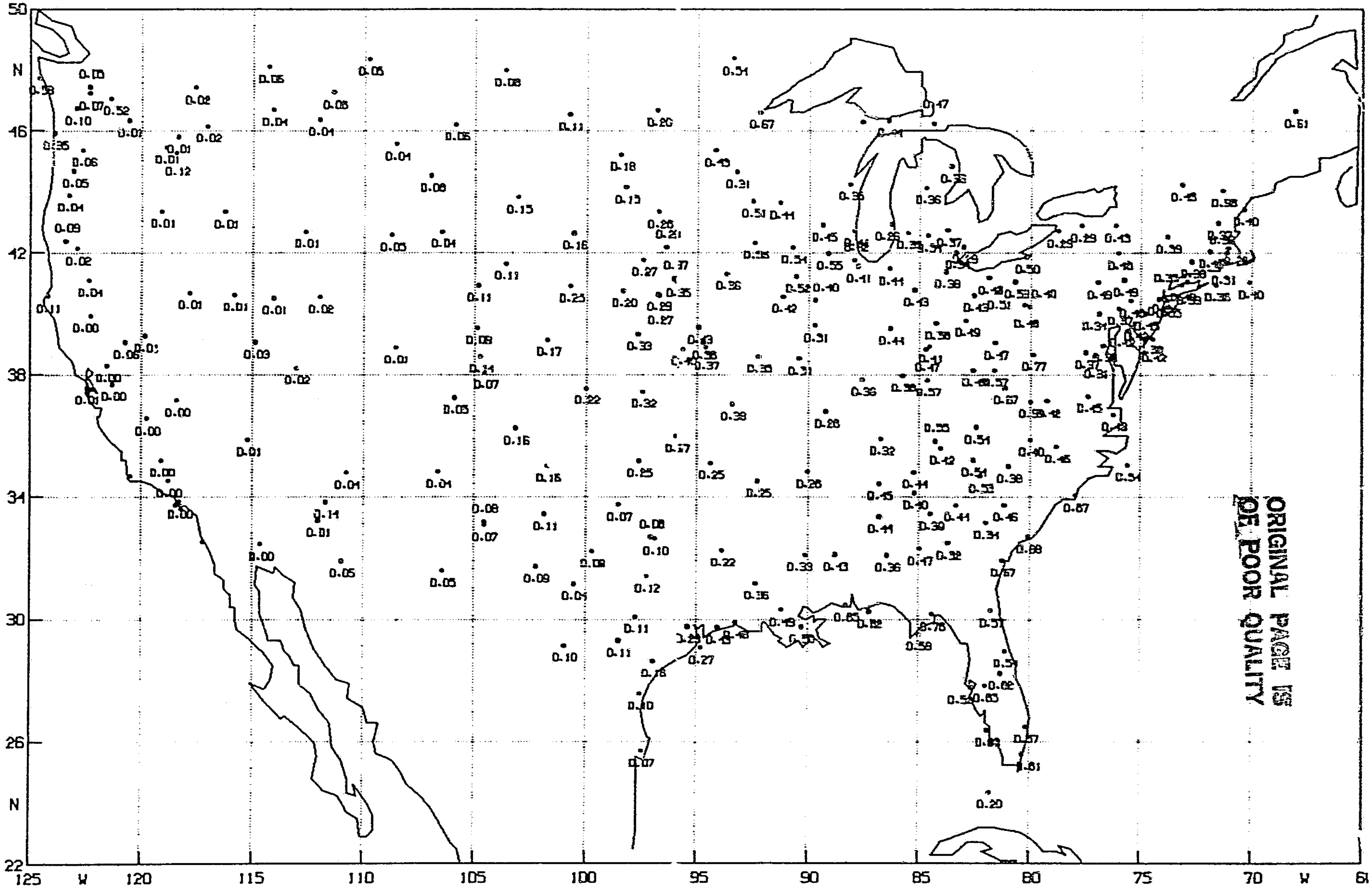


Fig. 5.a.9

SEPTMBER NCC LCD MEAN SOIL MOISTURE FRACTION

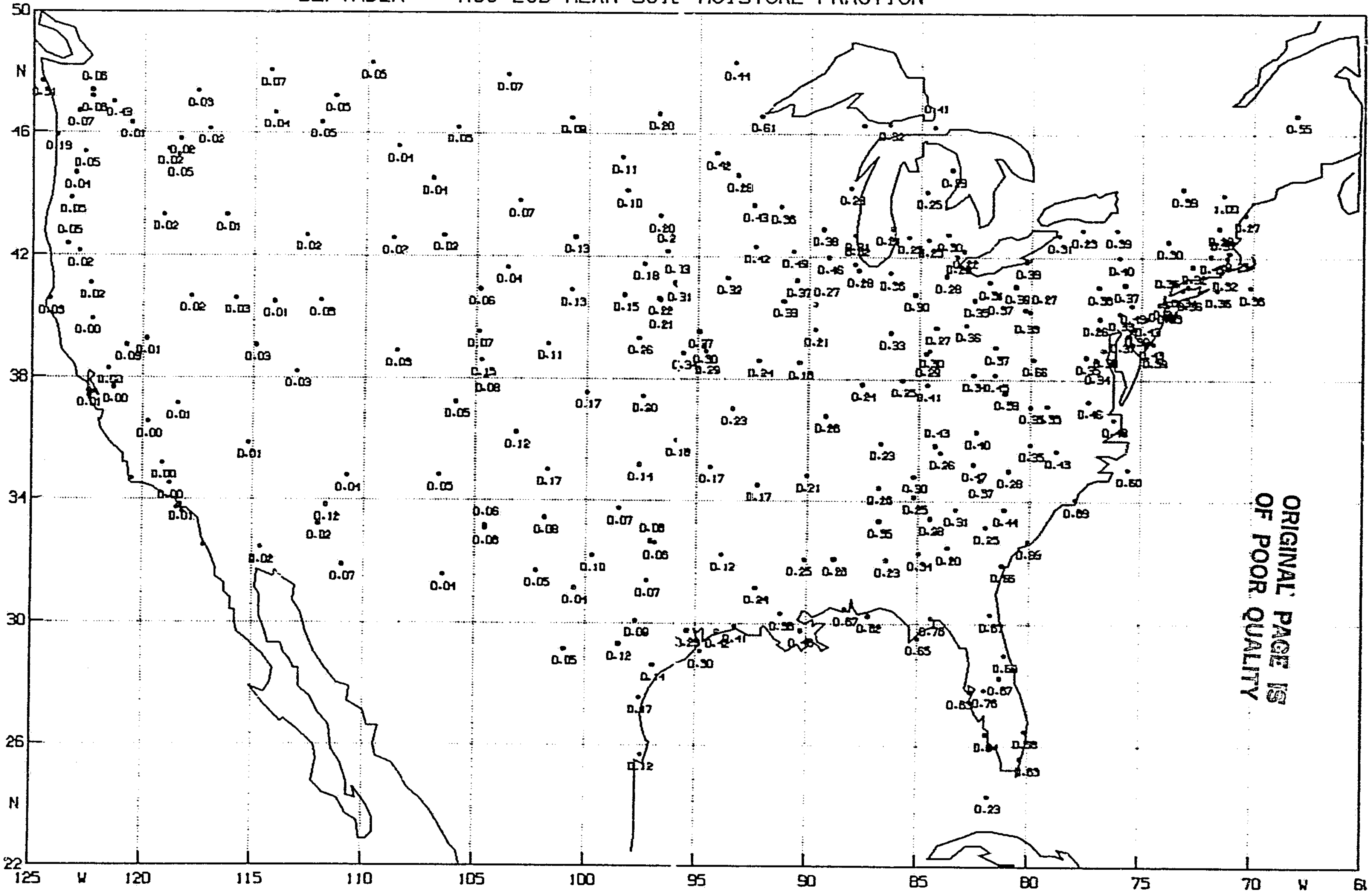


Fig. 5.a.10

OCTOBER NCC LCD MEAN SOIL MOISTURE FRACTION

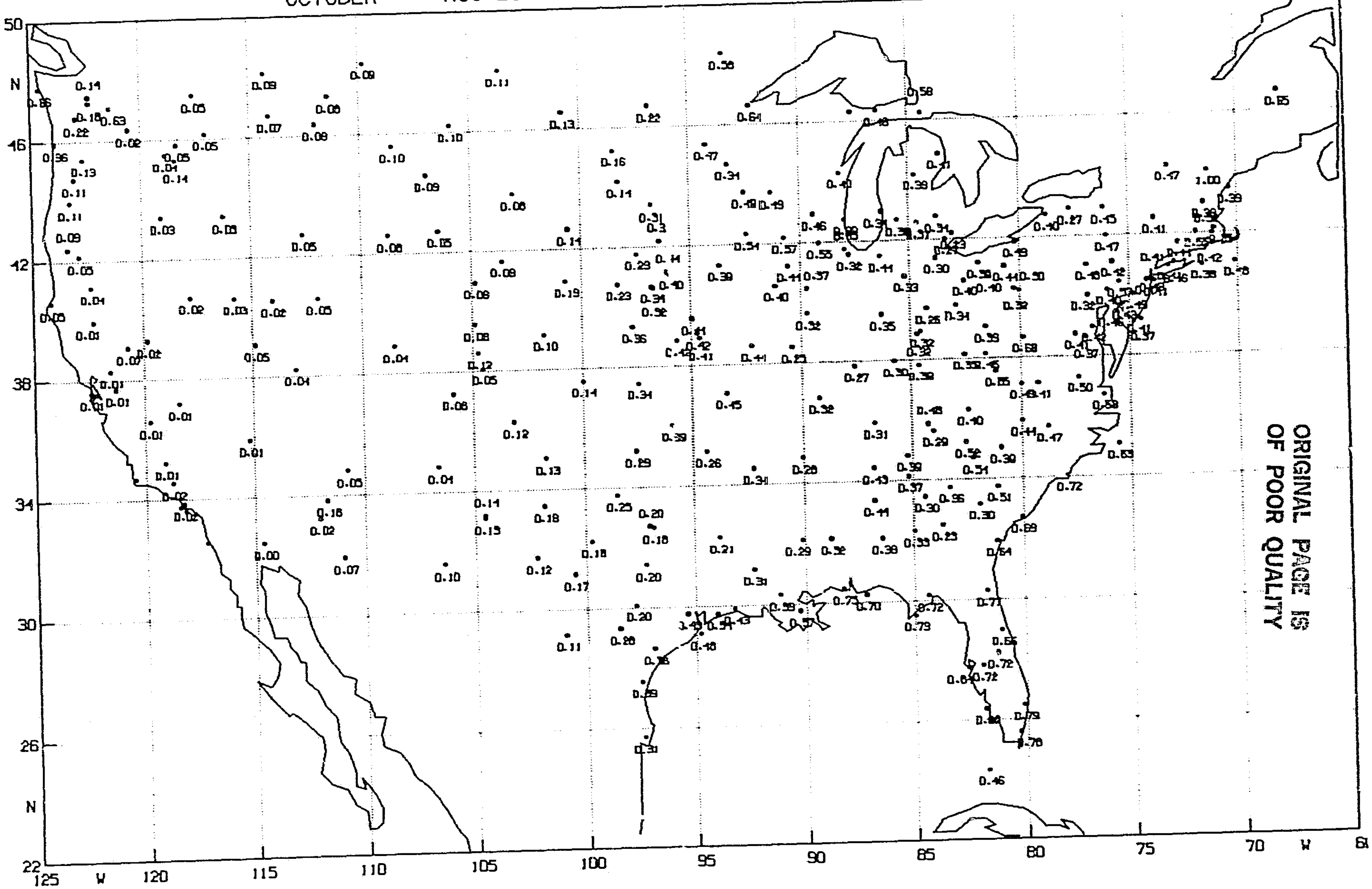


Fig. 5.a.11

NOVEMBER NCC LCD MEAN SOIL MOISTURE FRACTION

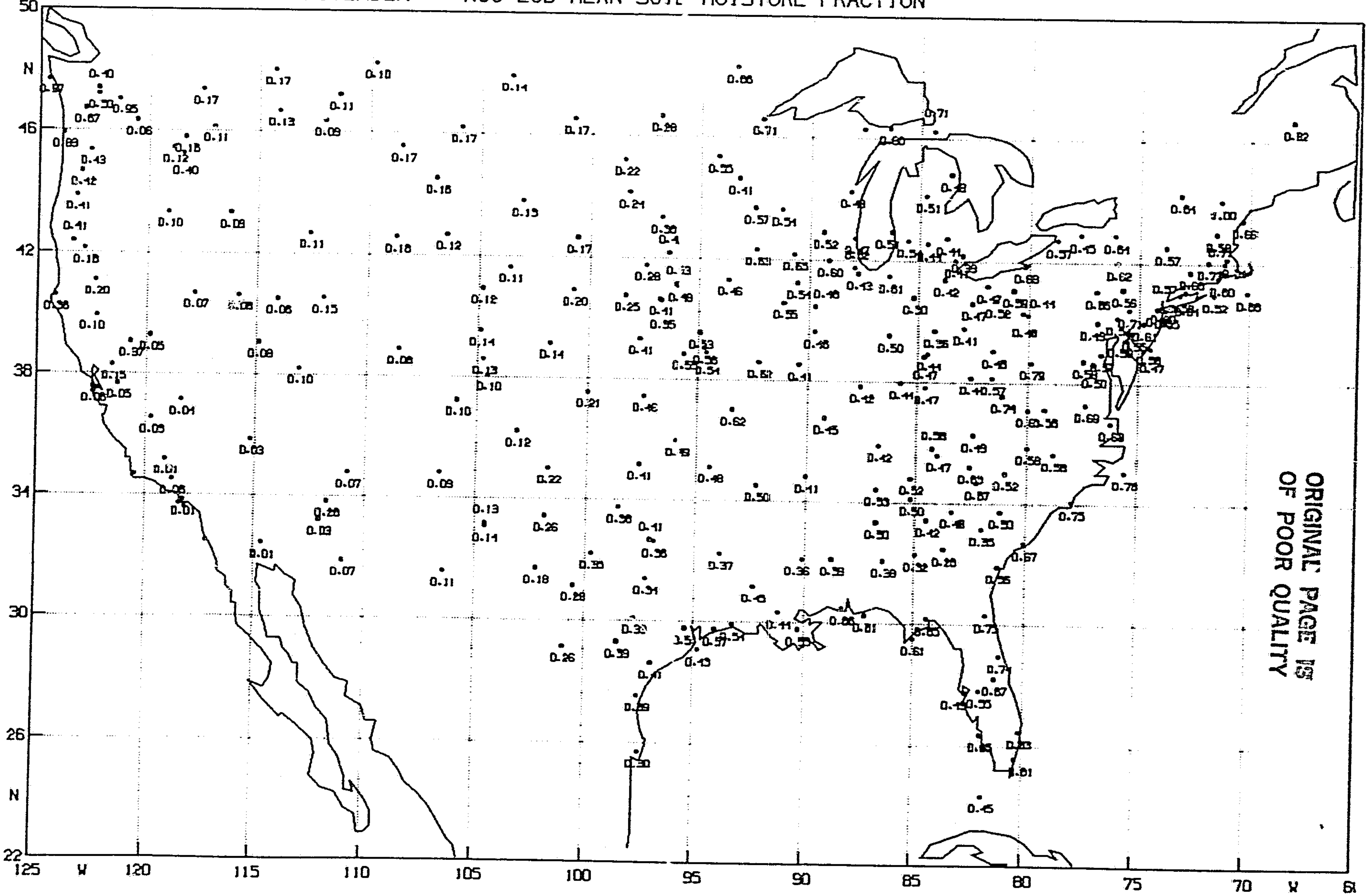


Fig. 5.a.12

DECEMBER NCC LCD MEAN SOIL MOISTURE FRACTION

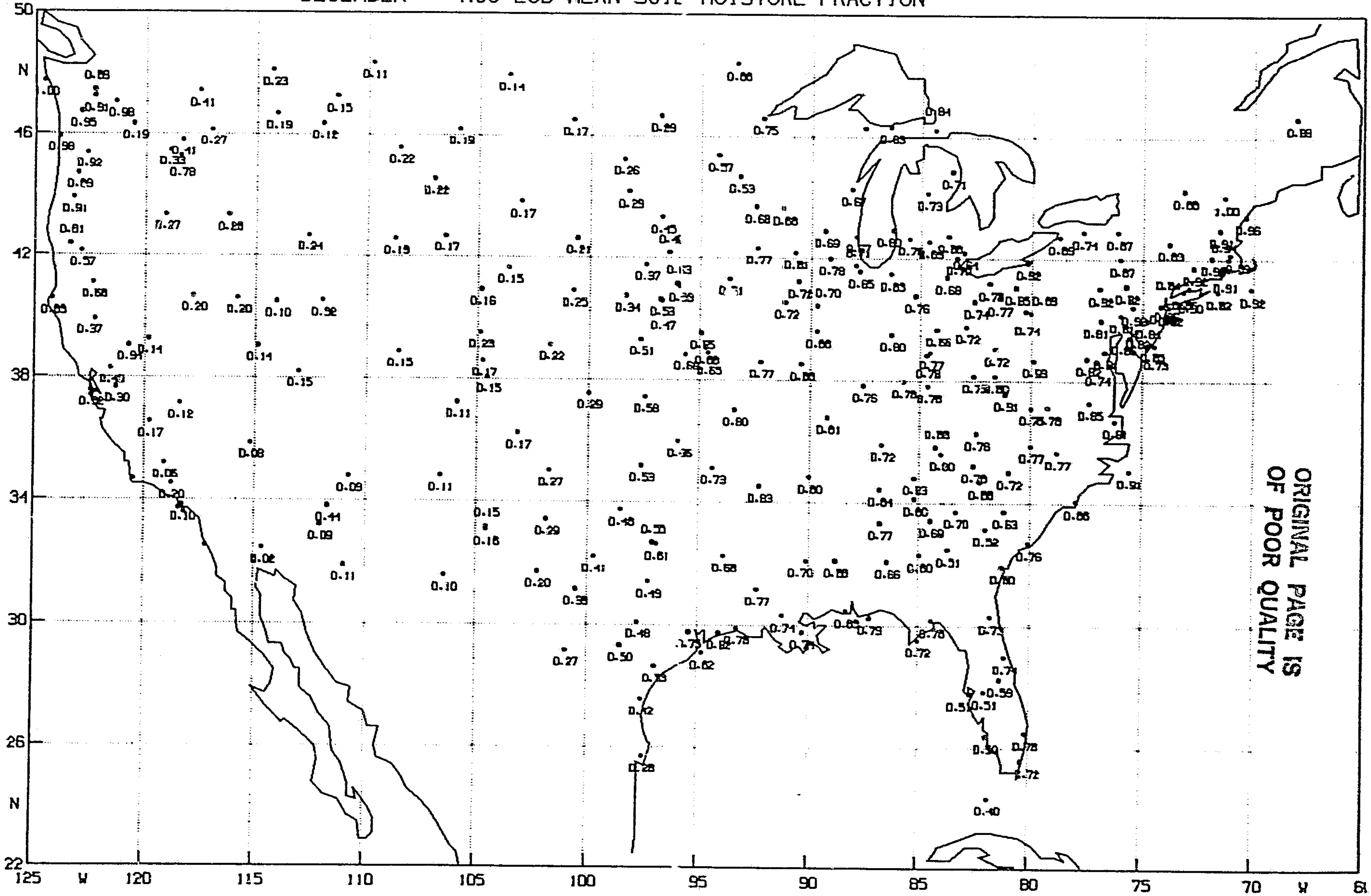


Fig. 5.b.1

JANUARY NCC LCD SDEV SOIL MOISTURE FRACTION

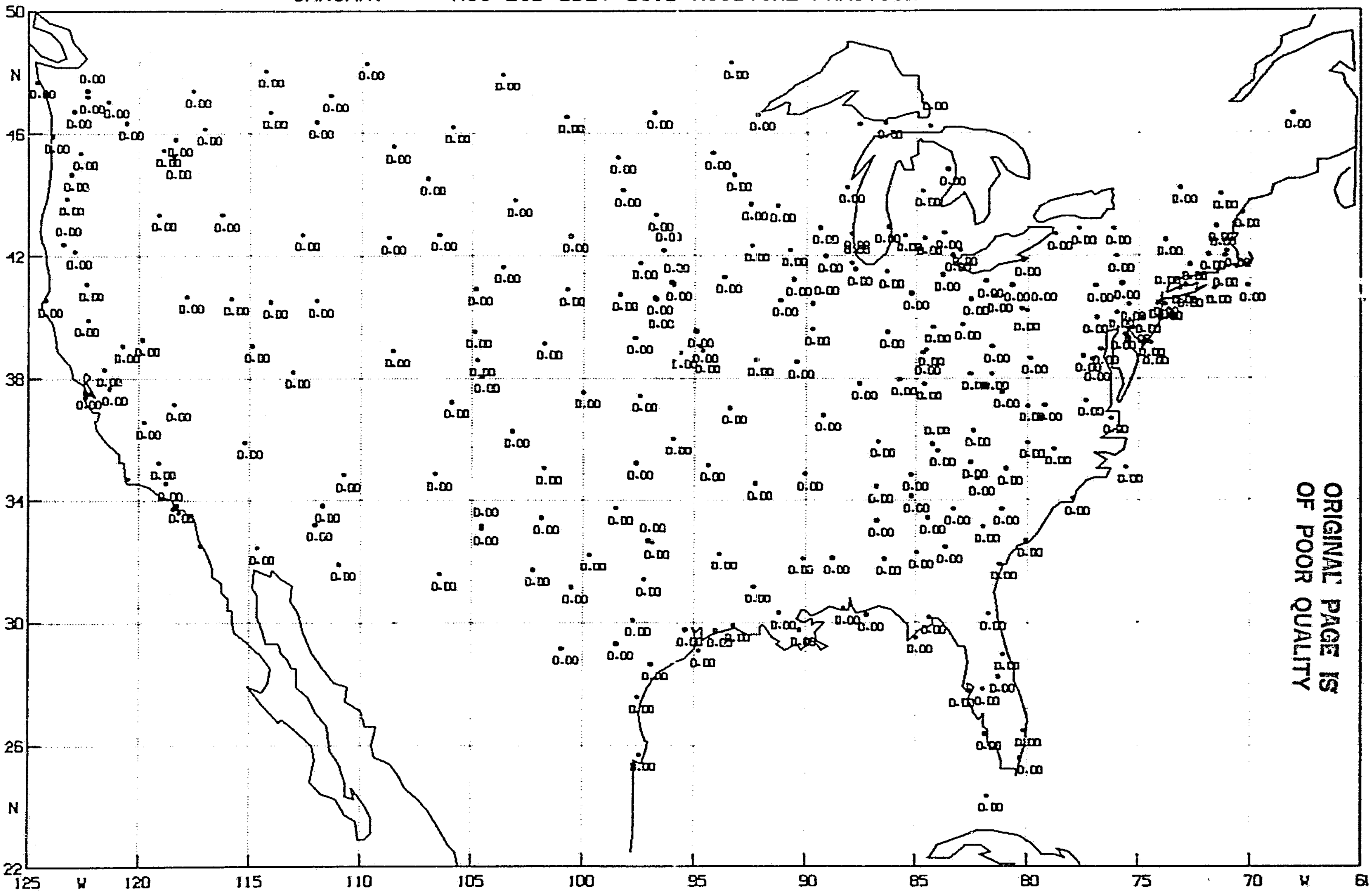


Fig. 5.b.2

FEBRUARY NCC LCD SDEV SOIL MOISTURE FRACTION

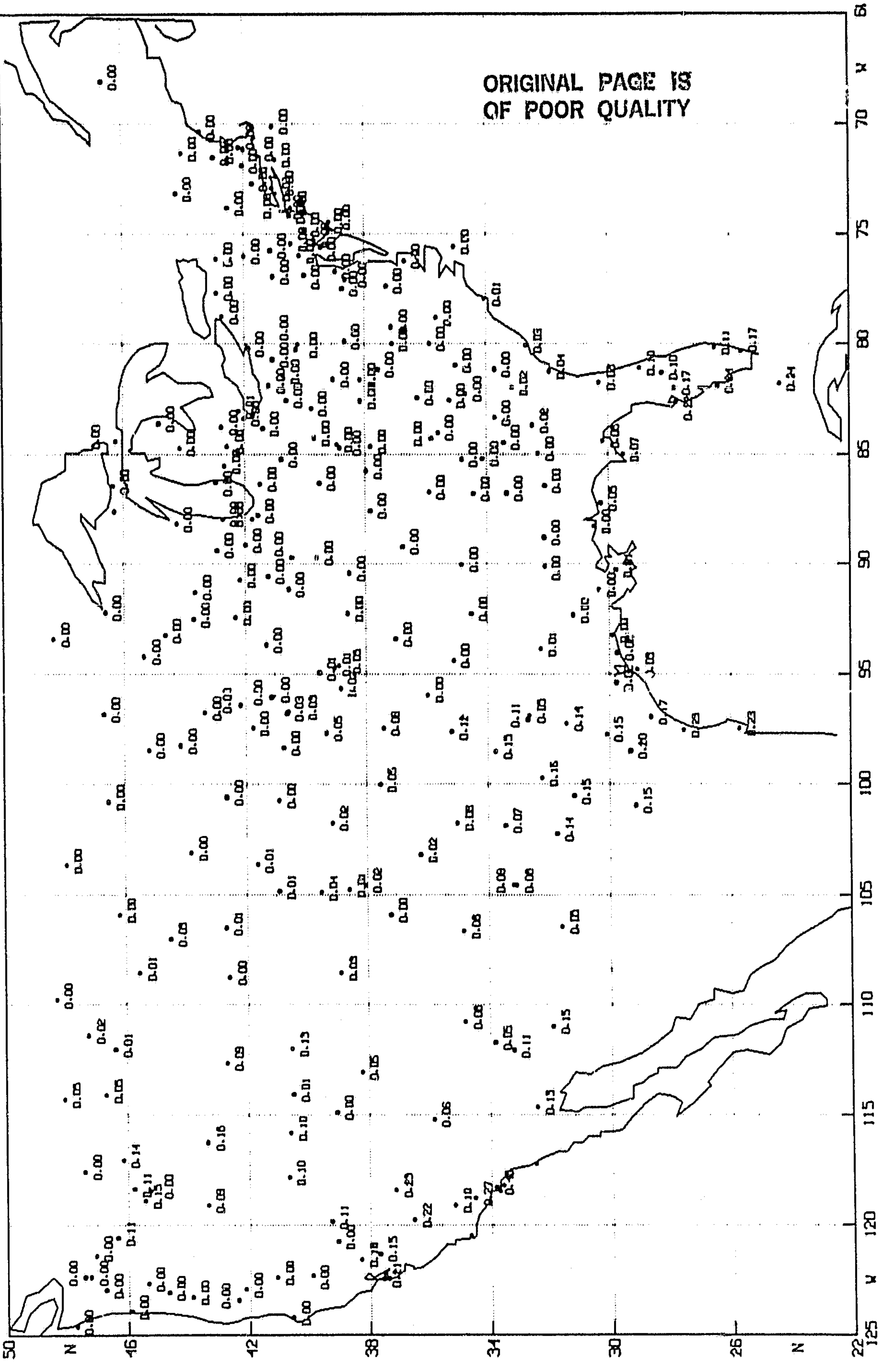


Fig. 5.b.3

MARCH NCC LCD SDEV SOIL MOISTURE FRACTION

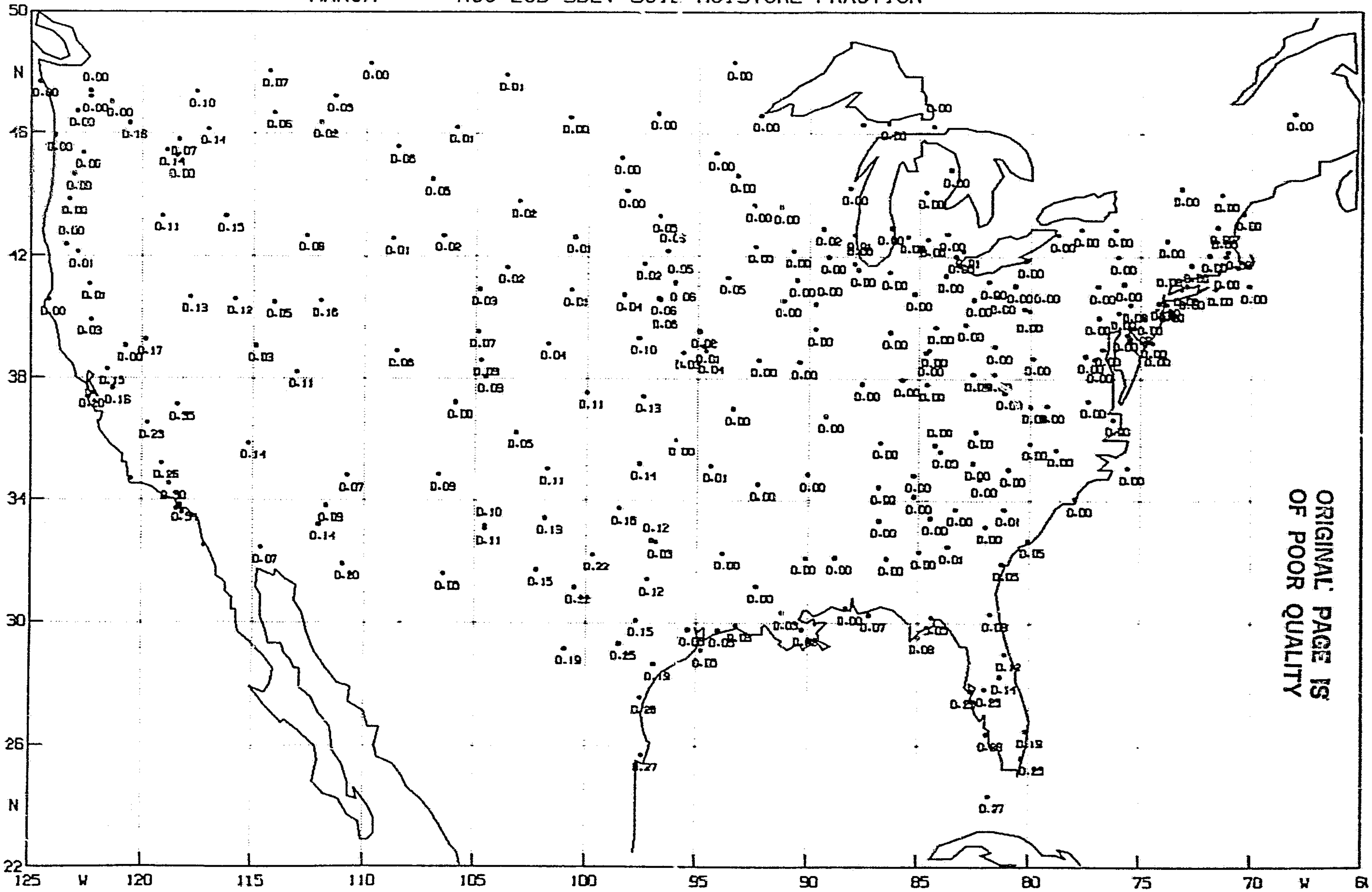


Fig. 5.b.4

APRIL NCC LCD SDEV SOIL MOISTURE FRACTION

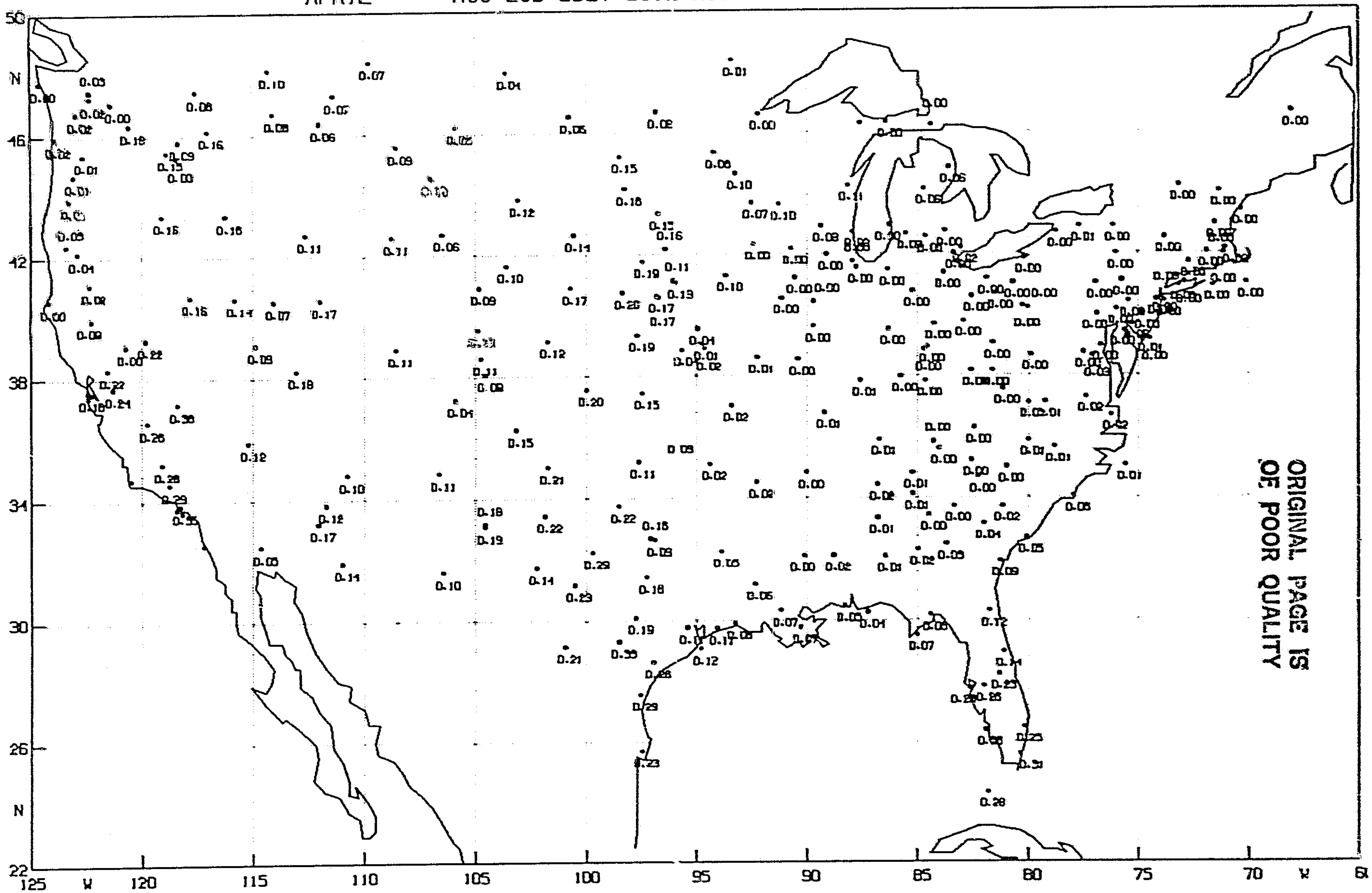


Fig. 5.b.5

MAY NCC LCD SDEV SOIL MOISTURE FRACTION

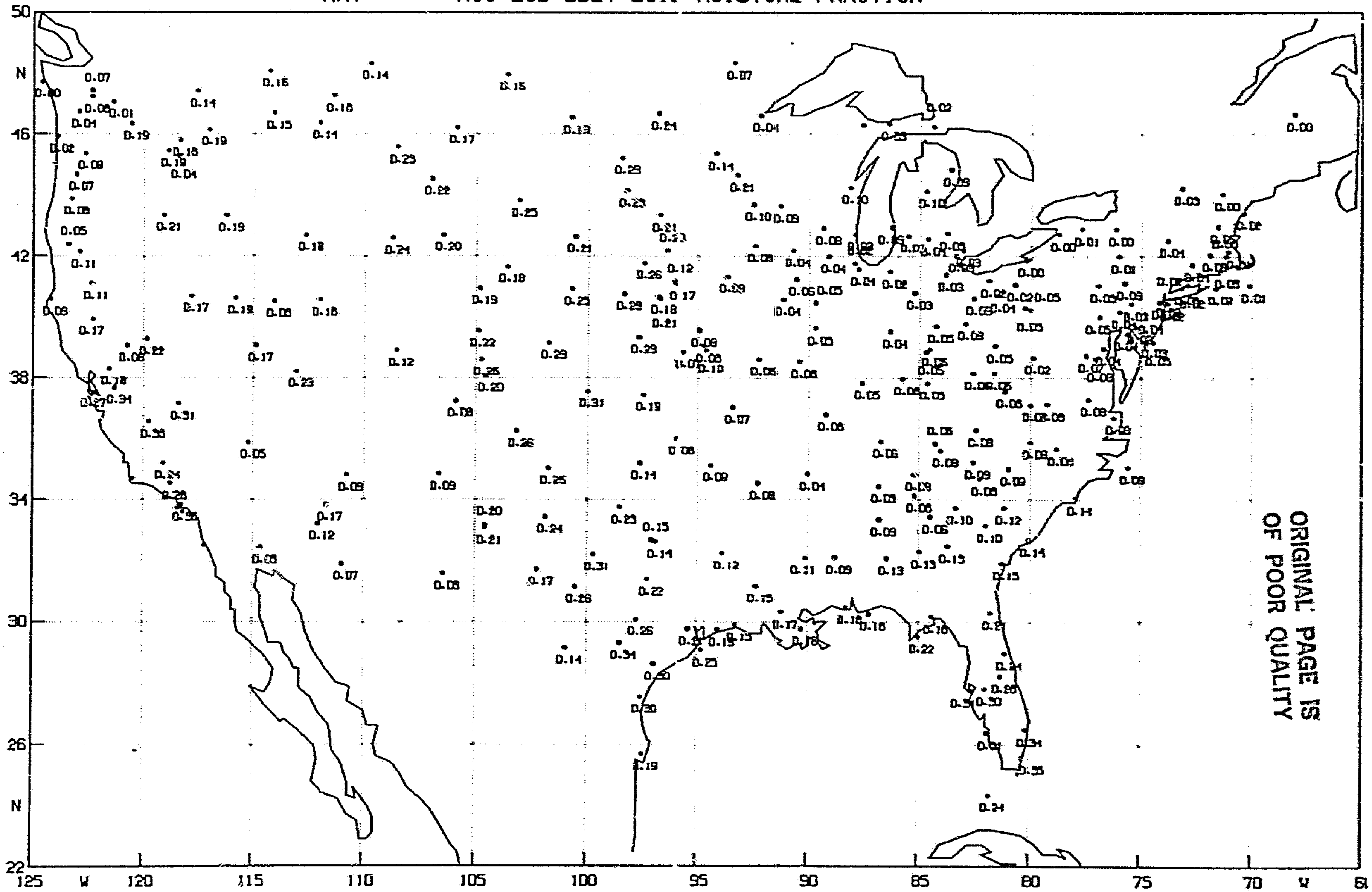


Fig. 5.b.6

JUNE NCC LCD SDEV SOIL MOISTURE FRACTION

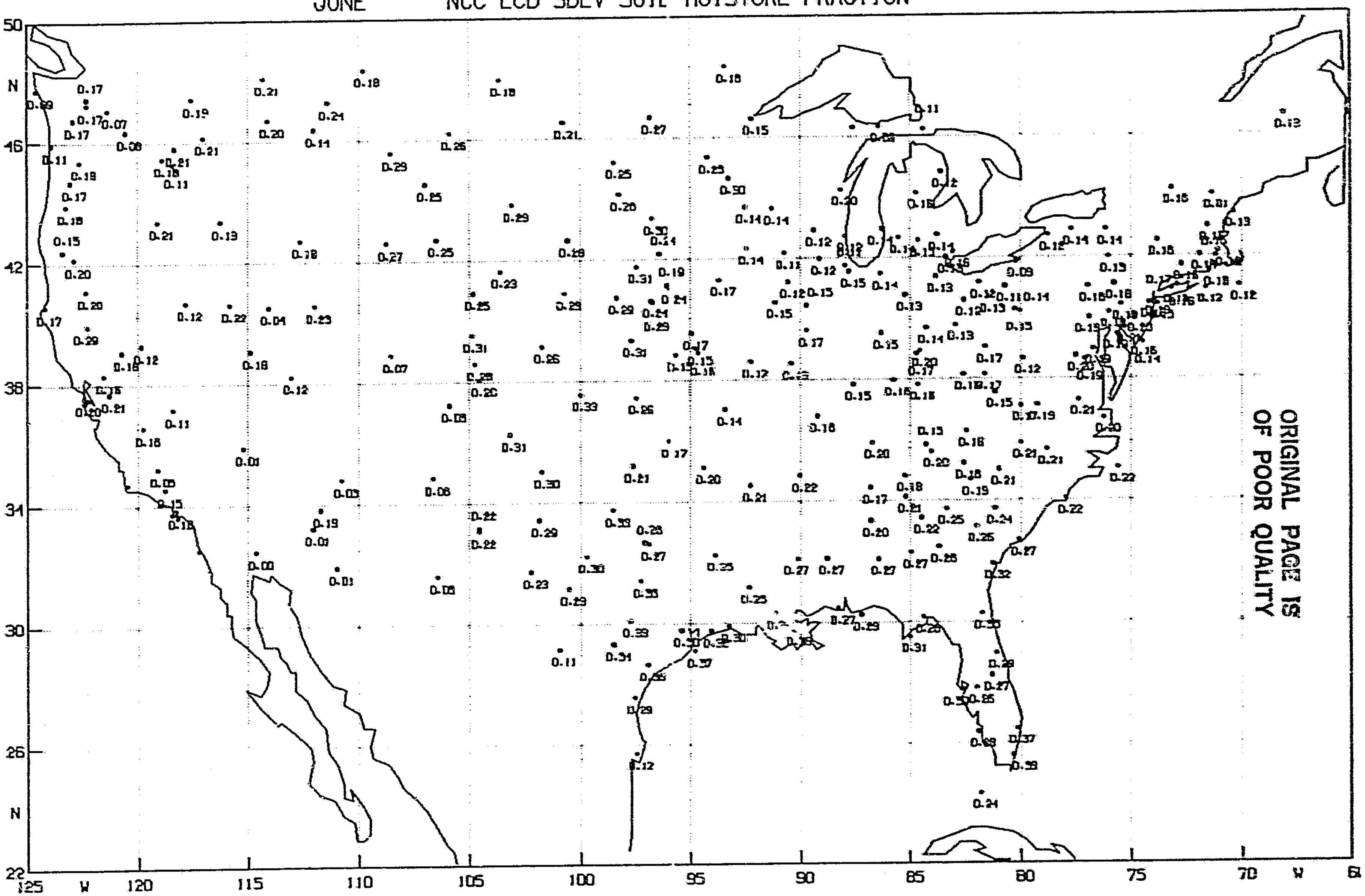


Fig. 5.b.7

JULY NCC LCD SDEV SOIL MOISTURE FRACTION

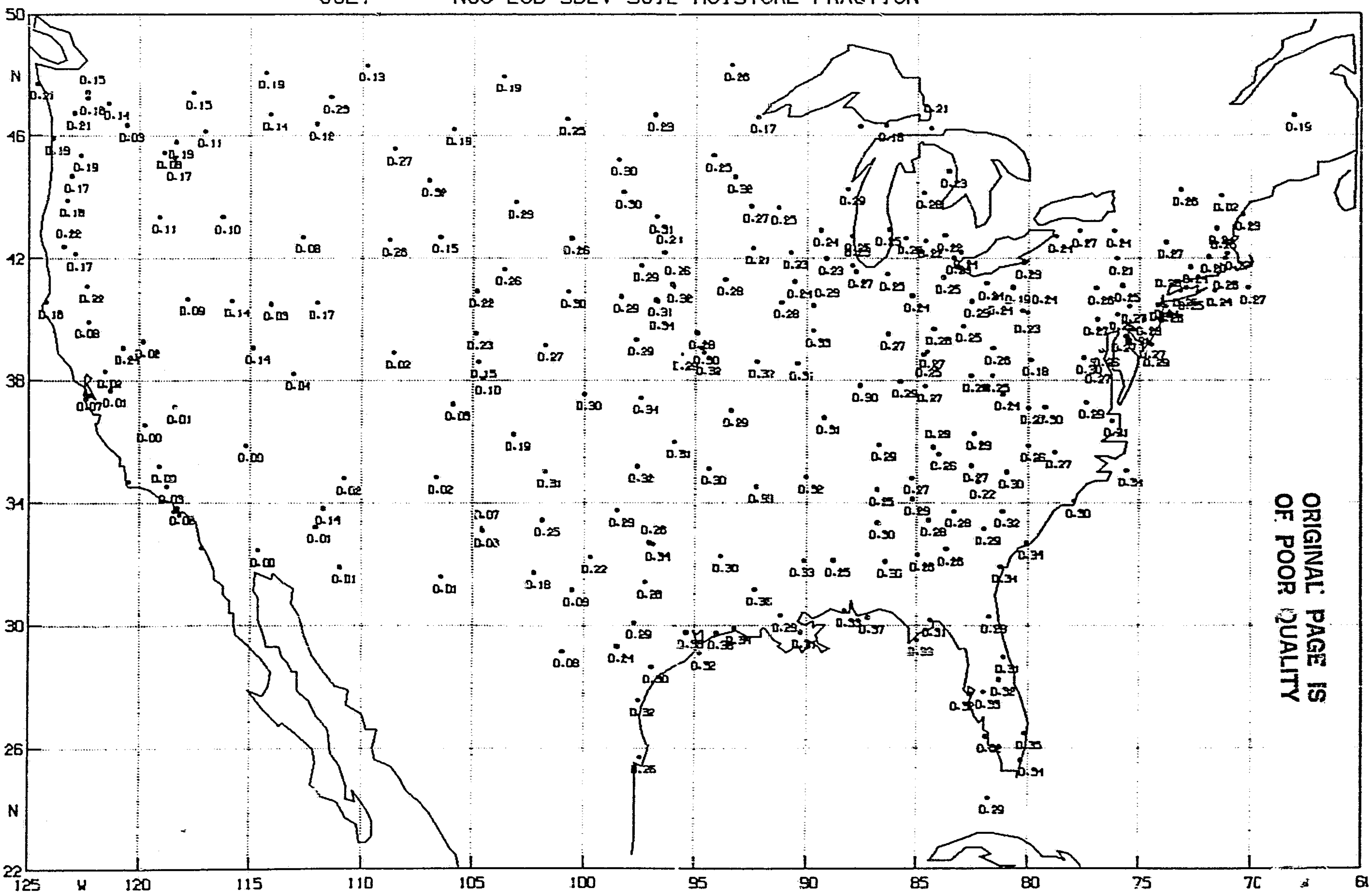
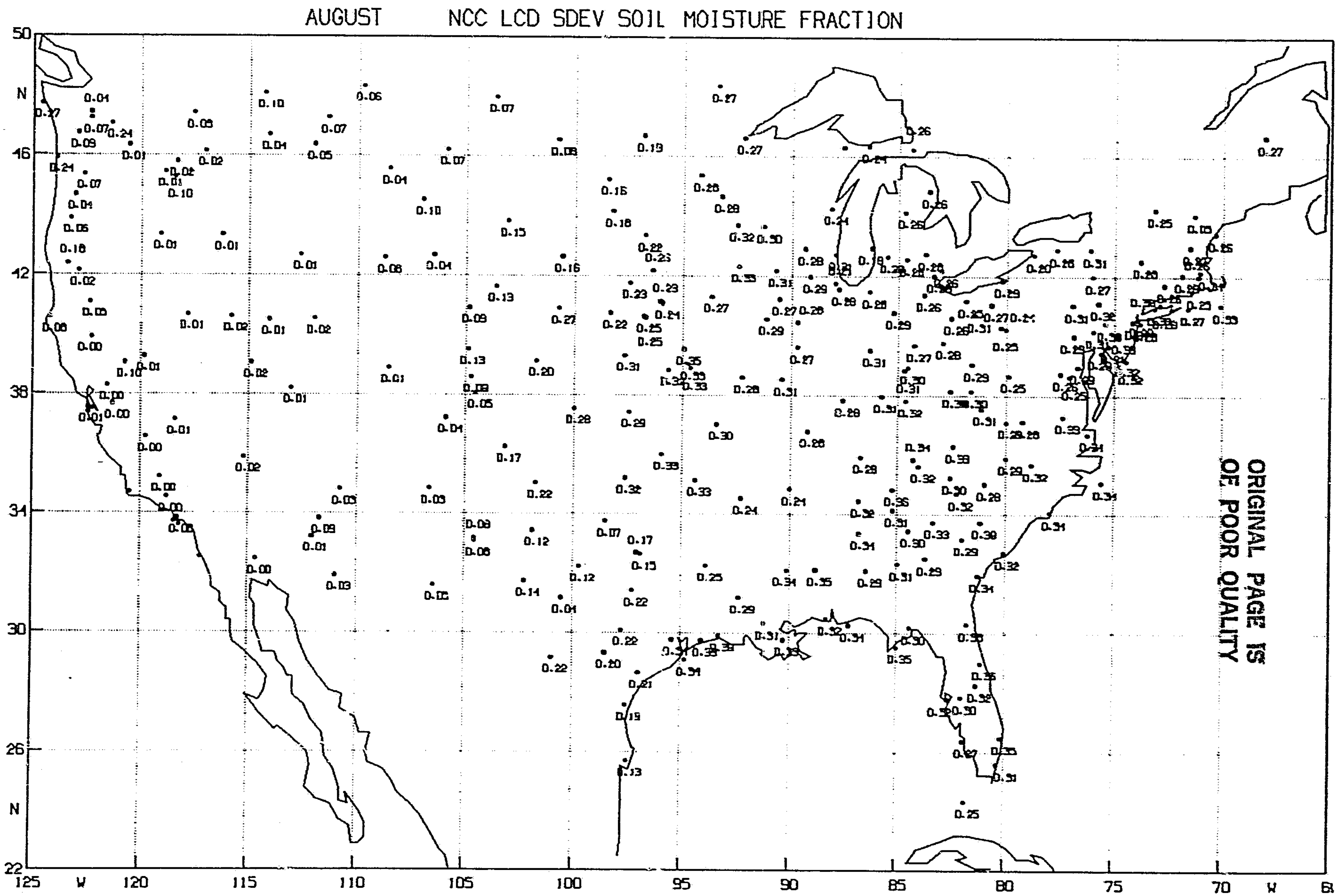


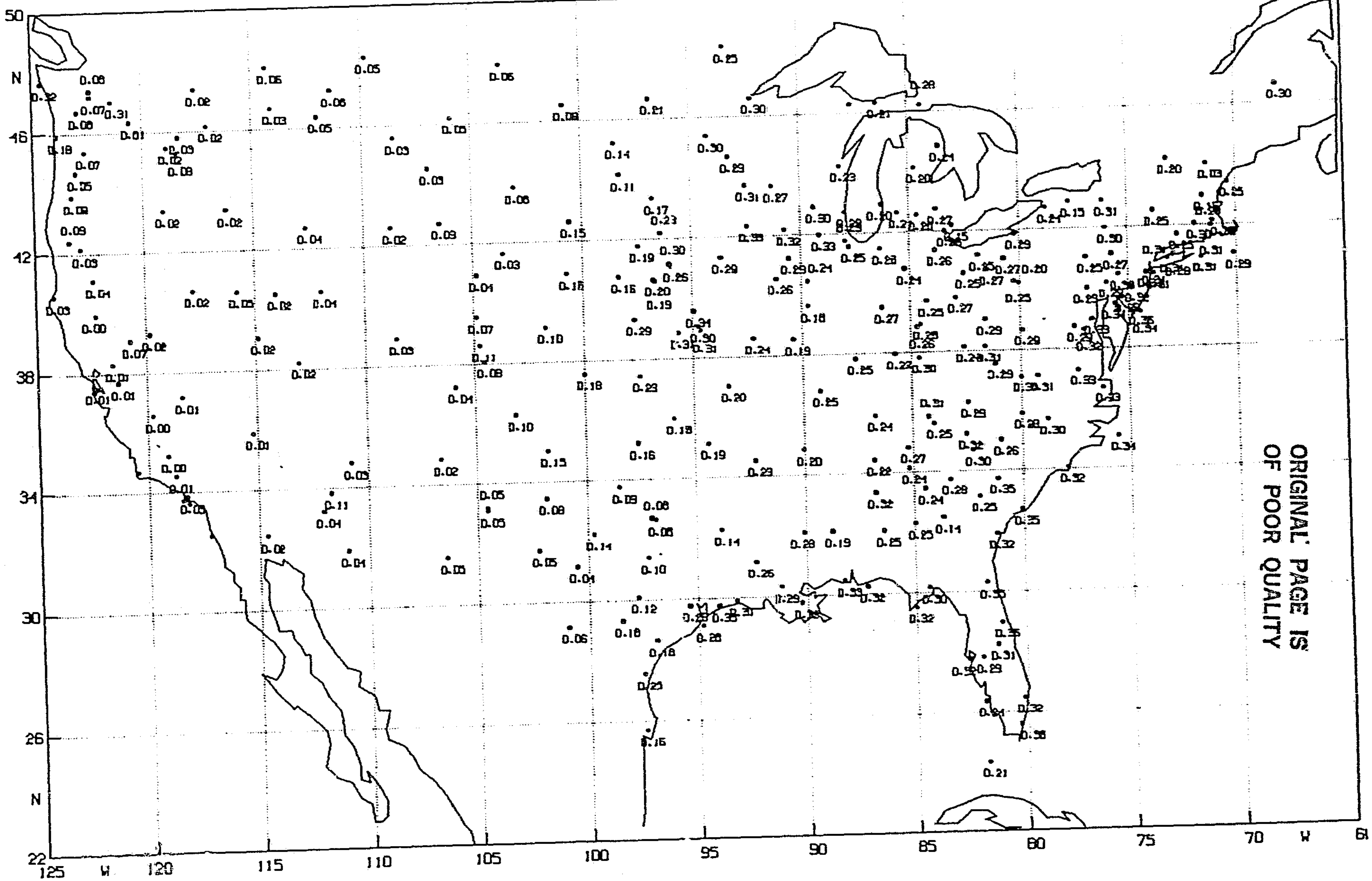
Fig. 5.b.8



AUGUST NCC LCD SDEV SOIL MOISTURE FRACTION
50
N
46
42
38
34
30
26
N
22
125
W
120
115
110
105
100
95
90
85
80
75
70
W
65
ORIGINAL PAGE IS
OF POOR QUALITY

Fig. 5.b.9

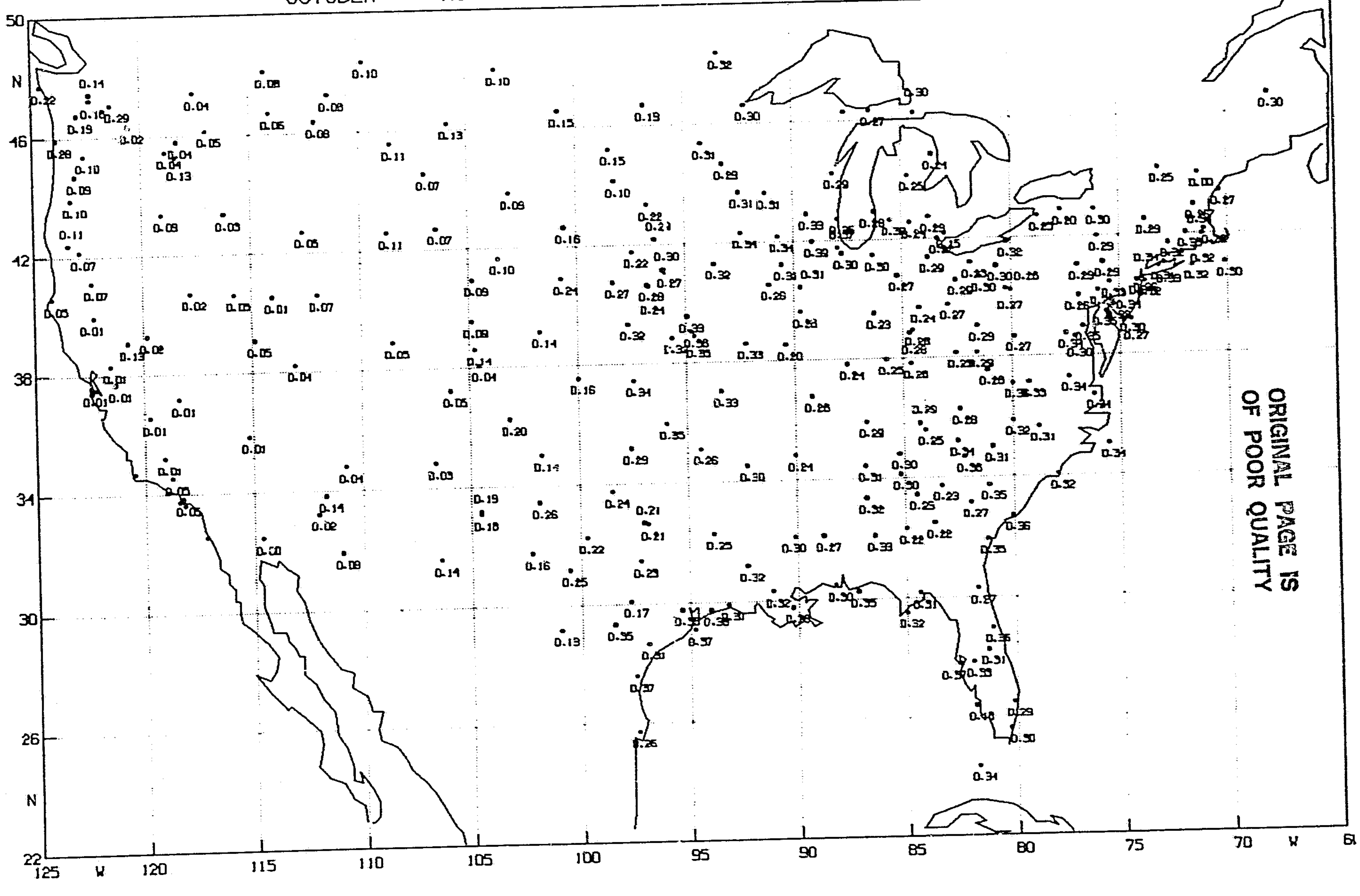
SEPTMBER NCC LCD SDEV SOIL MOISTURE FRACTION



ORIGINAL PAGE IS
OF POOR QUALITY

Fig. 5.b.10

OCTOBER NCC LCD SDEV SOIL MOISTURE FRACTION



ORIGINAL PAGE IS OF POOR QUALITY

Fig. 5.b.11

NOVEMBER NCC LCD SDEV SOIL MOISTURE FRACTION

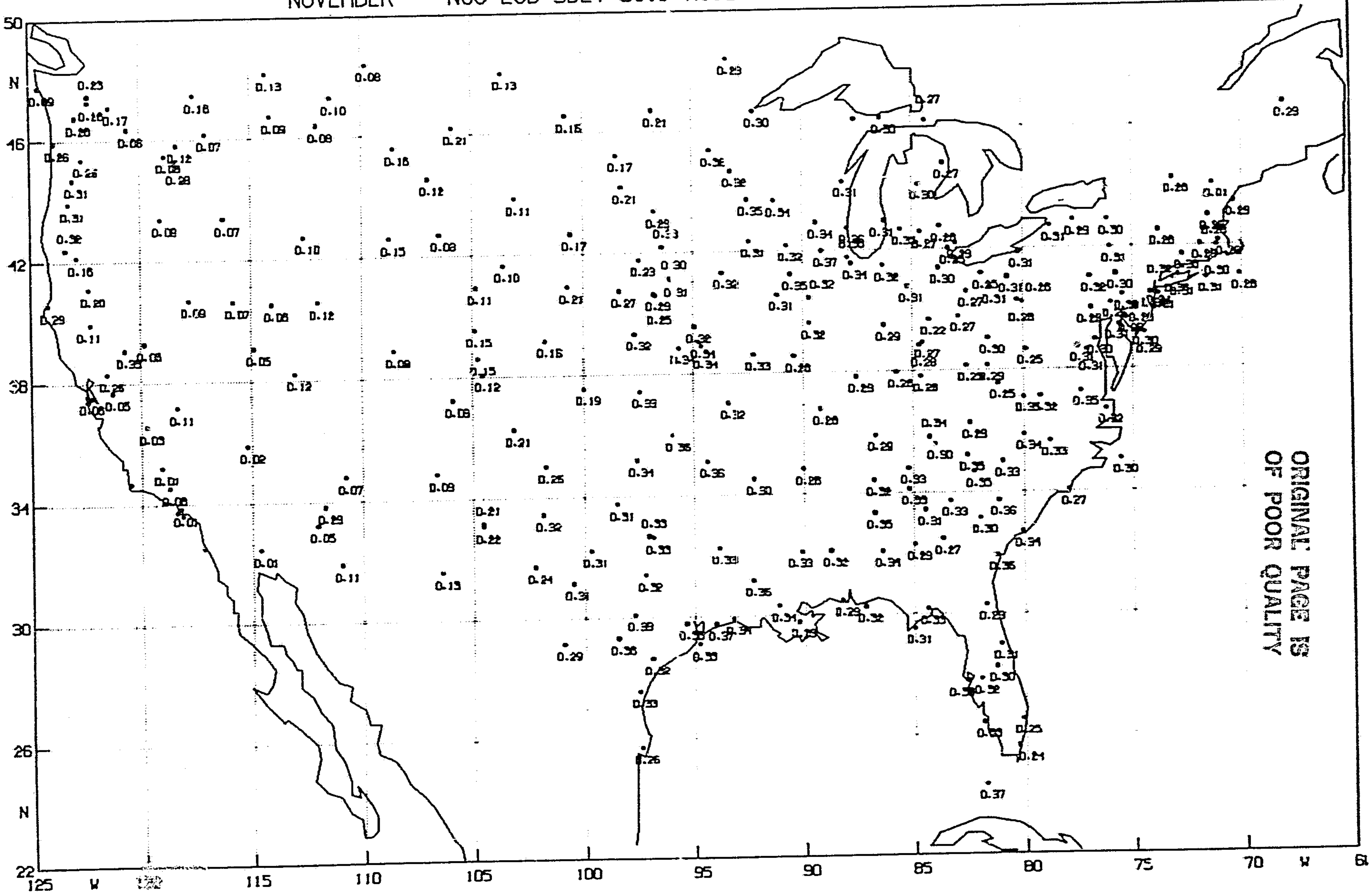
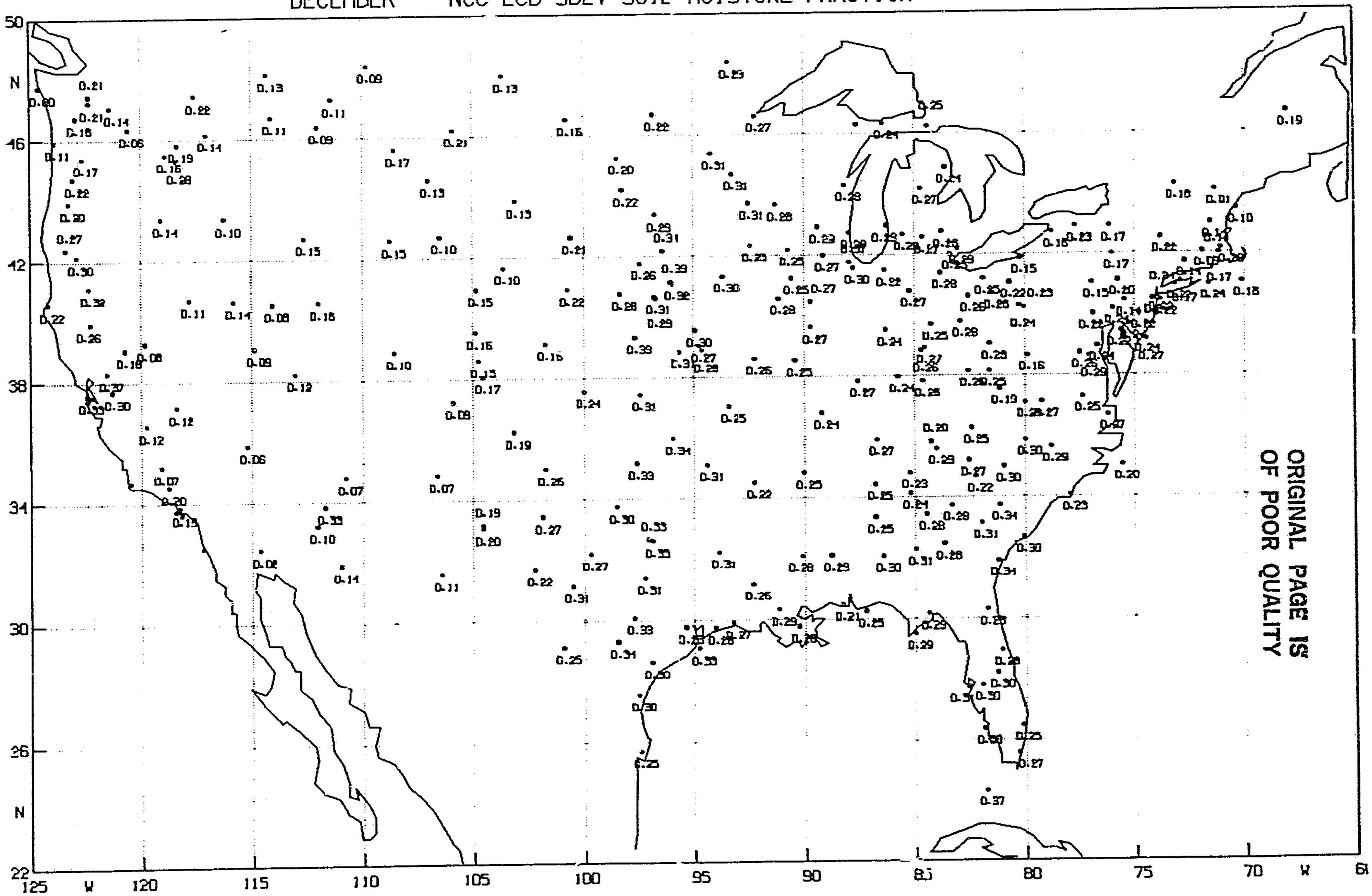


Fig. 5.b.12

DECEMBER   NCC LCD SDEV SOIL MOISTURE FRACTION



PART II: DEPENDENCE OF LOCAL PRECIPITATION ON ANTECEDENT SOIL MOISTURE OVER THE CONTIGUOUS 48 STATES

ABSTRACT

In the present study forty years of precipitation data as observed over 261 Local Climatic Data (LCD) stations in the Continental United States and calculated soil moisture fields were utilized to investigate the feedback effect of antecedent soil moisture on precipitation. A month-by-month soil moisture and evapotranspiration dataset was constructed using observed surface temperature and precipitation data in a simple ground water balance model. The monthly precipitation was correlated with antecedent monthly precipitation, soil moisture and evapotranspiration separately. The results show a perceptible signal indicating a positive feedback between the correlated fields in some regions. The maximum positive correlation is found to be in the drought prone western Great Plains region during the latter part of summer. There is also some negative correlation in coastal regions. The correlations between soil moisture, and precipitation, particularly in the latter part of summer, suggest that large scale droughts over extended periods may be partially maintained by the feedback influence of soil moisture on rainfall. In many other regions the lack of positive correlation shows that there is no simple answer such as higher land-surface evapotranspiration leads to more precipitation, and points out the complexity of the influence of soil moisture on the ensuing precipitation.

INTRODUCTION

Whether changes in land-surface evapotranspiration can significantly influence the future precipitation, is a question which has generated some controversy in the past. Prior to 1937, it was generally believed that the land-surface evapotranspiration had an important influence on the future precipitation. However, beginning with the study by Holzman (1937) several investigators (Benton *et al.*, 1954, Budyko, 1958) presented results contrary to this belief. Subsequently, Libby (1959) found that 33% of the rainfall in the Mississippi watershed came from local evaporation. For a detailed history of this controversy, see Stidd (1968).

Retrospectively, it can be stated that much of the aforementioned controversy arose because most of these studies were based on annual averages. Since, in the wintertime the rainfall is largely produced by large-scale baroclinic systems and the land-surface evapotranspiration is generally small, there is no reason to expect a strong correlation between the two. However, the summertime situation is quite different. Generally, over the land surface the evapotranspiration exceeds the precipitation, with the exception of monsoonal regions. Also, the precipitation is largely of convective character, and derives a significant amount of precipitable water from the mixed layer (ML) of the planetary boundary layer (PBL). Therefore, we naturally expect a significant correlation between evapotranspiration and precipitation.

Observationally very little has been done to understand this influence. Soil moisture measurements at climatic data stations have been virtually nonexistent. This has been a great handicap for similar correlation studies as well as for general circulation simulation studies. To date, there are only a few systematic studies (e.g. Schickendanz, 1976) which shed some light on this subject. By employing methods of statistical inference Schickendanz showed

ORIGINAL PAGE IS
OF POOR QUALITY

that the observed precipitation in the western Great Plains increased after the introduction of farming and artificial irrigation. He attributed this finding to the influence of increased evapotranspiration. Other researchers have made conjectural references to the importance of this influence. For example, Sutcliffe (1956) stated that in summertime there is a strong possibility that the same moisture can precipitate several times by continual overturning. Namias (1959) suggested that the anomalously high rainfall in the summertime in Texas in 1957 was perhaps related to the soil moisture anomaly produced by an antecedent wet springtime.

In a recent study of the spatial coherence of monthly precipitation over the U. S., Walsh et al., (1982) found maximum as well as most persistent correlations between monthly precipitation and the Palmer Drought Index to occur in the growing regions of the Midwest. They argued that this was due to the greater moisture holding capacity of the soils there. They also noted that the monthly precipitation was both least spatially coherent as well as least persistent during the summer months.

In the last ten years, the subject of feedback between land surface evapotranspiration and precipitation in numerical models has also drawn considerable attention. Studies by Walker and Rowntree (1977), Miyakoda et al. (1979) and Shukla and Mintz (1982) have indicated the important role of soil moisture anomalies on the simulated precipitation. Shukla and Mintz (1982) further inferred that the influence of a global scale soil moisture anomaly in the summertime can be quite complex.

In this study, we have examined the relation among monthly precipitation, evapotranspiration and soil moisture at 261 Local Climatic Data (LCD) stations over the contiguous 48 states in the United States (C48S). The soil moisture and evapotranspiration fields were constructed by a surface water balance model using the observed precipitation and surface temperature as detailed in Section I of this report.

2. PHYSICAL BASIS

The relationship between monthly evapotranspiration and precipitation for a region is simply:

$$P = E + C_m \tag{1}$$

where P, E and C_m represent monthly mean precipitation, evapotranspiration and atmospheric moisture convergence in a region. Obviously, (1) neglects moisture storage in the atmosphere. In the summertime, generally speaking, evapotranspiration exceeds precipitation which leads to depletion of soil moisture and drier ground by the end of summer. Therefore, if C_m were independent of E, it would be a simple matter to infer that a reduction in E would naturally lead to a corresponding reduction in P. However, there is no justification for such an assumption, particularly on the time scale of a month or more. There are several other feedbacks on the large scale circulation which play an important role in determining the outcome of these effects.

A soil moisture anomaly is directly related to antecedent precipitation anamolies (Walsh et al., 1982). Because the soil moisture has a time scale of up to a month or so, even in the summertime, it is plausible to examine these feedback effects on a monthly time scale. Therefore, we propose to use monthly averaged fields for this analysis. Secondly, because the evapotranspiration anomaly caused by a soil moisture anomaly can be expected to influence moisture convergence, it is important to separate these effects. Let us try to explain this by an example of near zero evapotranspiration, a drought situation. In such a case precipitation, P, equals the net moisture convergence, C_m. Since evapotranspiration is a moisture source term, its near absence would lead to moisture deficiency in the ML. The moist static energy, which essentially determines the onset of moist-convection, thereby determining convective precipitation is given by:

$$h = C_pT + gz + Lq \tag{2}$$

Absence of evapotranspiration would reduce the Lq term in the ML. On the other hand a corresponding increase in the sensible heat flux must show up in the C_pT term. The increase in the C_pT term will largely, though not entirely, compensate the reduction in the Lq term. The difference would presumably be due to the higher albedo and enhanced longwave cooling of the dry and hotter ground. Therefore, it can be argued that a reduction in evapotranspiration lowers the moist static energy of the ML which in turn could lead to reduced moist convective activity. This reduction in evaporation reduces moisture in the ML which then leads to raising of the lifting condensation level, reduction in rising motion due to reduced condensation heating and lower precipitation, which implies a positive feedback. Simultaneously, enhanced moisture convergence produced by a relative thermal low induced by sensible heating in a drier region introduces a negative feedback. With these two influences operating simultaneously, the overall influence of a reduction in evapotranspiration on rainfall is not obvious. Nearness of other moisture sources, such as an ocean, may provide moisture to the ML for convergence into the dry region. Thus the induced moisture convergence may compensate the deficit in moisture produced by lower evaporation. How does this local soil moisture anomaly then influence the large scale circulation? It is difficult to answer this question intuitively. One approach is to look at the observational data to understand how different regions respond to soil moisture anomalies. The problem is complex because of the innumerable temporal and spatial structures of soil moisture anomalies, as well as the effect of the peculiarities of large scale circulation themselves, having their origin in the multiplicity of solutions of the earth-atmosphere system, which in turn produce the soil moisture anomalies besides being affected by them. The current study attempts to identify regions of positive and negative feedback influences so as to understand the role of soil moisture on future precipitation. However, this study is directly applicable only to summertime in the continental United States and the conclusions may not hold for other regions or seasons.

3. SURFACE MOISTURE BALANCE

Mean monthly Local Climatic Data (LCD) consisting of precipitation and surface temperature fields, from 261 stations over the C48S, was obtained from the National Climatic Center (NCC) in Asheville, North Carolina. The data covers a period of 40 years (1940-1980). Missing data periods were ignored as opposed to filling the numbers in by interpolation. Fig. 1 shows the station locations with number of years of complete data at each station. Time series of potential evapotranspiration, actual evapotranspiration and soil moisture were calculated at each station. The details of this calculation are given in Section I of this report. We particularly focused on the drought prone semi-arid region of the western Great Plains, shown boxed in Fig. 1. This subset region as well as the entire C48S were statistically analyzed.

C-2

4. STATISTICAL CALCULATIONS

The observed precipitation and the constructed fields of antecedent soil moisture and evapotranspiration were analyzed to obtain the relationship among them. Attention was focused on the entire C48S region and its subset: the drought prone western Great Plains. To avoid the feedback of the current precipitation upon the calculated evapotranspiration, a pseudo-evapotranspiration was calculated based on the soil moisture and surface temperature on the first of the month. Furthermore, the surface temperature was obtained by adding its climatological variation to the antecedent observed value. Thus, the caculated antecedent soil moisture and evapotranspiration fields do not use the furture precipitation or surface temperature data. This ensures that the correlations are truely between future rainfall and antecedent soil moisture or evapotranspiration fields.

a. Correlation coefficients:

Three separate temporal correlations were calculated between mean-monthly precipitation with a) antecedent mean-monthly precipitation, b) soil moisture at the beginning of the month, and (c) monthly evapotranspiration at the beginning of the month. Of these only the first correlation is truly between the observed fields. We obtained correlation coefficients at each station for each month using the 40 year time series. This calculation eliminates non-linear bias introduced by spatial averaging and is free of the influences of the seasonal cycle. In order to isolate the regions of strong correlations, a two-tailed T-test was applied to isolate stations showing a strong signal. The correlation of rainfall with antecedent fields (predictors), determined purely from the past history of precipitation, ensures the sanctity of this statistical procedure.

ORIGINAL PAGE IS
OF POOR QUALITY

b) Contingency tables:

This is an alternative approach to correlation analysis which displays the structure of the relationship between the analyzed fields. For variables showing a skewed (non-normal) distribution this approach is used with better success. For each of the two fields to be correlated, the values were divided into five categories: very small, small, average, large, and very large. An event, e_{ij} is designated to belong to a location i, j (referring to i^{th} column of j^{th} row) of this table (i = 1, 5 & j = 1, 5) depending upon the category index of each of the variables being correlated. The diagonal of events, e_{ij}, from i = j = 1 to i = j = 5, represents the strength of the correlation. In a purely random process the number of events, n_{ij} in a location should be calculated from:

$$n_{ij} = N\, p_i\, p_j \qquad (5)$$

where N is the total number of events and p_i is the probability of i to be associated with any value j and vice versa for p_j. To facilitate interpretation of the contingency table it is normalized by dividing e_{ij} by n_{ij} and then multiplying by 100. Thus a normalized contingency table shows positive (negative) correlations for numbers more (less) than 100.

Obviously, there is no unique way to determine the categorical boundaries which divide the rows and columns in a contingency table. The authors tried several methods, but found the following to be logical as well as statistically appropriate. The precipitation at each station for each month was first ordered by magnitude, and then divided into categories containing 7.5, 10, 65, 10 and 7.5 percent of the data, from lowest to highest values respectively. Thus, assuming a normal distribution, these categories correspond to standard deviation cutoffs at $\pm 2\sigma$ and $\pm 1\sigma$ representing strong, weak or noise level signals. Each column in the tables represents a different precipitation category. Thus, even though a given table may be constructed by compositing data from many stations, the location of an event in the contingency table depends only on the variability of the field at that station. For example, entries in the driest column truly represent locally dry events. The rows of the tables were determined for the variable related to the precipitation, and were filled by the same procedure. The contingency tables were tabulated for two regions. One region included all 261 stations over the C48S, and the other contained 23 stations over the drought prone western Great Plains.

A standard χ^2-test was conducted to see the strength of the signal in these contingency tables. It should be noted that by examining the rows and columns constituting the boundaries of a contingency table one can examine the correlation of drought (wet season) with the antecedent predictors such as dry (wet) soil moisture.

5. RESULTS

For complete monthly means and standard deviations of temperature, precipitation and soil moisture fields over C48S the reader is referred to the first section of this report. The mean monthly soil moisture shows a distinct seasonal cycle, exhibiting near saturated soil during winter, and very dry soil in the latter summer months over most of the stations. The frequency distribution of the first of the month soil moisture over C48S, as well as over the subset region are shown in Table 1. Over both regions the soil moisture is lowest during August, September and October, at which time the standard deviation of soil moisture is of the same order as the mean soil moisture itself. The mean soil moisture over C48S for the driest month, September, is shown in Fig. 2a, while the corresponding standard deviations are shown in Fig. 2b.

The correlation coefficients between precipitation and the generated hydrology fields over the C48S follow a pattern very similar to that of precipitation with itself with a one month lag. Over most of the C48S there is no coherent pattern of significant correlations between these fields. September and October show the largest number of significant correlations, and have a coherent pattern of significant correlations over the western Great Plains. Fig. 3a shows the September - October precipitation correlations, while Figs. 3b and 3c show the soil moisture - precipitation and evapotranspiration - precipitation correlations for October. In these figures correlation coefficients significant at the 80% level or above are enlarged, while those at a few stations with less than 8 years of data are omitted. Also notable in these figures is the coherent region of negative correlations along the northwest and the Gulf coasts. The September correlations (not shown) are similar, with the western Great Plains again being the only coherent region of significant correlations.

ORIGINAL PAGE IS
OF POOR QUALITY

The contingency tables over C48S for interdependence of precipitation with itself at a one month lag, and for soil moisture and evapotranspiration with precipitation are shown in Tables 2a, b and c. The contingency table at the bottom right is a composite of July, August, September and October. Chi-squared test values are included at the bottom of each contingency table. The corresponding tables for the subset region are shown in Tables 3a, b and c. A diagonal dominance from upper left to lower right can be observed in the latter summer months, particularly September and October, in all six sets of tables. This dominance, which represents well correlated fields is stronger over the subset region. The July through October composite contingency tables display this dominance well, particularly in the two corners, which represent well correlated extreme cases. The large X^2 values reflect the strength of the signal. Figure 4 shows the normalized table values in the driest (solid) and wettest (dashed) soil moisture categories for the July to October composite case. Over both regions (Fig. 4a and 4b) the same trends appear, although they are stronger over the subset region. Dry (wet) soil corresponds to less (more) precipitation.

6. DISCUSSION AND CONCLUSIONS

We have isolated some regions and a few months of a significant positive relationship between precipitation and antecedent soil moisture. The correlations over the drought-prone western Great Plains were perceptibly stronger than those over the rest of the United States. In coastal regions, particularly the west coast, the correlations, though small, often had a coherent negative pattern. It should be pointed out that smaller negative correlation coefficients are to be expected in negative feedback situations, and their significance must be interpreted in light of this. Since recent simulation studies by Shukla and Mintz (1982) and Sud and Fennessy (1983) with the GLAS GCM have also shown that soil moisture influences on precipitation can be both positive or negative, the present results are not surprising. Increased moisture convergence due to higher ground temperature could explain this negative feedback in regions near moisture sources, e.g. the west coast of United States. The correlation coefficients generally are not too large, but nonetheless are significant in some regions. The overall distribution of correlation coefficients is somewhat complicated, which indicates the complexity of the feedback, as well as the strong influence of many other factors not taken into account. However, the summertime contingency tables do show that for extreme cases, particularly for very dry events, there is a clear dependence of precipitation on soil moisture. The July to August correlations and the August contingency tables seem to be an exception to this rule, showing no clear-cut relation between these variables. This could perhaps be due to the effect of local irrigation, which Schickedanz (1976) has shown to have a significant effect on the local precipitation. Schickedanz found increased local precipitation in irrigated regions of the western Great Plains during June, July and August, with the strongest effect occurring during July. As we do not account for this effect in the current study, it would lead to a degradation of our results.

The correlations were obtained by constructing soil moisture and evapotranspiration fields from a simple water balance model, which itself may only be adequate in semi-arid regions. Neither the field capacity ($w^* \equiv 150$ mm) nor the use of Nappo's (1975) evapotranspiration function are so suitable in forested regions found over many parts of the United States. We must also point out yet another drawback of a study such as this. The actual observations have many other influences such as changes in the boundary forcing and initial conditions in the real earth-atmosphere system. Some of the competing influences, such as sea-surface temperature anomalies, the initial state of the atmosphere, etc. are known to be important, but are not a part of this analysis. Perhaps, the true magnitude of the impact of soil moisture anomalies on the precipitation can only be studied by controlled experiments with GCMs.

For the present study, it is important to point out that some statistically significant influence has been found, both in space and time, between precipitation and surface evapotranspiration parameters. This influence may perhaps play a key role in determining the late summer precipitation in such regions and may therefore have an important role in the maintenance of droughts.

ACKNOWLEDGMENTS

This work is a precursor to a proposed study of the influence of land-surface evapotranspiration on maintenance of droughts. Dr. J. Shukla recommended a preliminary investigation of this effect through precipitation data analysis. An attempt to do this consistently has resulted in this paper. Professor Yale Mintz's active interest and many suggestions on the conduct of this study were very helpful. We would like to express our gratitude to him.

The paper was typed by Ms. J. Reckley and Mary Ann Wells and the figures were drafted by Ms. L. Rumburg. We would like to thank them for their assistance.

REFERENCES

Benton, G. S. and M. A. Estoque, 1954: Water Vapor Transport over the North American Continent. J. of Meteor., 11, 462-467.

Budyko, M., 1958: The Heat Balance of the Earth's Surface. Translation, OTS, PB 131692.

Fennessy, M. J. and Y. C. Sud, 1982: Local precipitation, temperature and soil moisture over the U.S. (NASA Tech. Memo to be published).

Holzman, B., 1937: Sources for Moisture for Precipitation in the U.S., U.S.D.A. Tech. Bull. 589.

Libby, W. F., 1959: Tritium in Hydrology and Meteorology. Researches in Geochemistry, edited by P.H. Abelson, J. Wiley and Sons, INC., NY, 151-168.

Mintz, Y. and V. Serafini, 1982: Monthly normal global fields of soil moisture and land surface evaporation. (To be published).

Miyakoda, K., G. D. Hembree and R. F. Strickler, 1979: Cumulative results of extended forecast experiments. Mon. Wea. Rev., 107, 395-420.

Namias, J., 1959: Persistence of mid-tropospheric circulation between adjacent months and seasons, in The atmosphere and the sea in motion (Rossby Memorial Volume) ed. B. Bolin, 240-248.

Nappo, C. T. Jr., 1975: Parameterization of surface moisture and evaporation rate in a planetary boundary layer model. J. Appl. Met., 14, 289-296.

Panofsky, H. A. and G. W. Brier 1976: Some applications of statistics to Meteorology. College of Earth and Mineral Sciences, The Pennsylvania State University, University Park, Pennsylvania USA.

Schickendanz, 1976: The effect of irrigation on precipitation in the Great Plains. Final Report, Illinois State Water Survey, University of Illinois, Urbana, Illinois.

Shukla, J. and Y. Mintz, 1982: The influence of land surface evapotranspiration on earth's climate. Science, 215, 1498-1501.

Stidd, C. K., 1968: Local moisture and precipitation. Reprint No. 45A, Center for Water Resources Research, Desert Research Institute, University of Nevada.

Sud, Y. C., and M. J. Fennessy 1983: Influence of subtropical evaporation anomalies on July circulation. (Submitted for publication).

Sutcliffe, R. C., 1956: Water balance and the general circulation of the atmosphere, Quart. J. R. Met. Soc., 82, 383-395.

Thornthwaite, C. W., 1948: An approach toward a rational classification of climate, Geog. Rev., 38, 55-94.

Walker, J. and P. R. Rowntree, 1977: The effect of soil moisture and rainfall in a tropical model. Quart. J. Roy. Meteor. Soc., 103, 29-46.

Walsh, John E., M. B. Richman and D. W. Allen, 1982: Spatial Coherence of Monthly Precipitation in the United States. Mon. Wea. Rev., 110, 272-286.

Willmott, C. J., 1977: A Fortran IV algorithm for calculating the climatic water budget. OWRT project No. A-040-DEL. Water Resources Center, Univ. of Delaware, Newark, Delaware.

ORIGINAL PAGE IS OF POOR QUALITY

FIGURE LEGENDS

Fig. 1. Number of complete data years from 1940 to 1980 for NCC LCD U.S. stations.

Fig. 2a. Mean September soil moisture fraction over NCC LCD U.S. stations.

Fig. 2b. Standard deviation of September soil moisture fraction over NCC LCD U.S. stations.

Fig. 3a. September to October precipitation correlation coefficients.

Fig. 3b. October first of the month soil moisture to October precipitation correlation coefficients.

Fig. 3c. October first of the month evapotranspiration to October precipitation correlation coefficients.

Fig. 4a. Graphical display of the normalized probability of correlation between antecedent soil moisture and precipitation over C48S.

Fig. 4b. Graphical display of the normalized probability of correlation between antecedent soil moisture and precipitation over subset region.

PRECEDING PAGE BLANK NOT FILMED

TABLE 1

SOIL MOISTURE FREQUENCY DISTRIBUTION

1a) Western Great Plains subset region

INTERVAL	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
0.0 - 0.2	.20	.16	.14	.16	.22	.27	.51	.77	.82	.68	.54	.38
0.2 - 0.4	.26	.28	.27	.20	.15	.14	.16	.11	.11	.15	.19	.25
0.4 - 0.6	.14	.11	.12	.12	.10	.13	.13	.05	.04	.07	.09	.10
0.6 - 0.8	.25	.15	.10	.13	.14	.13	.06	.03	.02	.03	.06	.10
0.8 - 1.0	.15	.29	.37	.39	.40	.32	.14	.04	.01	.06	.12	.17

1b) Contingent 48 states (C48S)

INTERVAL	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
0.0 - 0.2	.04	.03	.03	.04	.07	.12	.25	.48	.56	.46	.32	.17
0.2 - 0.4	.14	.13	.13	.10	.07	.09	.17	.19	.18	.19	.20	.15
0.4 - 0.6	.07	.07	.07	.07	.07	.12	.18	.12	.10	.12	.14	.12
0.6 - 0.8	.08	.07	.07	.07	.09	.16	.15	.08	.06	.07	.11	.13
0.8 - 1.0	.67	.69	.71	.73	.70	.51	.25	.13	.10	.15	.23	.43

ORIGINAL PAGE IS
OF POOR QUALITY

TABLE II.A

NORMALIZED CONTINGENCY TABLES FOR C48S

MONTHLY PRECIPITATION WITH ANTECEDENT PRECIPITATION

MAY

100	93	10[illegible]	96	98
96	98	101	87	105
101	101	100	100	93
105	99	98	93	114
86	99	94	123	128

CHISQ= 15.8

JUNE

90	94	109	76	65
102	94	100	102	97
98	99	99	102	99
111	103	94	116	111
100	109	99	77	123

CHISQ= 27.6

JULY

121	102	94	126	86
116	105	98	87	103
101	101	99	97	99
85	85	102	105	105
65	93	104	100	104

CHISQ= 24.3

AUGUST

109	120	94	88	128
97	117	98	94	96
97	93	100	103	100
111	98	99	102	91
102	112	101	83	83

CHISQ= 21.7

SEPTEMBER

107	108	99	97	90
103	106	98	106	88
102	96	100	100	98
85	102	98	103	119
88	108	100	88	113

CHISQ= 10.9

OCTOBER

165	126	98	70	54
134	108	98	85	88
88	102	100	101	102
97	71	100	113	123
92	82	100	116	109

CHISQ= 76.1

NOVEMBER

115	87	96	111	119
117	103	100	93	80
94	99	99	99	110
103	106	102	95	68
100	106	101	111	58

CHISQ= 33.2

JUL - OCT

125	114	96	95	89
112	109	98	93	94
97	98	100	100	100
95	89	100	106	109
87	99	101	97	102

CHISQ= 48.0

TABLE II.B

NORMALIZED CONTINGENCY TABLES FOR C48S

MONTHLY PRECIPITATION WITH ANTECEDENT SOIL MOISTURE

MAY

111	87	101	99	94
85	102	96	113	125
103	105	99	98	91
117	96	97	94	116
56	64	107	106	119

CHISQ= 41.3

JUNE

83	108	98	116	96
106	97	98	103	102
109	102	99	94	103
54	82	105	117	97
86	100	103	103	75

CHISQ= 35.7

JULY

130	120	102	67	65
99	118	98	91	102
94	98	100	102	99
114	91	96	118	106
96	82	100	99	123

CHISQ= 37.4

AUGUST

115	109	95	94	117
140	120	93	97	94
92	97	99	104	106
87	97	106	94	65
113	83	106	80	79

CHISQ= 47.7

SEPTEMBER

109	99	102	80	92
109	103	96	105	105
101	101	100	97	99
80	97	98	113	112
86	87	102	112	90

CHISQ= 14.8

OCTOBER

134	122	94	93	90
123	108	101	79	79
99	97	100	102	101
73	88	99	112	129
73	105	103	99	86

CHISQ= 40.4

NOVEMBER

125	111	93	106	104
114	92	100	98	96
92	103	100	95	102
120	86	96	125	91
90	85	104	99	88

CHISQ= 27.8

JUL - OCT

122	112	98	83	91
118	112	97	93	95
97	98	100	101	101
88	93	100	109	103
92	89	103	98	95

CHISQ= 58.2

ORIGINAL PAGE IS
OF POOR QUALITY

TABLE II.C

NORMALIZED CONTINGENCY TABLES FOR C48S

MONTHLY PRECIPITATION WITH ANTECEDENT EVAPOTRANSPIRTATION

MAY

102	112	104	82	60
129	91	101	79	97
95	104	98	103	103
109	91	100	106	93
77	71	103	103	123

CHISQ= 38.4

JUNE

92	91	101	96	115
105	97	98	116	91
104	99	100	94	101
87	95	101	113	90
77	125	97	114	92

CHISQ= 20.6

JULY

138	108	102	68	71
97	105	99	85	119
98	99	100	100	96
97	91	97	126	99
83	100	97	106	130

CHISQ= 37.1

AUGUST

115	116	95	93	111
143	114	92	104	94
89	95	101	102	103
96	113	102	93	71
121	83	101	91	102

CHISQ= 41.4

SEPTEMBER

104	102	102	85	86
120	102	95	104	108
98	101	100	97	101
93	93	99	113	103
86	93	102	111	83

CHISQ= 14.0

OCTOBER

142	129	93	90	90
123	109	103	68	74
96	99	100	98	98
82	79	98	128	119
75	87	96	125	134

CHISQ= 66.4

NOVEMBER

167	108	92	99	83
148	115	92	86	116
85	96	101	103	102
102	97	101	98	87
86	106	103	88	92

CHISQ= 64.8

JUL - OCT

125	114	98	84	89
121	107	97	90	99
95	99	100	99	100
92	94	99	115	98
91	92	99	108	112

CHISQ= 68.4

ORIGINAL PAGE IS OF POOR QUALITY

TABLE III.A

MONTHLY CONTINGENCY TABLES FOR SUBSET REGION

MONTHLY PRECIPITATION WITH ANTECEDENT PRECIPITATION

MAY

115	39	106	78	144
117	92	100	132	39
97	110	100	96	85
97	92	106	92	58
87	78	75	117	347

CHISQ= 32.1

JUNE

202	78	100	78	58
39	92	115	66	78
106	94	99	98	109
78	92	96	172	58
58	195	88	78	144

CHISQ= 21.3

JULY

347	58	85	117	29
97	92	108	92	39
79	106	101	102	97
78	79	100	92	156
87	117	91	78	202

CHISQ= 35.4

AUGUST

58	156	103	0	173
117	105	98	92	97
118	78	98	117	106
58	145	96	119	78
0	176	121	19	0

CHISQ= 32.4

SEPTEMBER

202	195	94	19	29
117	39	108	119	58
94	100	99	108	100
58	132	104	66	97
87	39	94	117	231

CHISQ= 29.3

OCTOBER

144	137	97	78	58
156	105	88	132	97
109	104	101	90	82
19	66	104	105	176
0	58	97	156	202

CHISQ= 24.3

NOVEMBER

115	58	91	137	173
39	172	112	39	19
103	88	97	108	121
97	145	98	105	39
144	78	112	58	29

CHISQ= 26.8

JUL - OCT

188	137	94	53	72
122	86	101	109	73
100	97	99	104	96
53	105	101	95	127
43	97	101	93	159

CHISQ= 38.9

TABLE III.B

NORMALIZED CONTINGENCY TABLES FOR SUBSET REGION

MONTHLY PRECIPITATION WITH ANTECEDENT SOIL MOISTURE

MAY

115	156	91	58	144
78	119	100	119	58
103	106	101	98	72
97	39	108	66	156
87	39	79	176	289

CHISQ= 32.4

JUNE

173	58	106	58	87
78	52	98	119	176
106	117	98	100	85
39	105	110	79	78
87	39	97	137	173

CHISQ= 19.0

JULY

173	117	100	39	87
137	105	100	105	39
97	104	99	94	106
58	92	96	119	156
58	39	106	176	58

CHISQ= 16.2

AUGUST

58	97	115	78	29
156	105	84	119	156
103	102	96	102	121
39	92	112	119	19
115	78	121	39	0

CHISQ= 23.7

SEPTEMBER

231	97	97	58	58
215	52	92	145	58
91	112	101	90	94
19	92	198	158	117
0	58	106	78	231

CHISQ= 37.2

OCTOBER

144	156	106	19	29
156	66	110	66	39
97	102	99	100	100
58	92	98	132	117
58	78	82	176	231

CHISQ= 26.2

NOVEMBER

58	19	109	156	87
39	119	100	79	156
106	127	95	94	103
156	13	104	132	78
87	19	124	78	29

CHISQ= 30.4

JUL - OCT

152	117	104	48	50
166	82	97	109	73
97	105	99	97	105
44	92	101	132	102
57	63	104	117	130

CHISQ= 43.6

ORIGINAL PAGE IS OF POOR QUALITY

TABLE III.C

MONTHLY CONTINGENCY TABLES FOR SUBSET REGION

MONTHLY PRECIPITATION WITH ANTECEDENT EVAPOTRANSPIRATION

MAY

173	97	103	39	87
215	132	71	92	215
79	115	102	104	69
97	26	104	119	137
58	19	109	97	173

CHISQ= 39.2

JUNE

144	137	106	19	58
78	92	98	105	137
121	100	97	102	94
0	79	108	132	97
29	97	103	97	144

CHISQ= 17.4

JULY

173	78	106	39	87
117	145	98	79	58
97	92	100	106	100
58	132	92	119	137
87	78	103	97	115

CHISQ= 11.0

AUGUST

58	97	118	78	0
195	79	84	132	137
100	100	96	102	124
39	119	112	79	39
87	97	115	78	0

CHISQ= 25.2

SEPTEMBER

231	97	97	58	58
156	52	96	145	78
97	117	100	90	91
39	66	106	145	78
0	58	97	97	289

CHISQ= 36.4

OCTOBER

144	156	109	19	0
156	66	106	66	78
100	98	100	106	85
39	119	84	172	176
58	78	97	58	260

CHISQ= 35.2

NOVEMBER

87	0	115	117	87
19	145	92	132	137
115	108	98	84	109
78	79	100	172	39
115	78	109	78	58

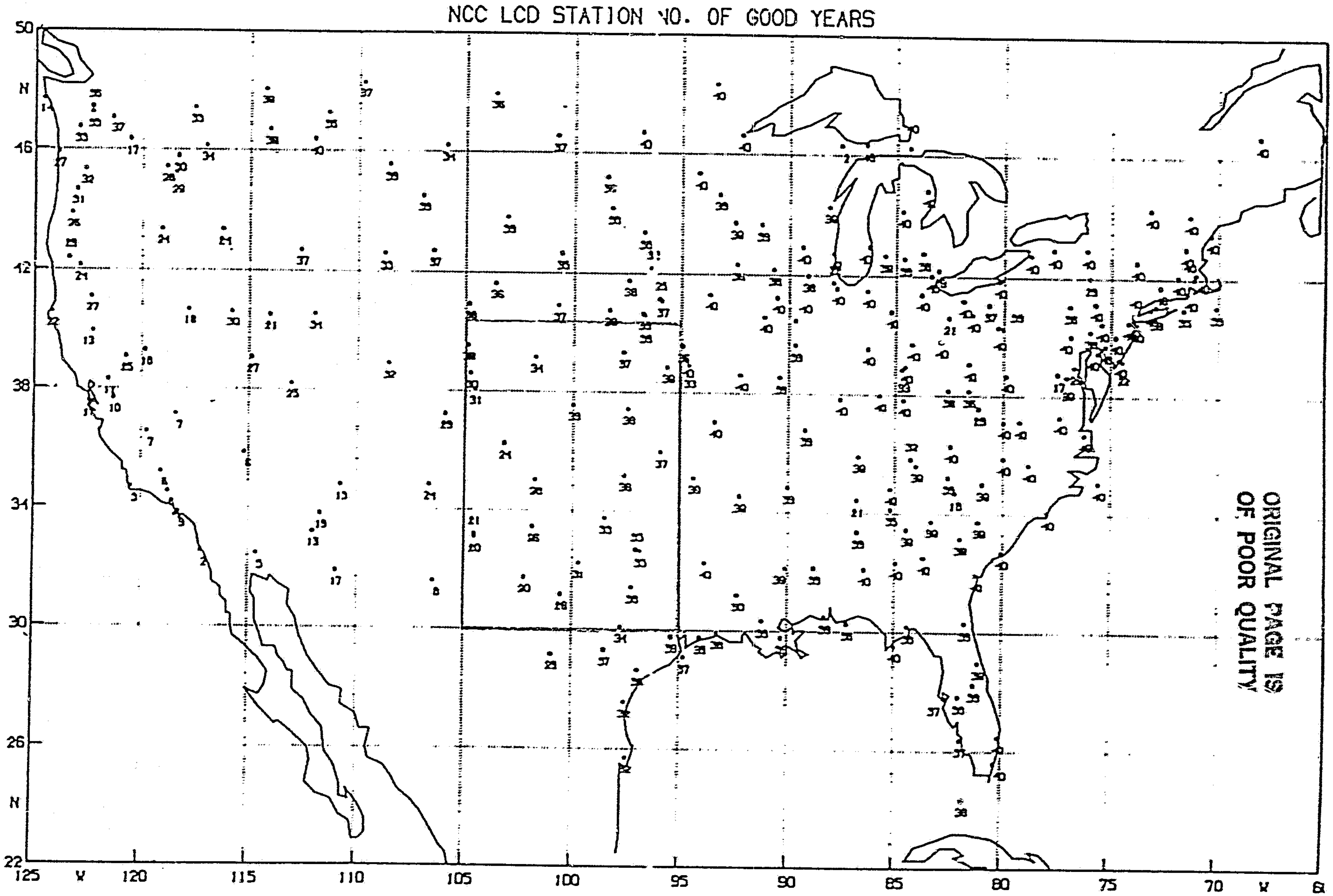
CHISQ= 23.4

JUL - OCT

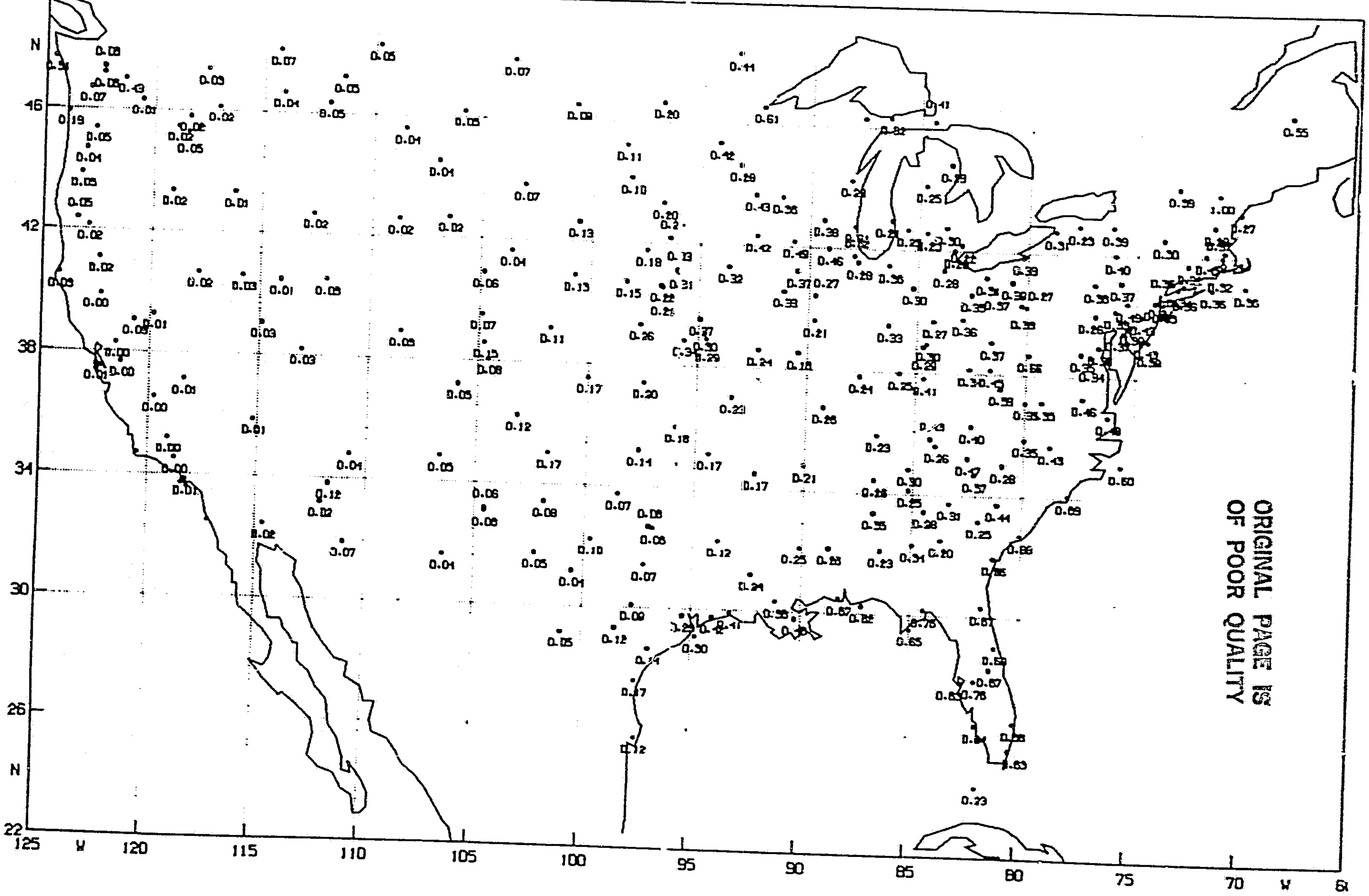
152	107	107	48	36
156	86	96	105	88
98	102	99	101	100
44	109	99	129	107
57	78	103	83	166

CHISQ= 43.2

Fig. 1


NCC LCD STATION NO. OF GOOD YEARS
50
46
42
38
34
30
26
22
N
125
W
120
115
110
105
100
95
90
85
80
75
70
65
ORIGINAL PAGE IS
OF POOR QUALITY

SEPTMBER NCC LCD MEAN SOIL MOISTURE FRACTION



ORIGINAL PAGE IS
OF POOR QUALITY

Fig. 2b

SEPTMBER NCC LCD SDEV SOI'L MOISTURE FRACTION

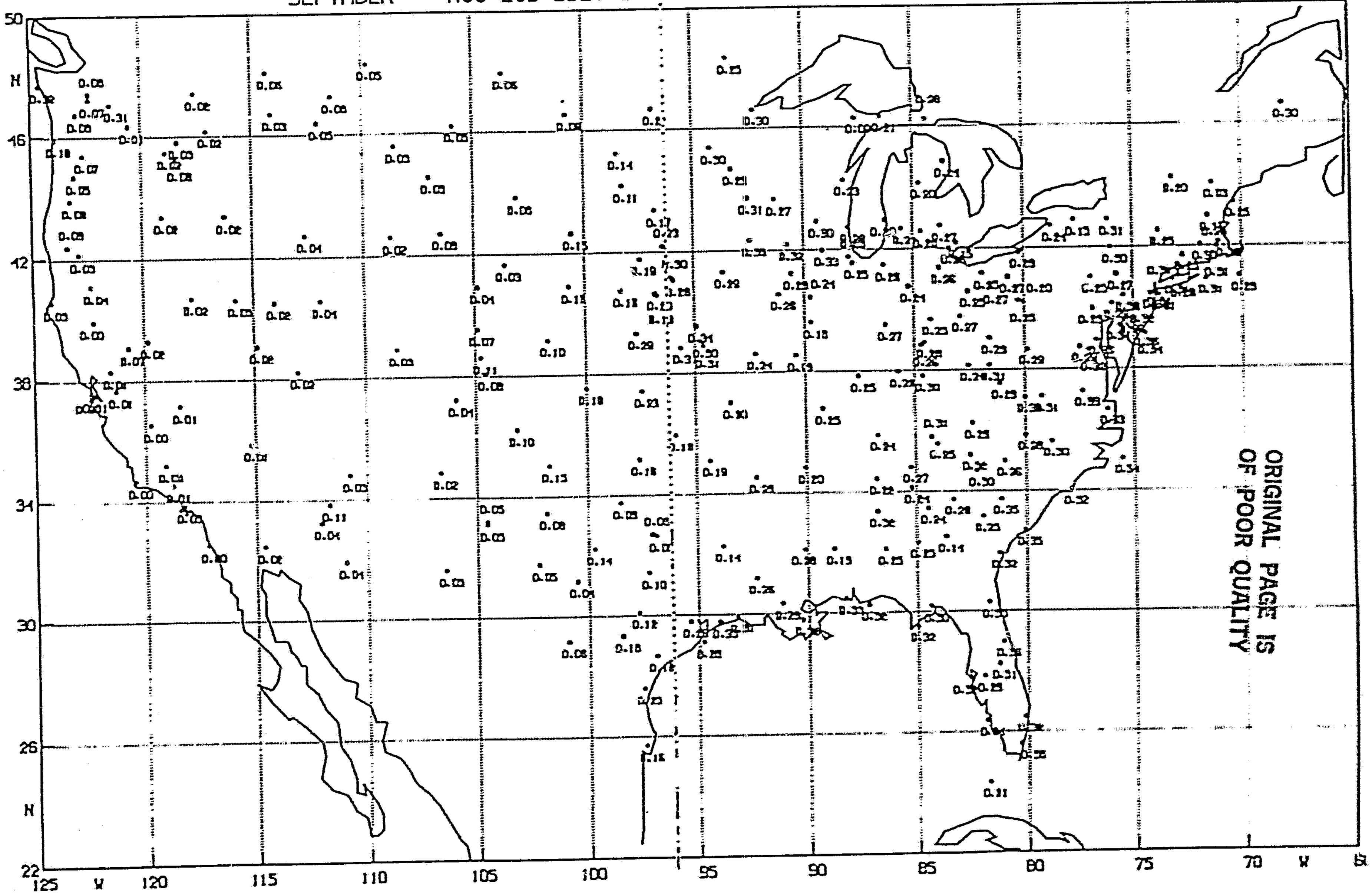


Fig. 3a

OCTOBER NCC LCD COR. CO. P-P PREVIOUS MO TO

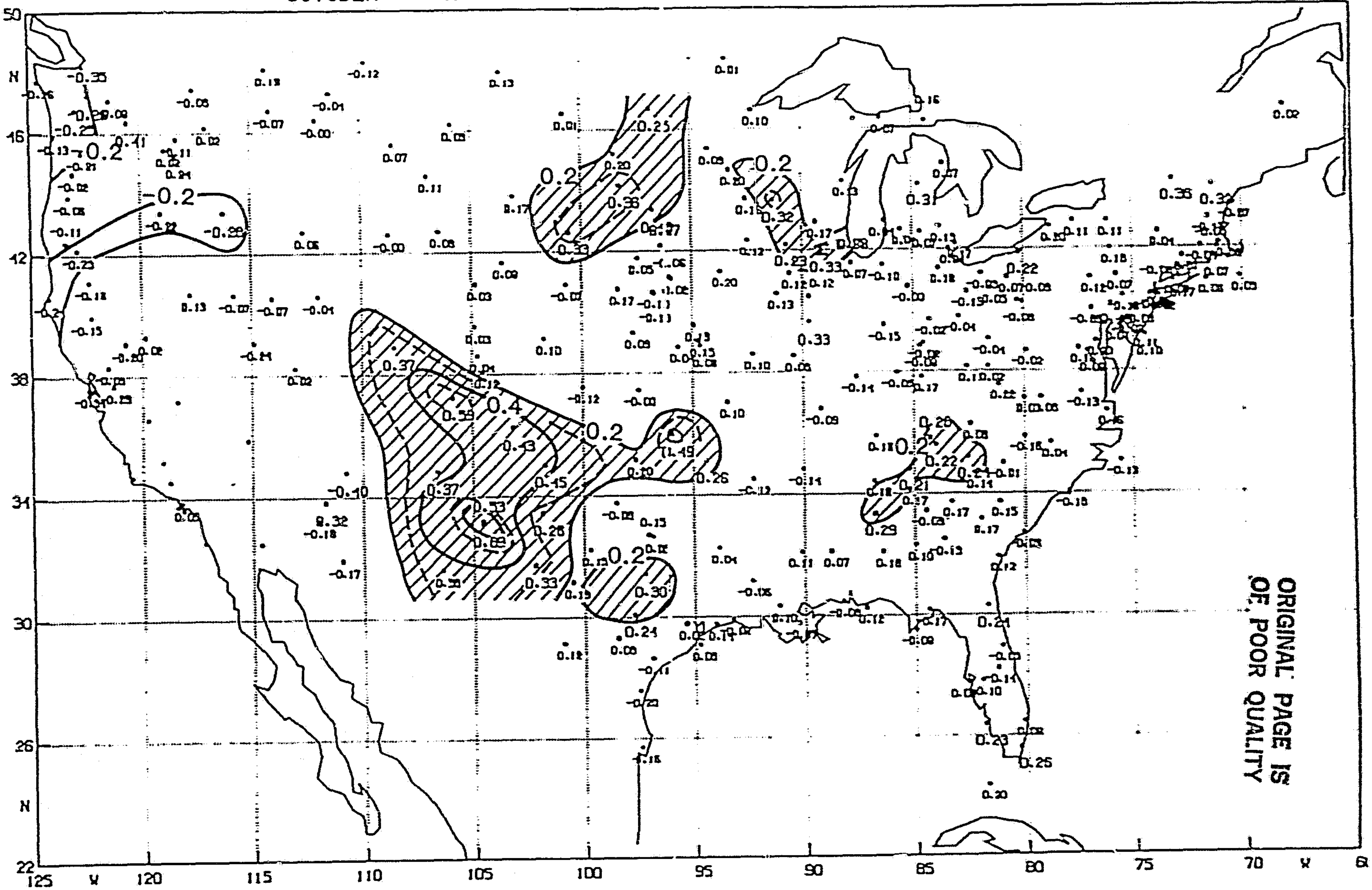


Fig. 3b

OCTOBER NCC LCD COR. CO. PRECIP. - SOIL MOISTURE

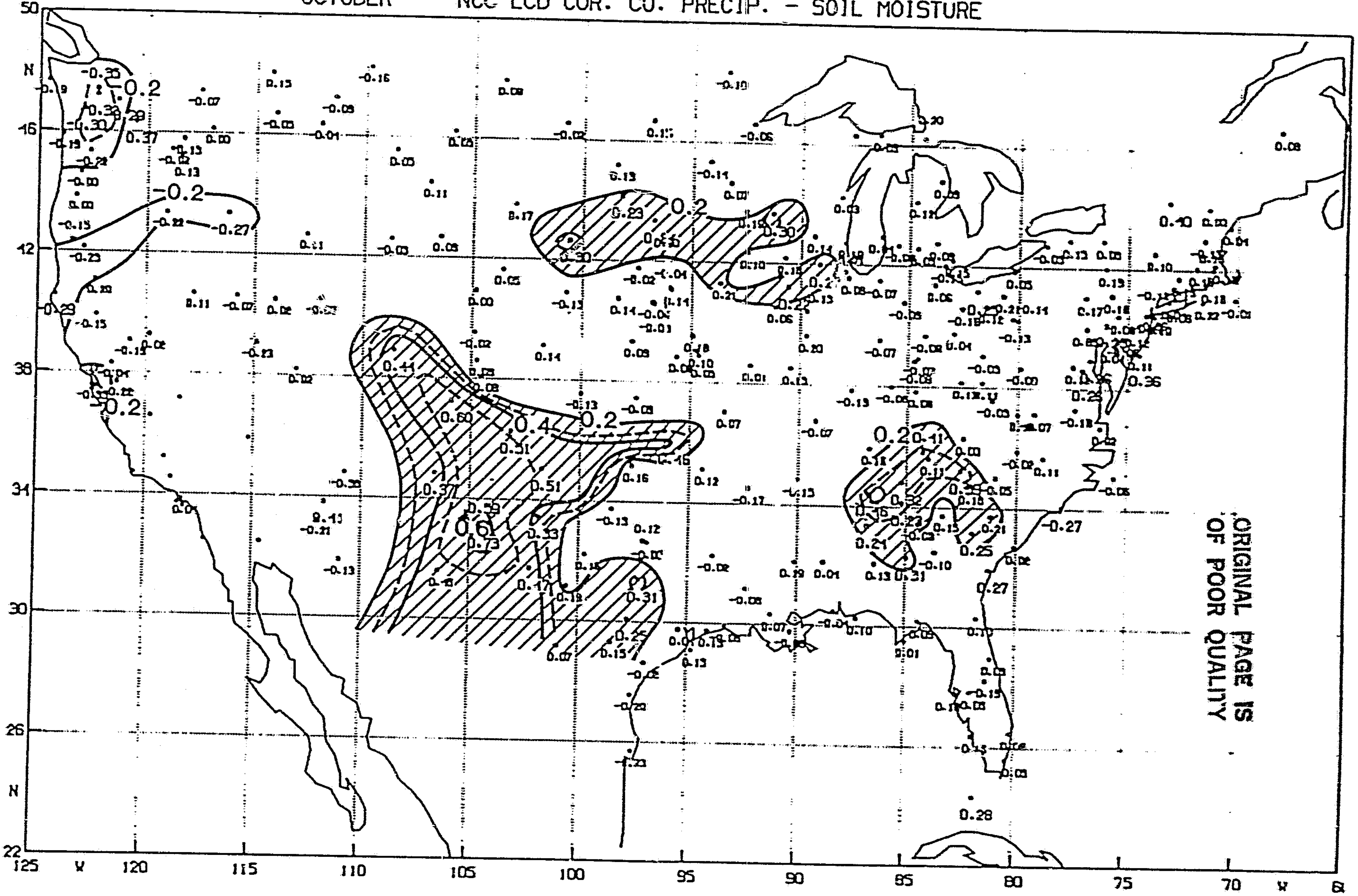


Fig. 3c

OCTOBER NCC LCD COR. CO. PRECIP. - EVAPORATION

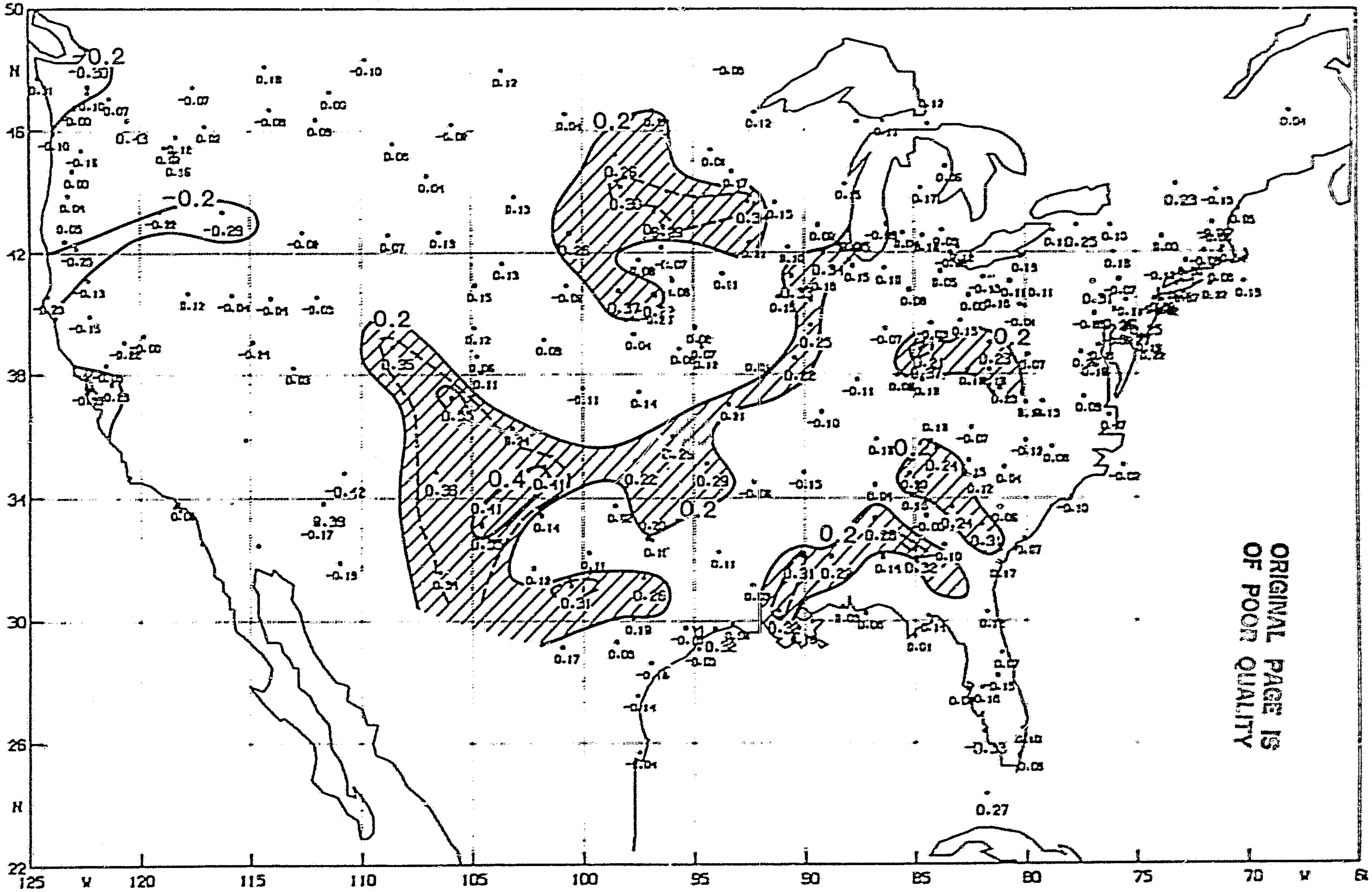


Fig. 4a

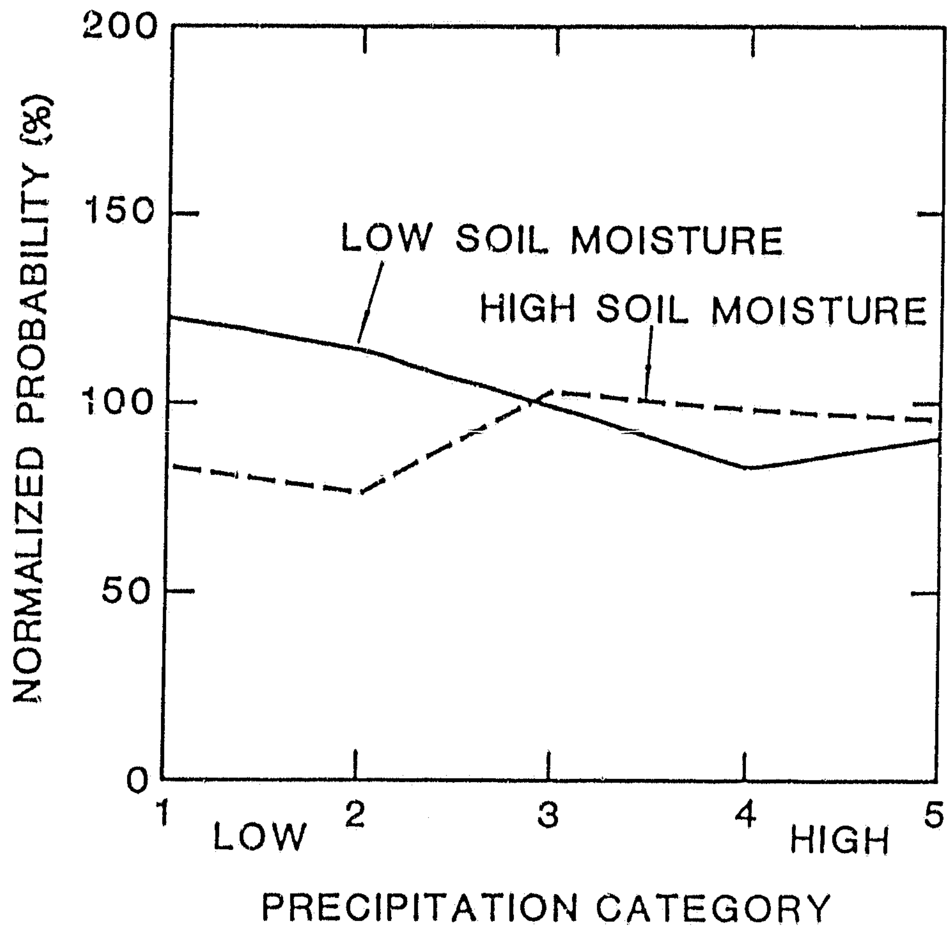

200
150
100
50
0
NORMALIZED PROBABILITY (%)
LOW SOIL MOISTURE
HIGH SOIL MOISTURE
1
2
3
4
5
LOW
HIGH
PRECIPITATION CATEGORY

Fig. 4b

ORIGINAL PAGE IS
OF POOR QUALITY