

General Disclaimer

One or more of the Following Statements may affect this Document

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.
- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.
- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.
- This document is paginated as submitted by the original source.
- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

(NASA-TM-85042) A STUDY OF THE INFLUENCE OF
SOIL MOISTURE ON FUTURE PRECIPITATION (NASA)
130 p HC A07/MF A01 CSCI 04B

N83-28825

Unclass
28018

G3/47



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.	1
Part II - Dependence of Local Precipitation on Antecedent Soil Moisture over the contiguous 48 states.	87

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 occurring 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, Schmutge 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 figure sets (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, E_p at each station was calculated by Thornthwaite's (1948) method, which was derived from observations of water use in irrigated regions. The method yields E_p as a function of surface temperature, T_s , 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 $T_s > 26.5^\circ\text{C}$ (See Willmott, 1977), the following relation is used:

$$E_p = a + b T_s + c T_s^2 \quad (1)$$

where $a = -415.8547$

$$b = 32.2441$$

$$c = 0.4325$$

(ii) For $T_s < 26.5^\circ\text{C}$ (Thornthwaite, 1948), the formulation is as follows:

$$E_p = 16 (10T_s/H)^k \quad (2a)$$

$$\text{Here } H = \sum_{i=1}^{12} (T_{si}/5)^{1.514} \quad (2b)$$

$$\text{and } k = a' + b'H + c'H^2 + d'H^3.$$

where $a' = 0.49239$

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

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

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

(iii) For $T_s < 0^\circ\text{C}$

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

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 $E_p = 4.50$ mm/day and equation (2) yields E_p between 4.44 mm/day and 4.60 mm/day depending upon whether T_s 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.

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

$$E_{p_c} = E_p \left(\frac{D}{30}\right) \left(\frac{L}{12}\right) \quad (4)$$

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

$$E = M E_{p_c} \quad (5)$$

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

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. Determination of soil moisture:

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

$$\frac{\partial w}{\partial t} = P - E \quad (7)$$

where P represents the precipitation rate.

Substituting from (5) and (6) we get

$$\frac{\partial w}{\partial t} = P - [1 - e^{-aw/w^*}] E p_c \quad (8)$$

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 $E p_c$ 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:

$$w^{n+1} = w^n + \frac{dw^n}{dt} \Delta t \quad (9)$$

and then,

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

This calculation is fairly accurate for small time steps. The limiting constraint, $w^{n+1} < w^*$, 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 saturated, as 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 actual 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.
- Schumge, 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.
- Thorntwaite, 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 Deviation 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.

ORIGINAL PAGE IS
OF POOR QUALITY

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

SEQ NC	WEA# NC	STATION NAME	STATE	ALT (M)	SEQ NC	WEA# NC	STATION NAME	STATE	ALT (M)
1	1102	FLAGSTAFF/WILLIAM	AZ	2139	133	14122	ROCHESTER	MA	402
2	1012	ASHEVILLE	NC	661	134	14922	ST CLOUD/WHITNEY MEM	MI	218
3	1013	MADON/LEWIS O WILSON	GA	110	135	14625	ABERDEEN	SD	294
4	1020	AUGUSTA/ASH	GA	45	136	14931	BURLINGTON	IA	194
5	1022	SAVANNAH/TRAVIS	GA	16	137	14932	DES MOINES	IA	246
6	1024	ATLANTA	GA	379	138	14933	GRAND IS	NE	246
7	1025	HUNTSVILLE/HSV-MADISON	AL	190	139	14934	HUFON/NEW FOWES	SD	393
8	1060	HUNTINGTON/STATE	WV	255	140	14935	LINCOLN 14571	NE	262
9	1070	GREENHILL/SPARTANBURG	SC	296	141	14941	NOV/CLM/RAEL STEFAN MEM	GA	473
10	1072	BECKLEY/WALEIGH	WV	766	142	14942	OMAHA/EMLEY	NE	295
11	1073	FT WORTH/RECTHAL	TX	175	143	14943	SIOUX CITY	IA	336
12	1074	WICHITA	KS	408	144	14944	SIOUX FALLS/FOSS	SD	435
13	1077	LAKE CHARLES	LA	10	145	14971	LINCOLN 14939	NE	262
14	1078	JACKSON/THEPSON	MS	101	146	21010	DEL RIO	TX	713
15	1079	CCUMETA/REG/FRN 13903	NC	274	147	21055	ROSELLE/BALMER/IND	MI	127
16	1080	WAKESVILLE 1388	MO	72	148	21062	SILOAM/SLEMAN	TX	112
17	1081	BINGHAMTON/ROCKWELL CC	NY	495	149	21034	SAN ANGELO/MATHIS	TX	582
18	1082	APLACHECKLA	FL	11	150	21042	LUBBOCK/WEST AIR TERM	TX	582
19	1083	DAYTONA BEACH	FL	12	151	21043	KCSWELL	TX	1103
20	1084	FT MYERS/FAGE	FL	6	152	21044	EL PASO	TX	1194
21	1085	KEY WEST	FL	6	153	21047	AMHILL/ENGLISH	TX	956
22	1086	MIAMI	FL	4	154	21050	ALBUQUERQUE/SUNPT-MERT	NM	1620
23	1087	ORLANDO/MCCOY	FL	4	155	21051	CLAYTON	NM	1515
24	1088	TAMPA	FL	3	156	21041	ALAMOSA	CO	2296
25	1089	WEST PALM BEACH	FL	3	157	21042	DENVER/STAFLETCH	CO	1652
26	1090	MIAMI AND	FL	72	158	21043	COULAND/SEWNER	KS	154
27	1091	VICTORIA/FOSTER	TX	30	159	21060	GRAND JUNCTION/WALKER	CO	1475
28	1092	NEW ORLEANS/MCLISANT	LA	3	160	21124	LCAG BEACH	CA	17
29	1093	PRT ARTHUR/JEFFERSON CC	TX	7	161	21154	ELY/YELLAND	CA	1509
30	1094	BROWNVILLE/RIO GRAND	TX	2	162	21155	BAKERSFIELD/MACOMBS	CA	150
31	1095	SAN ANTONIO	TX	242	163	21157	GISHOP	CA	120
32	1096	CORPUS CHRISTI/CLIFF MAUS	TX	33	164	21158	YULCAN	AZ	703
33	1097	GALVESTON	TX	10	165	21166	LAS VEGAS/MCCARRAN	NV	664
34	1098	HOLSTON/INTCONF 12910	TX	33	166	21174	LAS ANGELES	CA	32
35	1099	RALEIGH/RALEIGH-DURHAM	NC	134	167	21172	HILFCRO	UT	1534
36	1100	GREENSBORO/GSO-MI	NC	270	168	21183	PHOENIX/SKY HARBOR	AZ	337
37	1101	ATLANTIC CITY/MARINA STR	NJ	3	169	21185	RENO	NV	1241
38	1102	EL PASO/ROCKWELL CO	TX	111	170	21187	SANDBERG	CA	1379
39	1103	LYNCHBURG	VA	206	171	21188	SAN DIEGO/LINDERBERG	CA	6
40	1104	NORFOLK REG	VA	9	172	21194	WINDSO	AZ	1488
41	1105	PHILADELPHIA	PA	5	173	21195	YUMA	AZ	673
42	1106	RICHMOND/RYRO	VA	58	174	21222	WILMA CANYON	CA	1213
43	1107	ROCKFORD	IL	358	175	21223	GALEND	CA	2
44	1108	WASHINGTON DC/NAT	DC	20	176	21233	SACRAMENTO/EXECUTIVE	CA	5
45	1109	WILMINGTON/NEW HANOVER	NC	12	177	21234	SAN FRANCISCO	CA	8
46	1110	WILMINGTON/GREATER	DE	24	178	21237	STOCKTON/MET	CA	16
47	1111	MERIDIAN/KEY	MS	94	179	21272	SAN FRANCISCO	CA	16
48	1112	CHARLESTON/KANAWHA	WV	290	180	21273	SANTA MARIA/PUBLIC	CA	7
49	1113	CHARLOTTE	NC	194	181	21611	BISMARCK	ND	506
50	1114	ATHENS/BOB EPPS	GA	247	182	24010	CHEYENNE	WY	1672
51	1115	ATLANTA	GA	315	183	24021	LAUDERHUNT	NY	1594
52	1116	BIRMINGHAM	AL	192	184	24022	NORTH FLATTE/LEE BIRD	NE	249
53	1117	BRIARCLIFF CITY	TN	463	185	24028	SCOTTSELUFF	NE	1206
54	1118	CHARLESTON	SC	3	186	24032	SHERMAN CC	NE	1209
55	1119	CHARLOTTE/DOUGLAS	NC	234	187	24032	VALENTINE/MILLER	NE	792
56	1120	CHATTANOOGA/LOVELL	TN	210	188	24033	BILLINGS/LOGAN	MT	1006
57	1121	COLUMBIA/MET	SC	69	189	24037	RIELES CITY	MT	603
58	1122	JACKSONVILLE	FL	10	190	24086	RASPER	WY	1212
59	1123	JACKSONVILLE	FL	299	191	24090	RAPID CITY	SD	960
60	1124	KENNESAW	TX	87	192	24121	ELKO	NV	1247
61	1125	MOBILE	AL	67	193	24127	SALT LAKE CITY	UT	1286
62	1126	MONTGOMERY/CANNELLY	AL	62	194	24126	WINNEMUCA	NV	1323
63	1127	NASHVILLE/MET	TN	184	195	24131	BOISE	ID	674
64	1128	PENSACOLA/AGLER	FL	36	196	24134	BURNS	OR	1271
65	1129	ALEXANDRIA/ESLER	LA	197	197	24133	GRIFF FALLS	MT	1115
66	1130	SHREVEPORT	LA	79	198	24144	HELENA	MT	1186
67	1131	ALSTIN/MUELLER	TX	109	199	24146	KALISPELL/LACIER PRK	MT	506
68	1132	MADON	TX	157	200	24149	LEWISTON/MERPERCE CO	OR	438
69	1133	DALLAS/LAVE	TX	149	201	24152	NEACHAP/EMERGENCY	OR	1236
70	1134	ABILENE	TX	534	202	24153	MISSOULA/JOHNSON-BELL	MT	572
71	1135	LITTLE ROCK/ADAMS	AR	81	203	24155	PHOENIX/FINGLETON	OR	458
72	1136	FT SMITH	AR	141	204	24156	POCATULLO	ID	1365
73	1137	LEICHTEN FIELDS/MUN	TX	31	205	24157	SECO	WA	721
74	1138	OKLAHOMA CITY/WILL ROGER	OK	307	206	24193	WENDOVER	UT	1292
75	1139	TULSA	OK	206	207	24212	EUREKA	CA	16
76	1140	EATON ROUGE/TYAN	LA	23	208	24215	MT SHASTA	CA	1093
77	1141	CCMCHORD/CLOSSER	KS	452	209	24216	RED BLUFF	CA	108
78	1142	COOK CITY	KS	790	210	24217	EUGENE/MALLEN SWEET	OR	114
79	1143	KANSAS CITY 03947	MO	238	211	24225	WOLFORD/JACKSON CTY	OR	405
80	1144	ST JOSEPH/ROCKWELL MEM	MO	249	212	24227	OLYMPIA	WA	61
81	1145	ST LOUIS/WHBERT	MO	172	213	24226	PORTLAND	OR	12
82	1146	SPRINGFIELD	MO	397	214	24232	SALEM/MCNARY	OR	61
83	1147	SEATTLE/PIELARC	WA	270	215	24233	SEATTLE/ADOMA	WA	127
84	1148	CARESCU	NE	191	216	24235	SEKON SUMMIT	OR	1171
85	1149	NEW YORK/LAGUARCIA	NY	16	217	24237	STAMPEDE PASS	WA	1209
86	1150	BUFFALO/GTR BUFFALO	NY	215	218	24242	YAKIMA	WA	225
87	1151	NEWARK	NJ	9	219	24281	SEATTLE	WA	6
88	1152	ALBANY/CO	NY	86	220	24307	CLC SPRINGS/PETERSON	CO	1601
89	1153	ALLENTOWN/FEETHLEHEN	PA	117	221	24312	PHOENIX/MERIAL	CO	1439
90	1154	BOZEMAN/LOGAN	MT	9	222	24314	LOS ANGELES	CA	156
91	1155	HARTFORD/ERADLEY	CT	55	223	24319	FRESNO SIF TERM/HANMER	CA	100
92	1156	BURLINGTON	VT	104	224	24321	CALTIPORE/FRIENDSHIP	CA	47
93	1157	GREENSBORO/STATE 94710	NC	102	225	24325	CAPE PATTERAS	NC	3
94	1158	HARRISBURG/STATE 94710	PA	102	226	24330	ATLANTIC CITY/NAPEC PCNON	NC	20
95	1159	BLUE HILL CR/MILTON	MA	204	227	24378	WASHINGTON DC/DULLES	VA	99
96	1160	MT WASHINGTON	MT	228	228	24381	RCHP/RUSSEL	CA	196
97	1161	NANTUCKET/MEM	MA	4	229	24385	TALLAHASSEE	FL	21
98	1162	NEW HAVEN/THED	CT	4	230	24385	CAIRO	IL	109
99	1163	NEW YORK	NY	15	231	24384	COVINGTON/GTR CINN	KY	271
100	1164	FRANCIS/FRANCIS/GREEN	RI	19	232	24385	DAYTON/JM CCK DAY	OH	206
101	1165	READING 14712	PA	422	233	24387	EVANSTON/AGRESS	IL	110
102	1166	ROCHESTER/MCNROE CO	NY	169	234	24385	INDIANAPOLIS/WEIR CCK	IN	246
103	1167	SYRACUSE/C E HANCOCK	NY	134	235	24385	LEXINGTON/BLUE GRASS	KY	301
104	1168	TRENTON 14706	NJ	58	236	24385	LCUESVILLE/STANDEFORD	KY	149
105	1169	WILKES-BARRER/SCRANTON	PA	289	237	24385	SPRINGFIELD/CAPITAL	IL	167
106	1170	WILKES-BARRER/ALYCONING	PA	160	238	24385	COLUMBUS	GA	120
107	1171	CHICAGO/WISVA	IL	190	239	24385	CLINTON/ATI/ABBE	OH	191
108	1172	CLEVELAND/MCPKINS	OH	245	240	24385	HAVRE CITY-COUNTY	MT	792
109	1173	COLUMBUS/FORT COLUMBUS	OH	224	241	24385	WILMINGTON/SLOULIN	NC	581
110	1174	DETROIT CITY 14853	MI	193	242	24385	WALLA WALLA	WA	302
111	1175	FLINT/BEHSON	MI	233	243	24385	ASTORIA/CLATSOP CO	OR	7
112	1176	FT WASHINGTON	IN	222	244	24385	QUILLANITA	WA	63
113	1177	LANSING/CAPITAL CITY	MI	266	245	24385	RODEFORT	CT	5
114	1178	MADISON/TRUAN	WI	204	246	24385	NEW YORK/CENTRAL PRK	NY	42
115	1179	MARQUETTE	MI	224	247	24385	WORCESTER	MA	310
116	1180	MILWAUKEE/RITCHEL	WI	211	248	24385	NEW YORK/J F KENNEDY	NY	30
117	1181	MILWAUKEE	WI	193	249	24385	BLOCK IS/IC STATE	RI	36
118	1182	PEORIA/GREATER PEORIA	IL	222	250	24385	HOUSTON/LAKE/ROCKWELL	MI	154
119	1183	SAULT STE MARIE	MI	221	251	24385	ROCKFORD/GTR ROCKFORD	IL	226
120	1184	SOUTH BEND/ST JOE	IN	226	252	24385	PITTSBURGH/GTR PITTSBURGH	PA	77
121	1185	YOUNGSTOWN	OH	361	253	24385	TOLEDO	OH	211
122	1186	GRAND RAPIDS	MI	225	254	24385	CHICAGO/CH/RE	IL	205
123	1187	INDIANAPOLIS	IN	310	255	24385	DETROIT/MEYEROPOLITAN	MI	202
124	1188	MADISON/BLD/LAMN	WI	409	256	24385	ALBANY/WELLS COLLINS	MI	210
125	1189	AKRON/ROCKWELL CANTON	OH	379	257	24385	MARQUETTE CO	MI	434
126	1190	GREEN BAY/ALSTIN STRABEL	WI	214	258	24385	GRAND RAPIDS/KENT CO	MI	242
127	1191	DULUTH	MN	432	259	24385	DUBUQUE	IA	329
128	1192	FARGO/NECTOR	ND	274	260	24385	WATERLOO	IA	206
129	1193	INTERNATIONAL FALLS	ND	261	261	24385	CHAMPA/ROTH OMAHA	NE	406
130	1194	LA CROSSE	WI	215					
131	1195	MINNEAPOLIS/ST PAUL	MN	235					
132	1196	MOBILE/QUICKLEY	AL	181					

Fig. 1

NCC LCD STATION SEQUENCE NUMBER

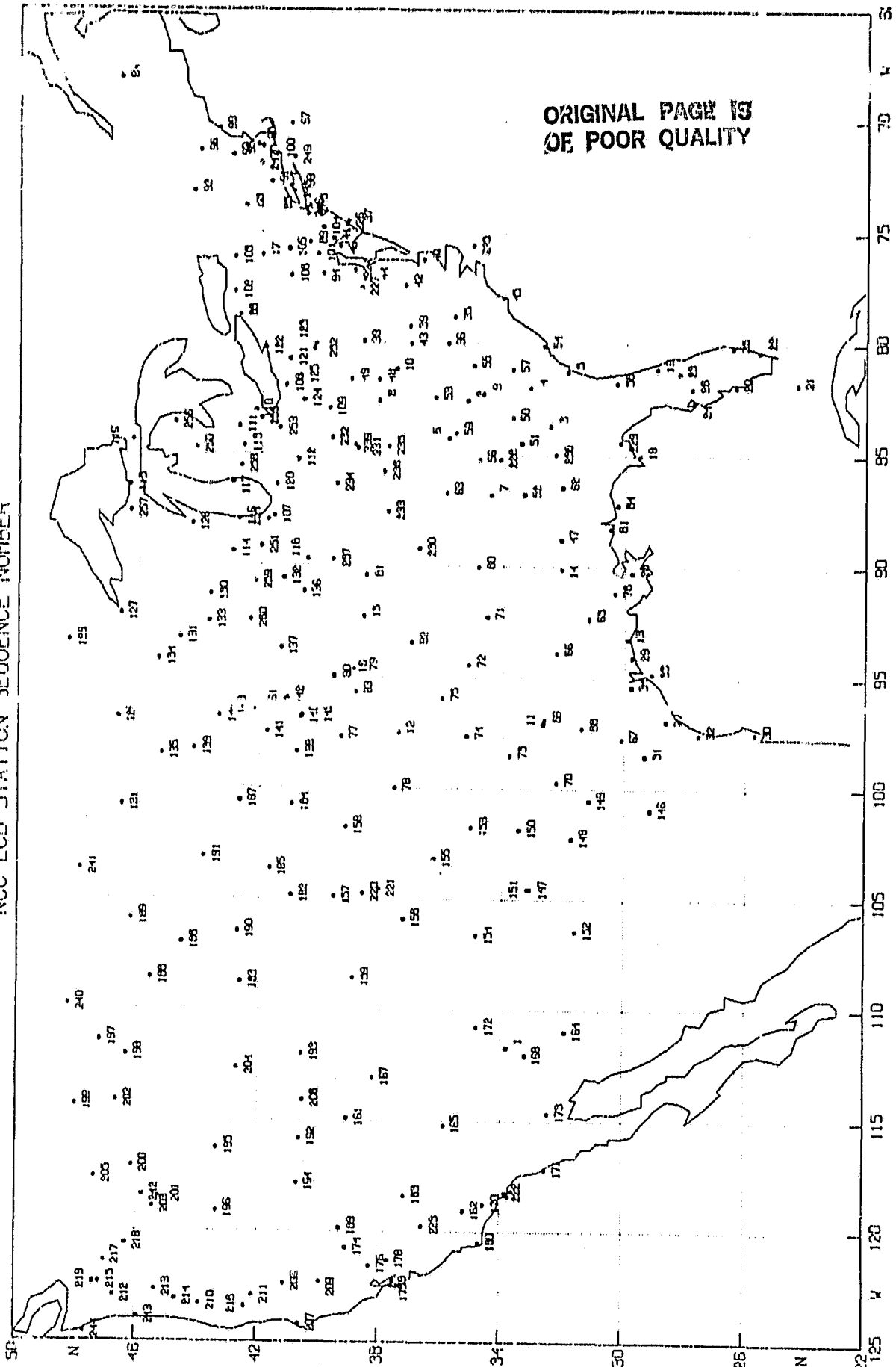


Fig. 2

NCC LCD STATION NO. OF GOOD YEARS

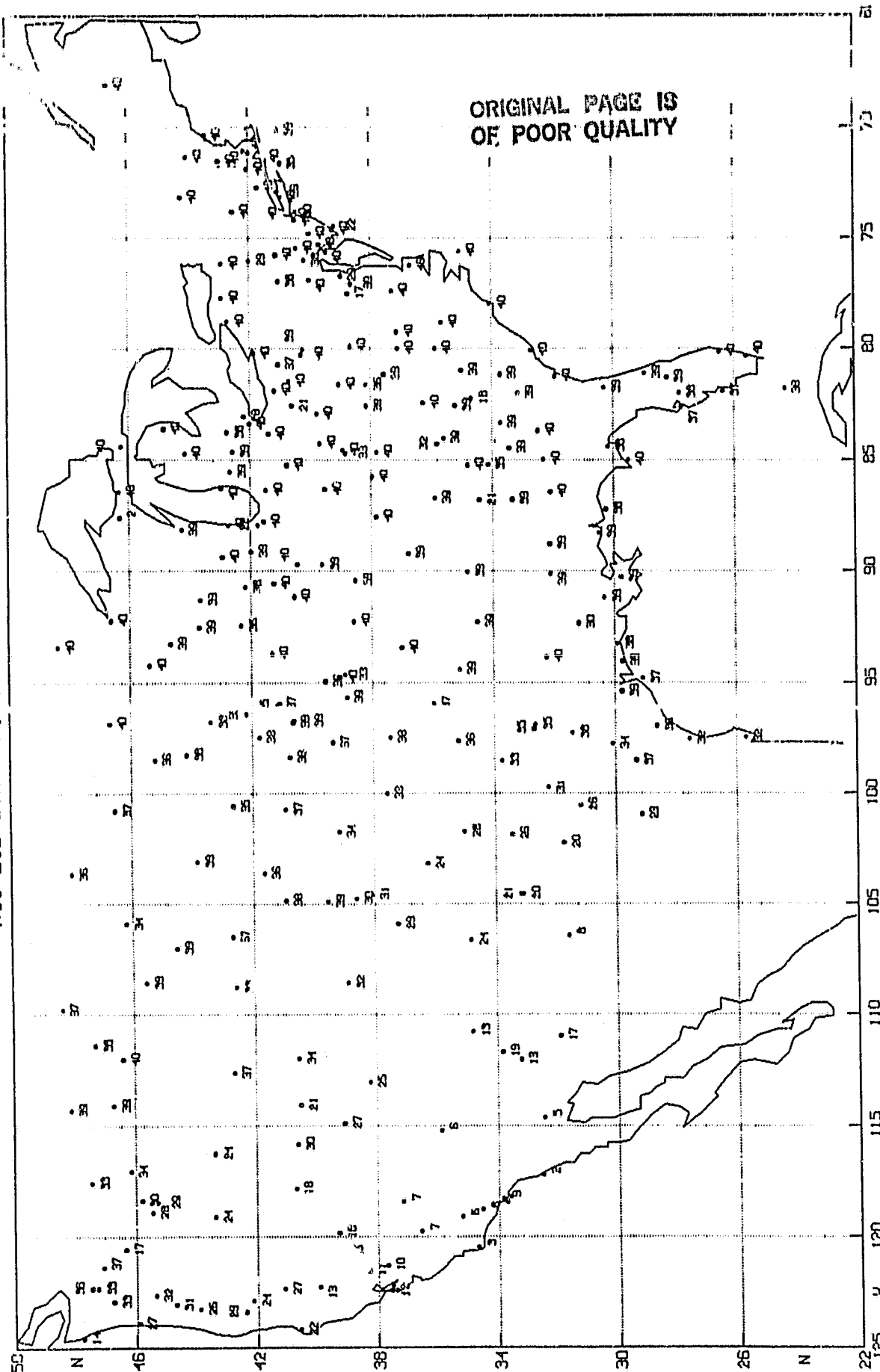


Fig. 3.a.1

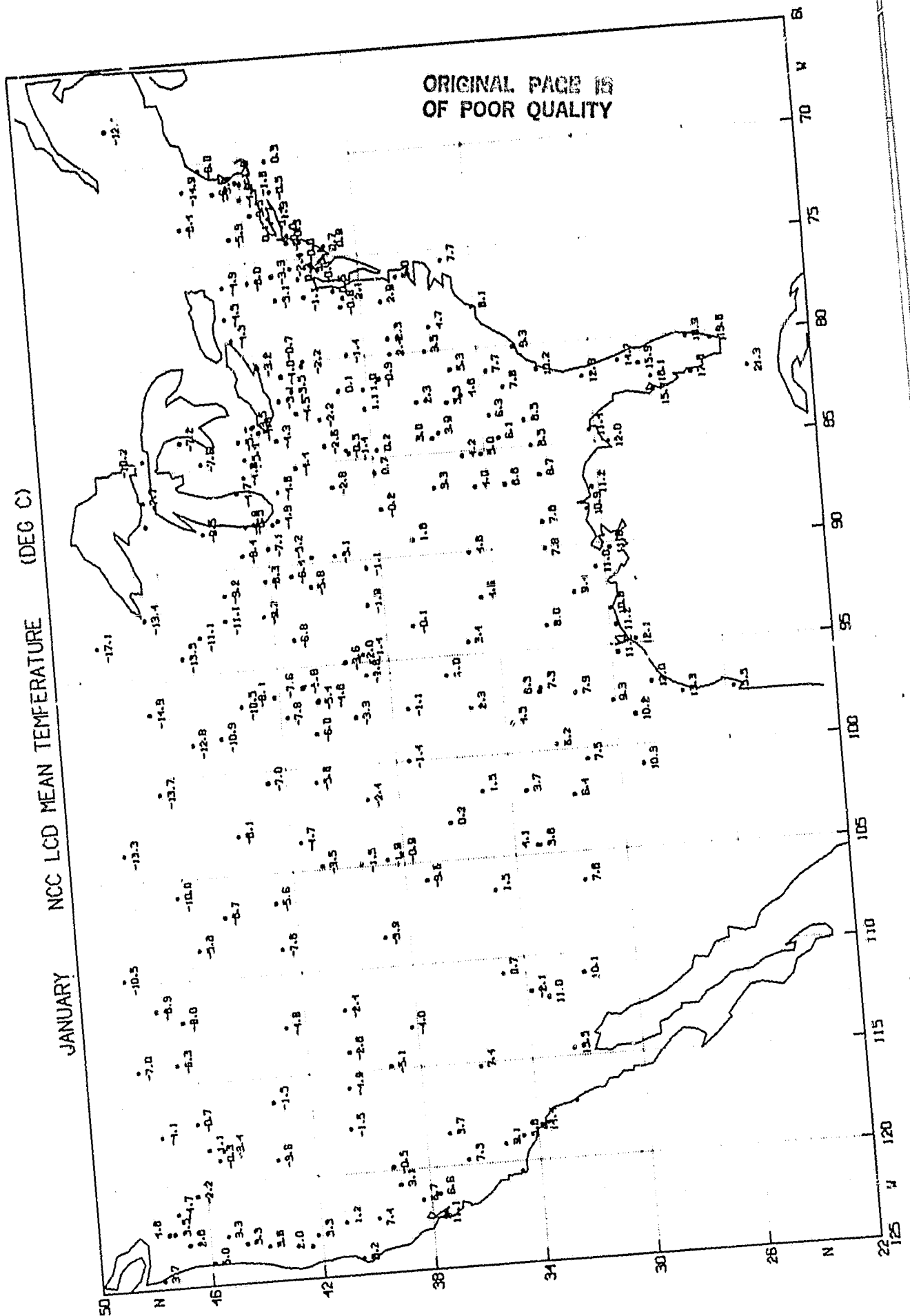


Fig. 3.a.2

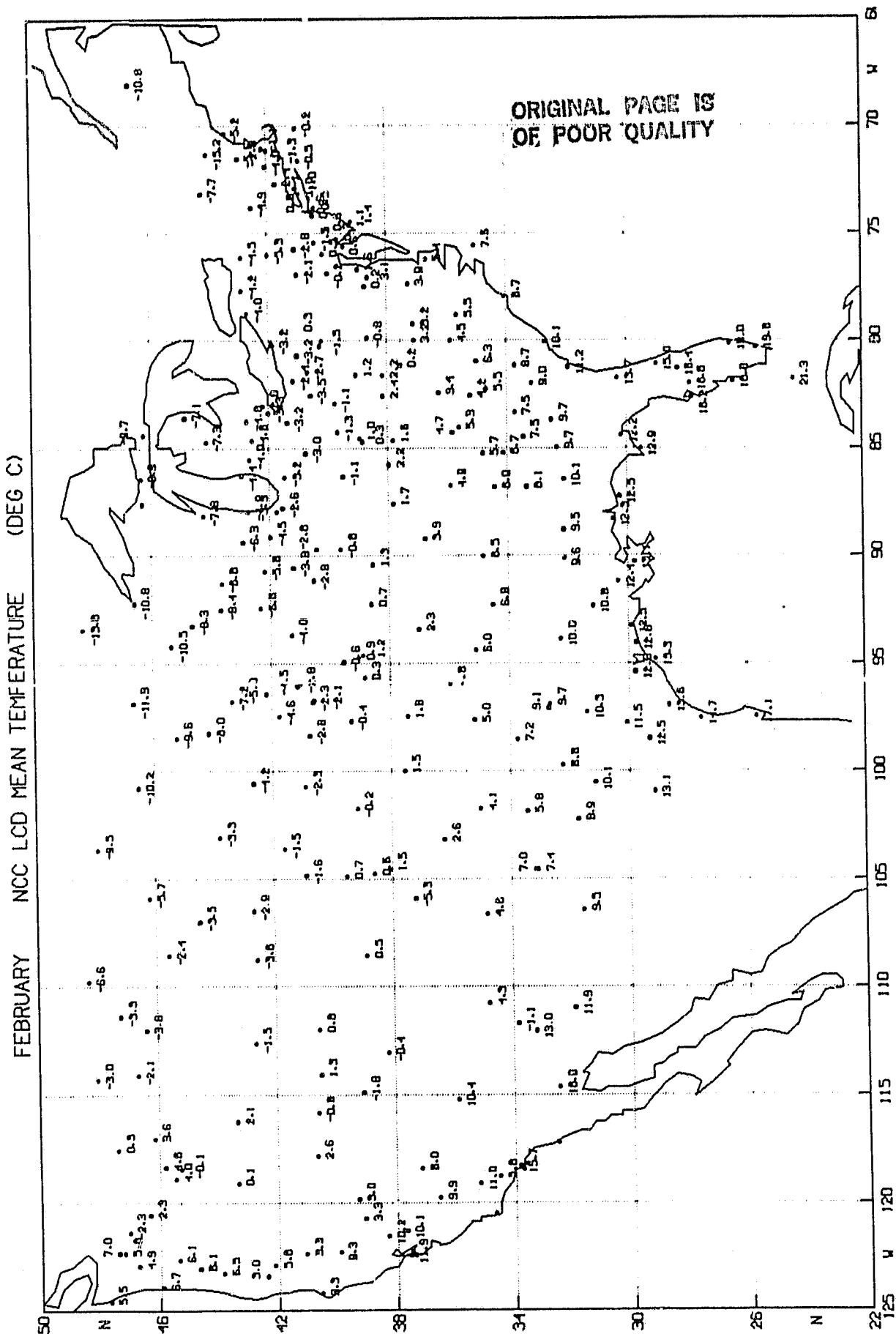


Fig. 3.a.3

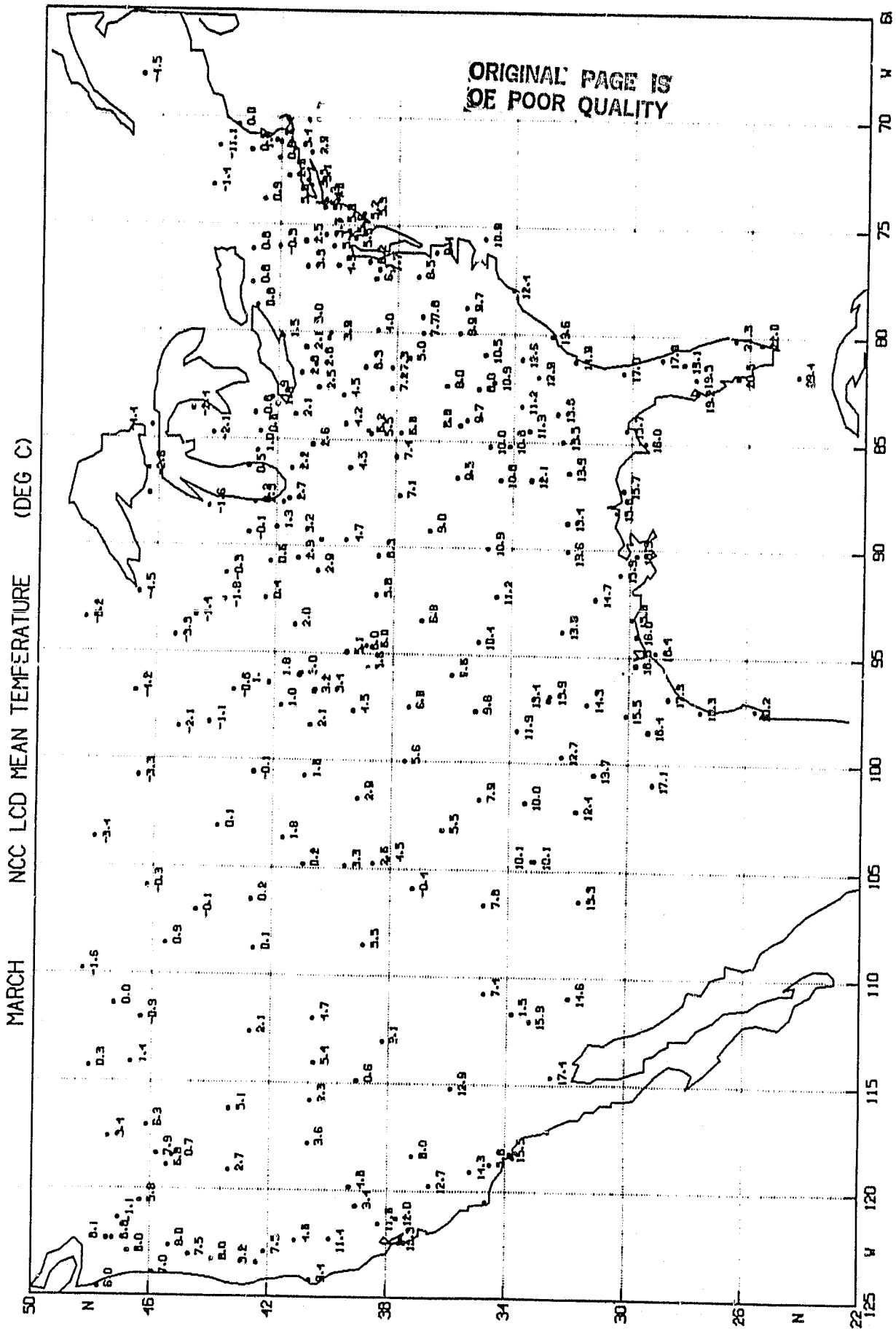


Fig. 3.q.4

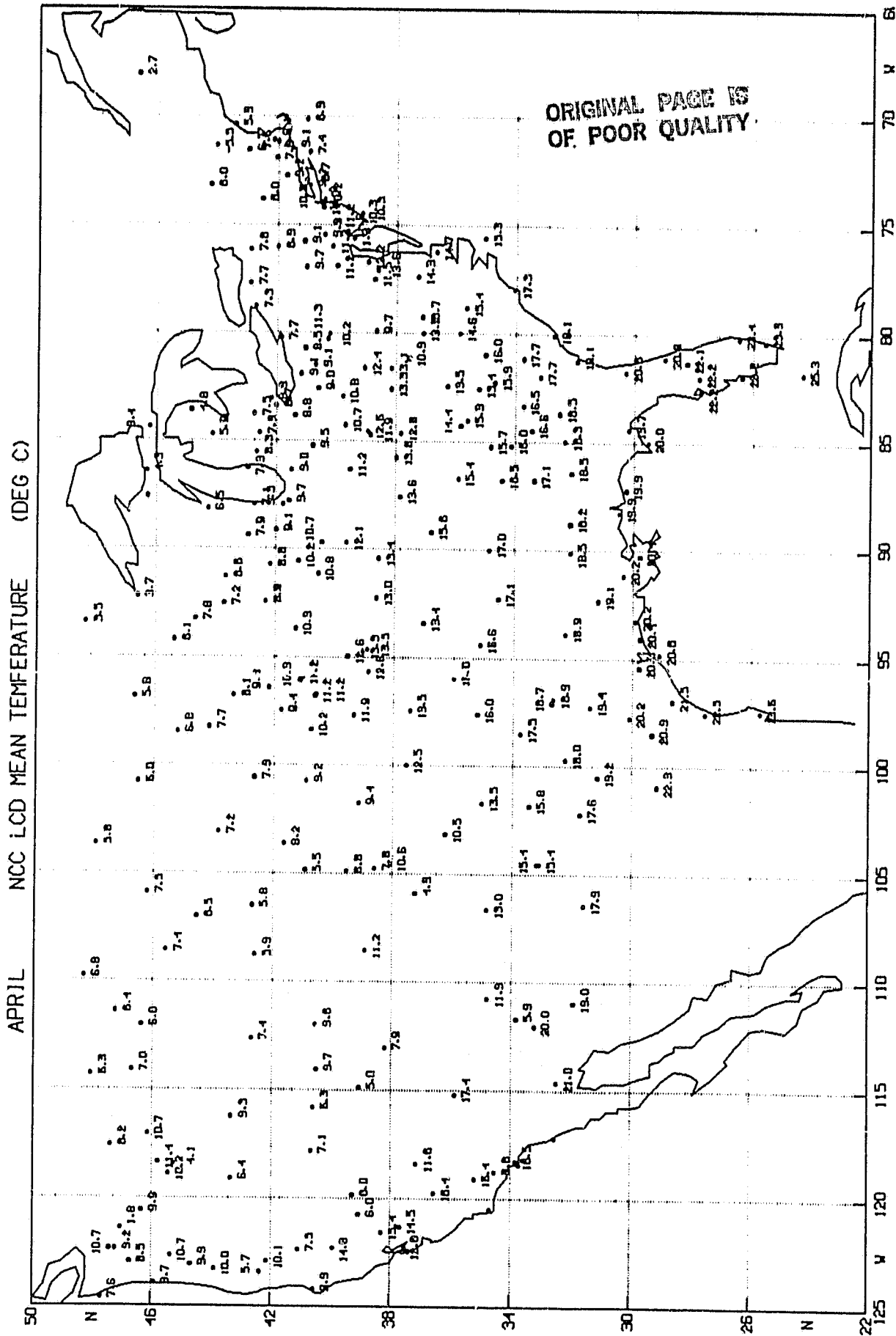


Fig. 3.a.5

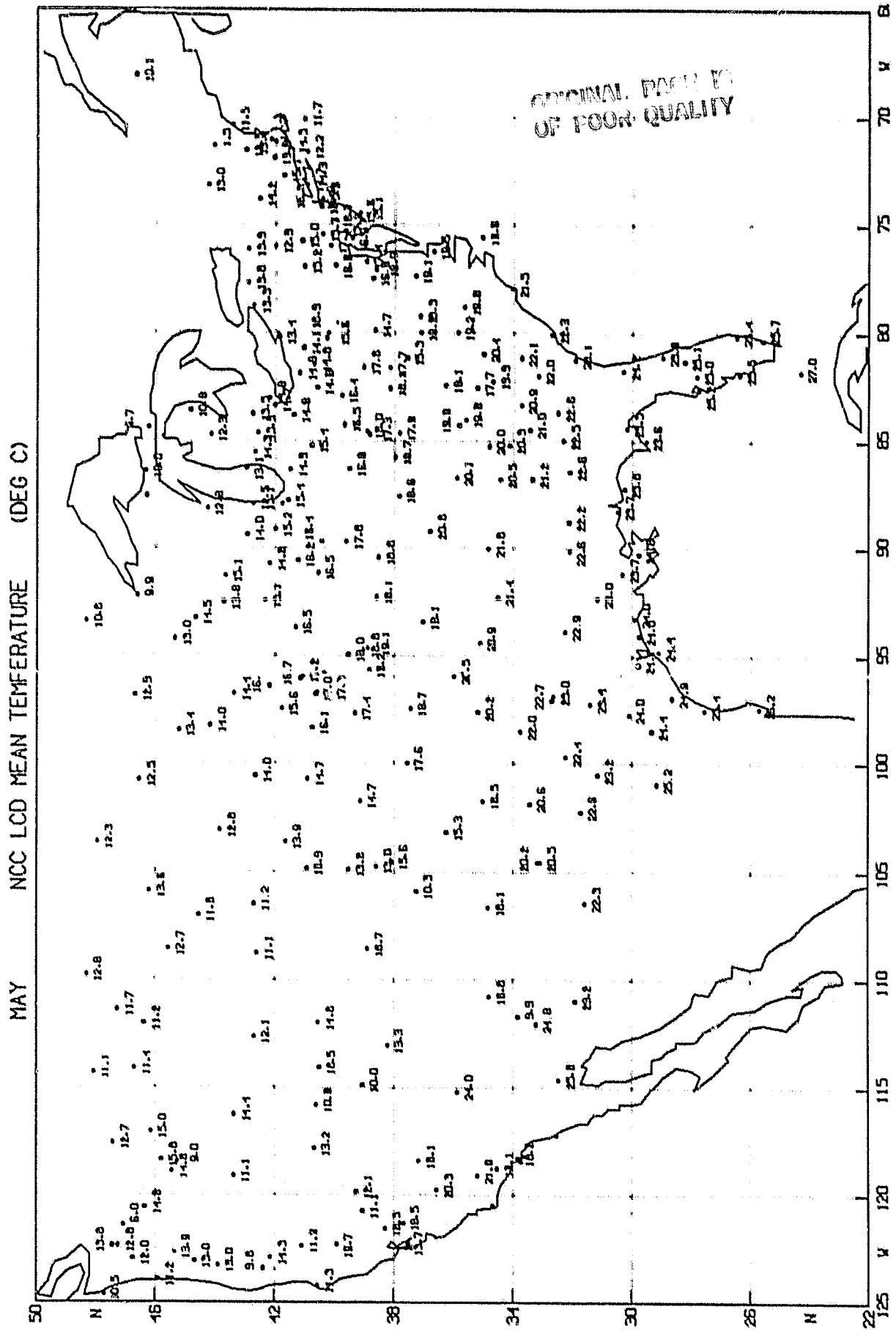


Fig. 3.a.6

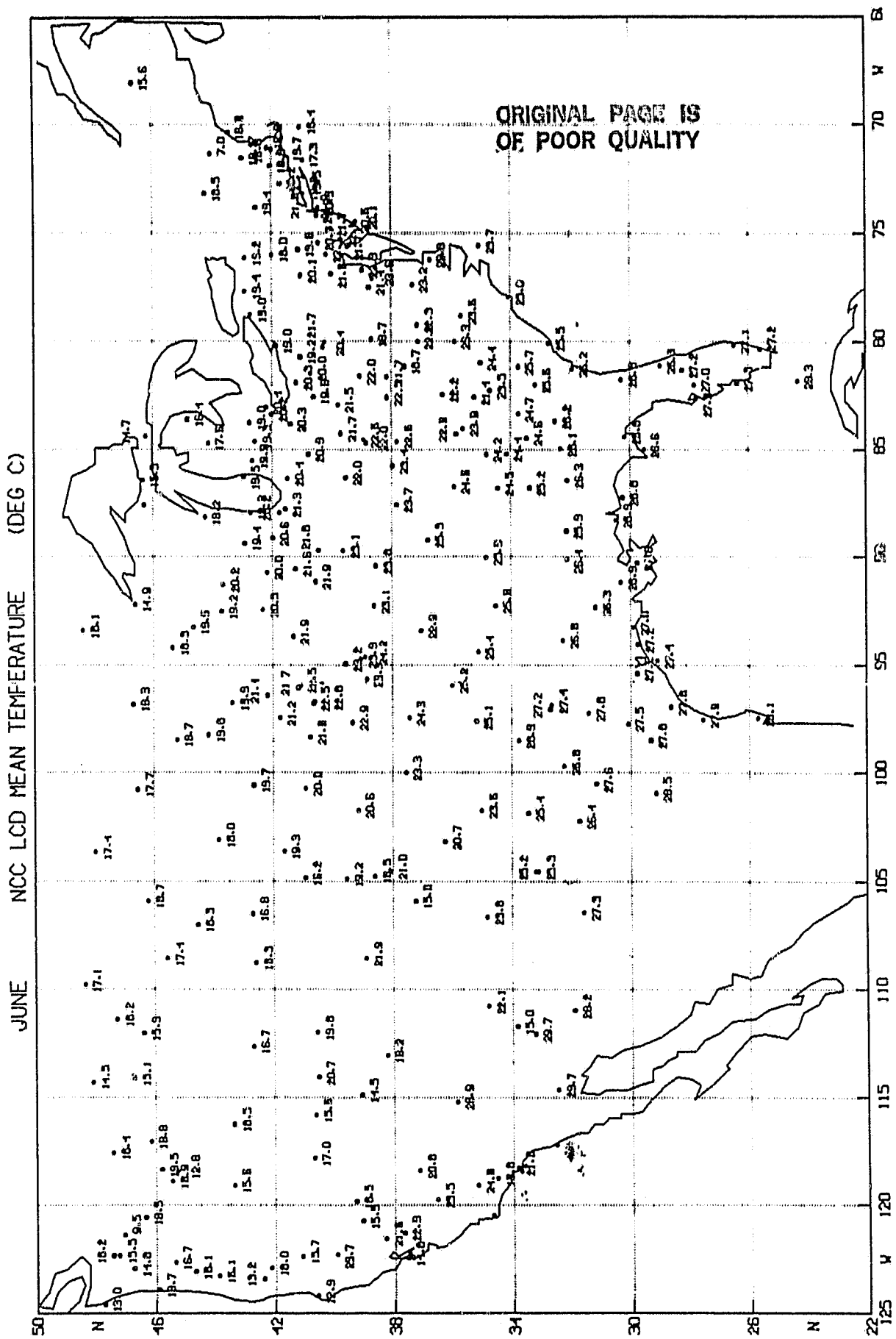


Fig. 3.a.7

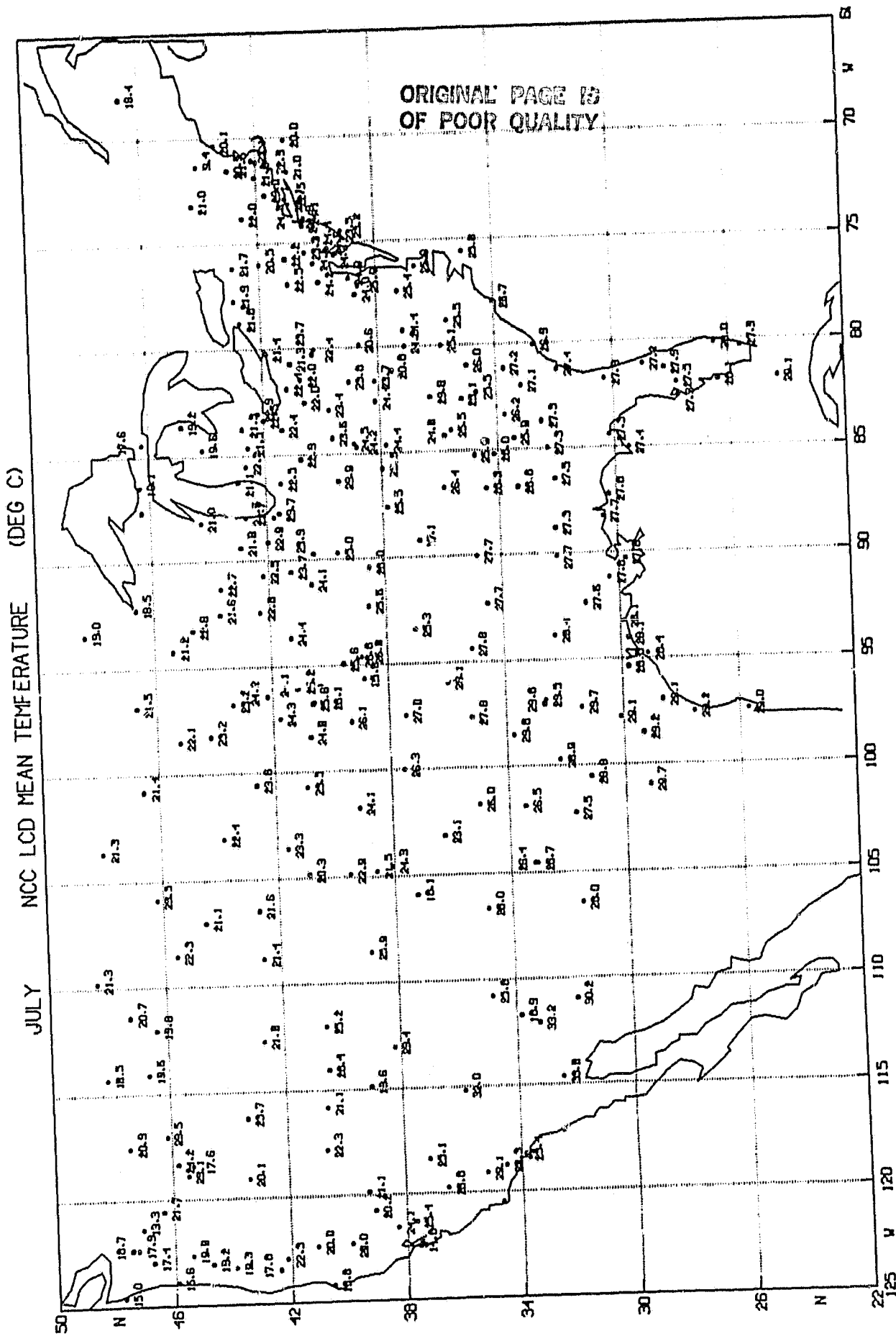


Fig. 3.a.8

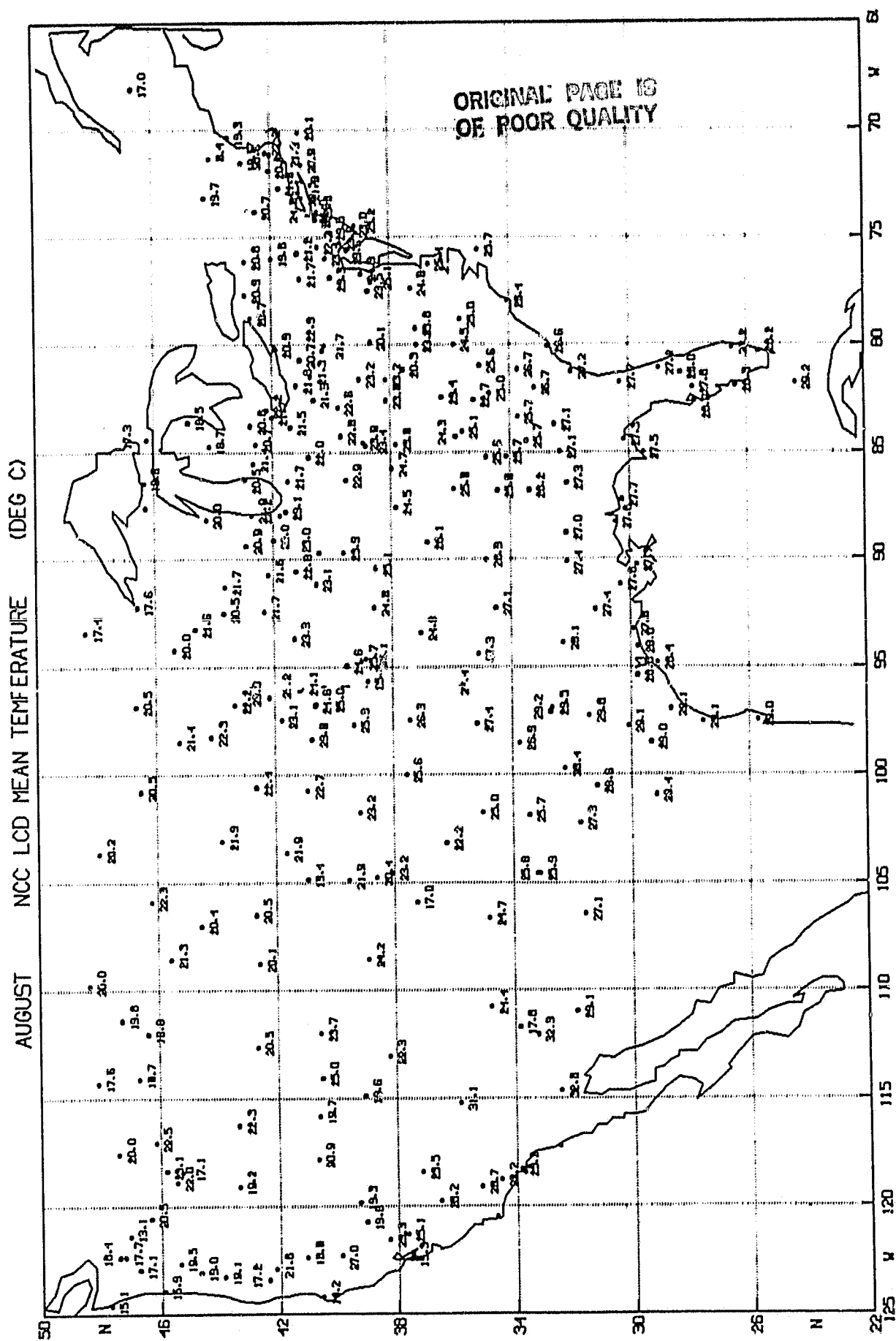


Fig. 3.a.9

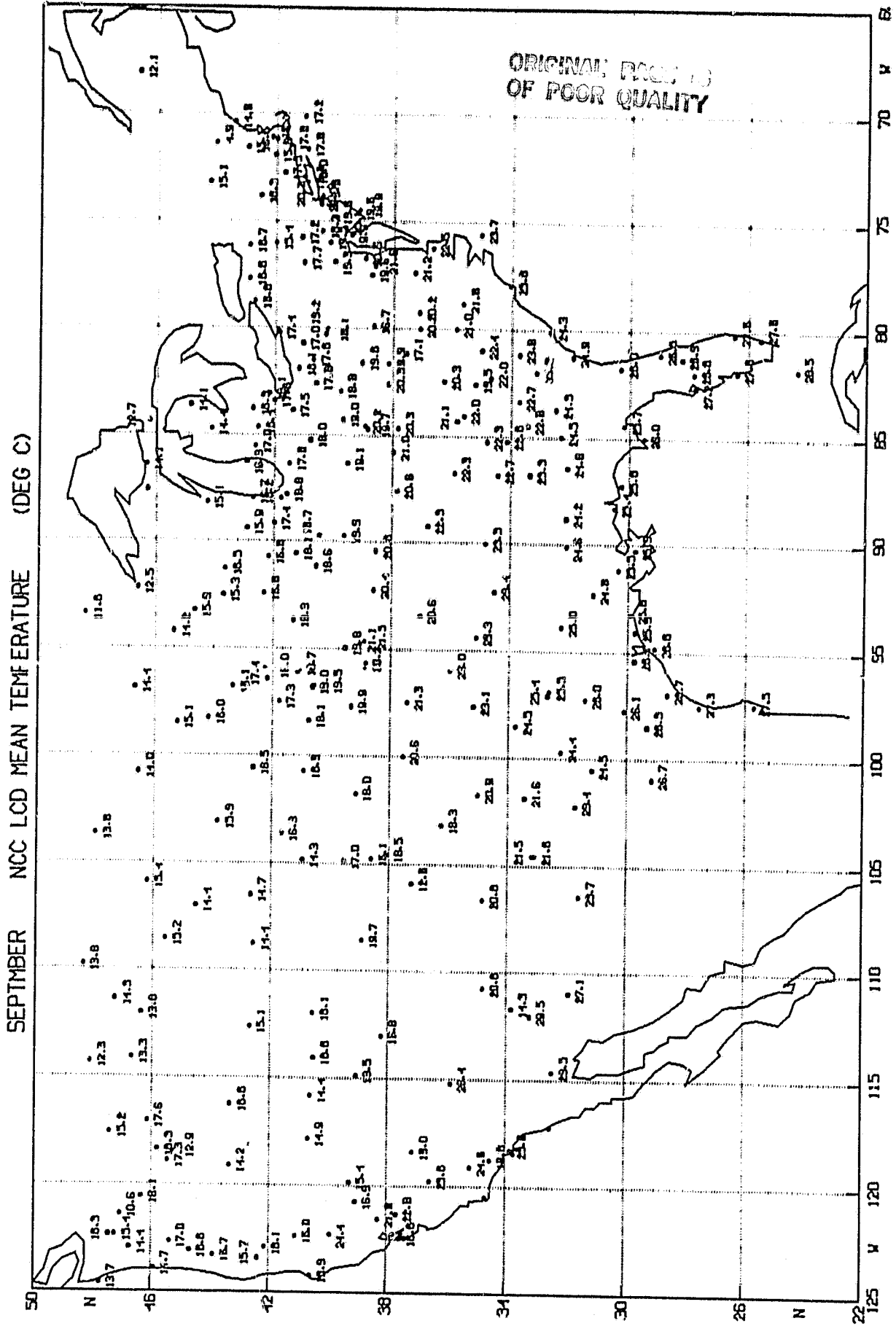


Fig. 3.a.10

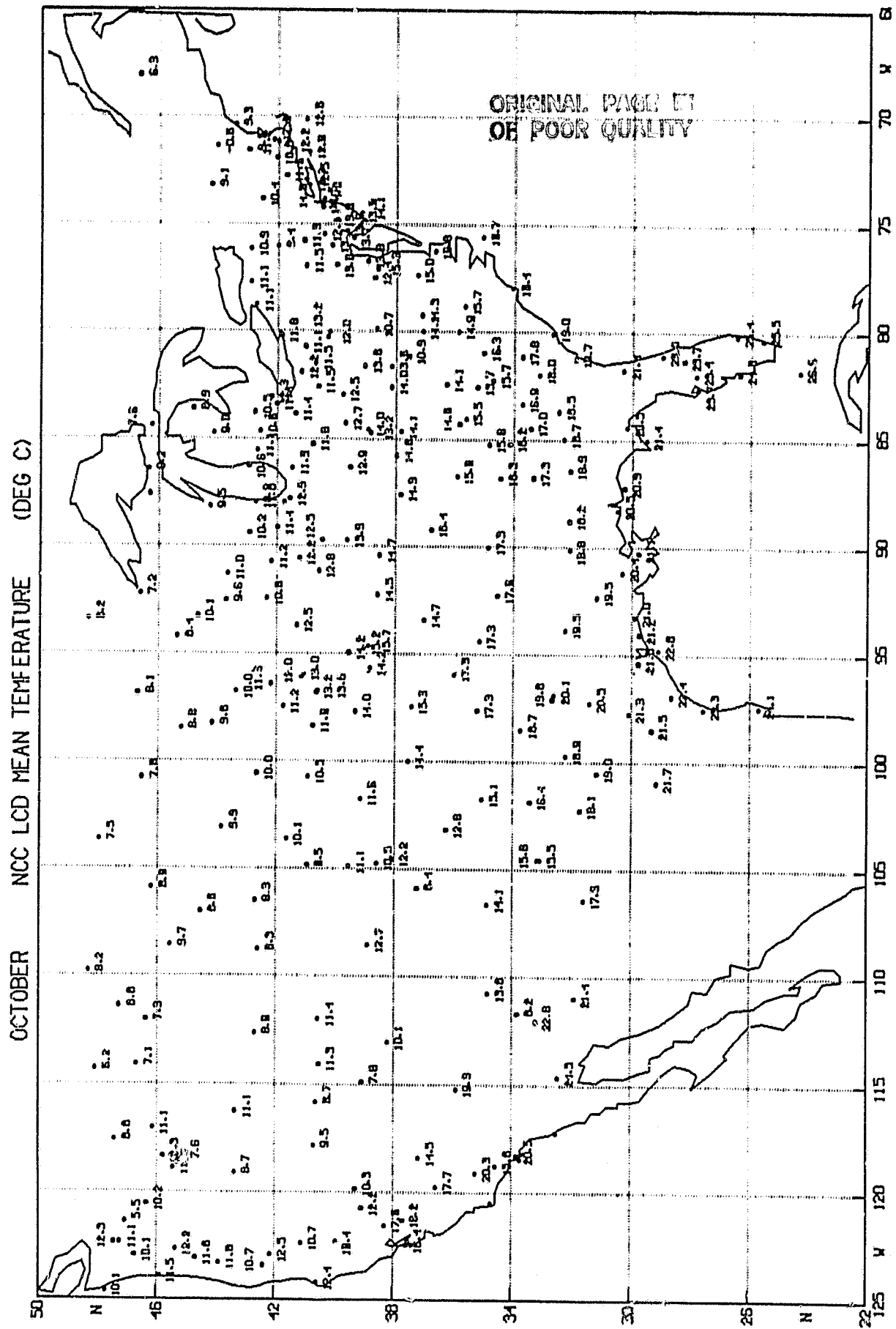


Fig. 3.a.12

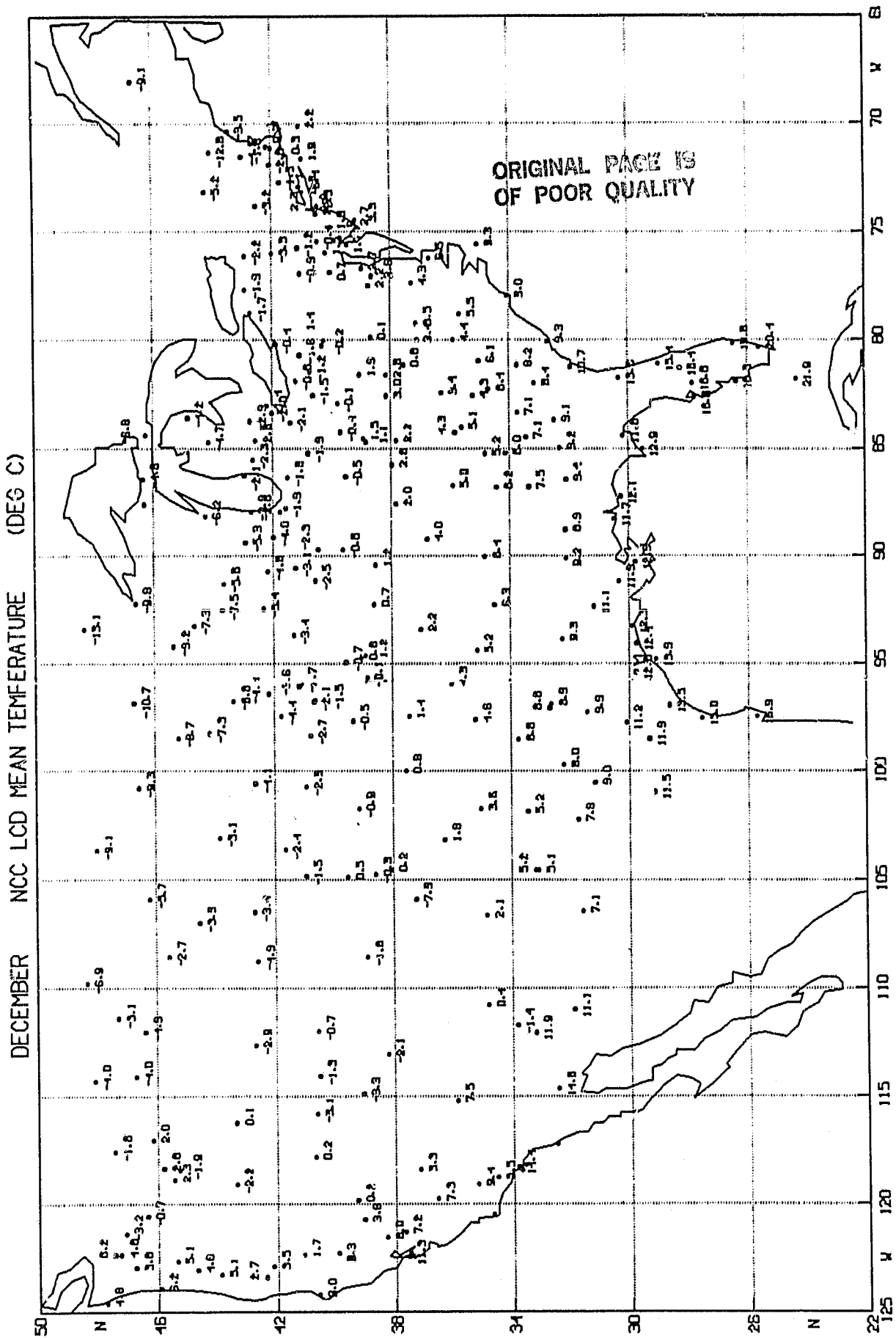


Fig. 3.b.1

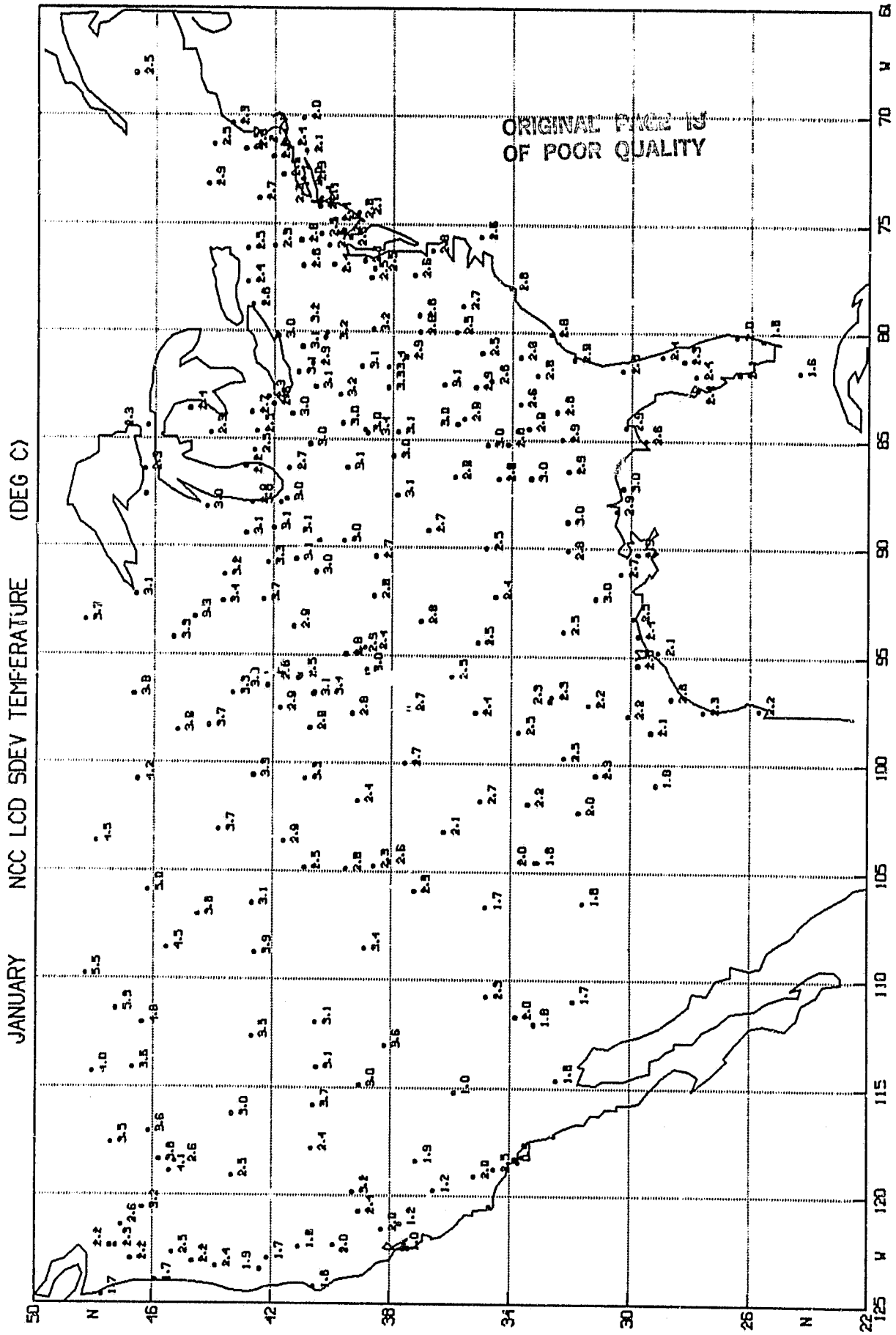


Fig. 3.b.2

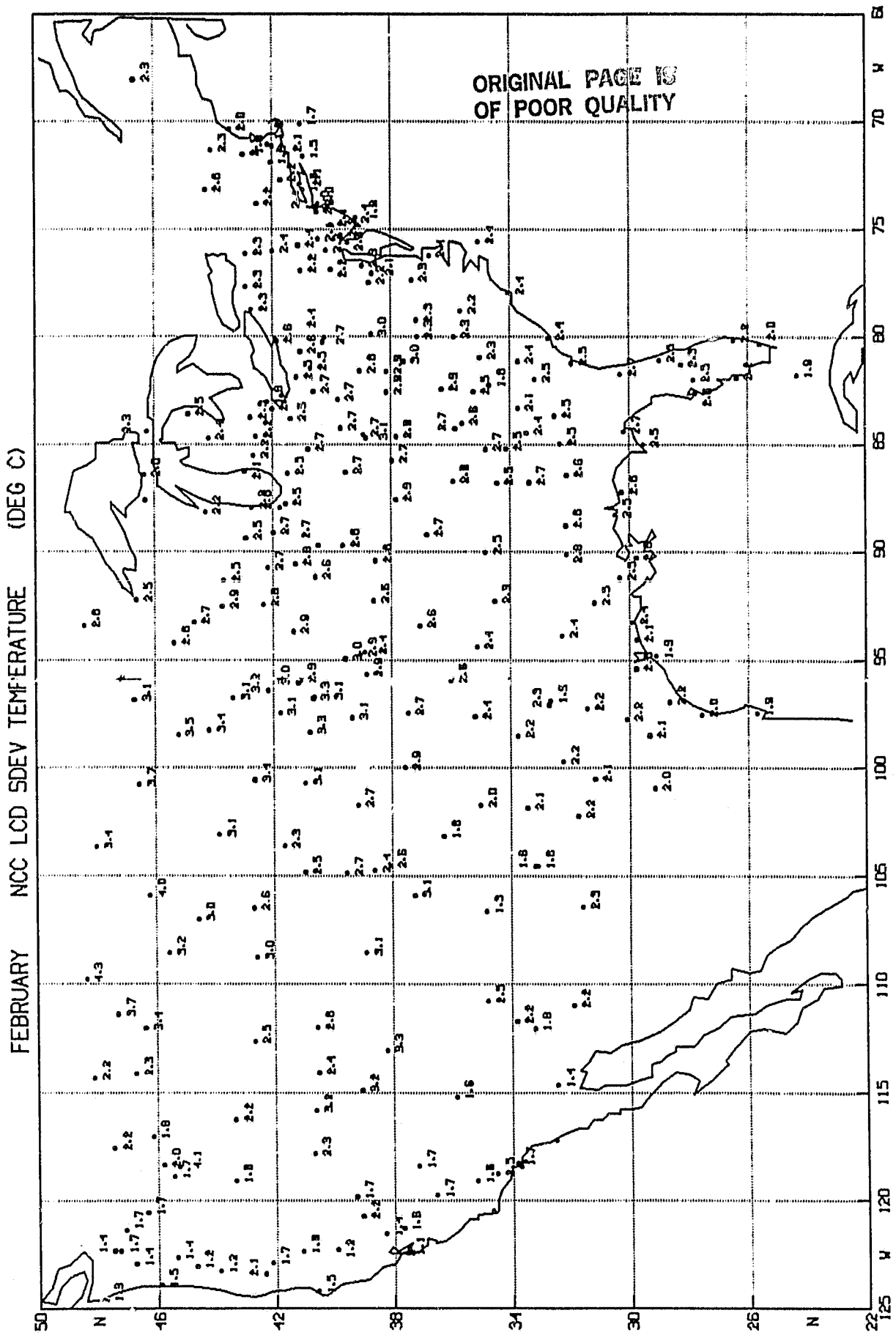


Fig. 3.b.3

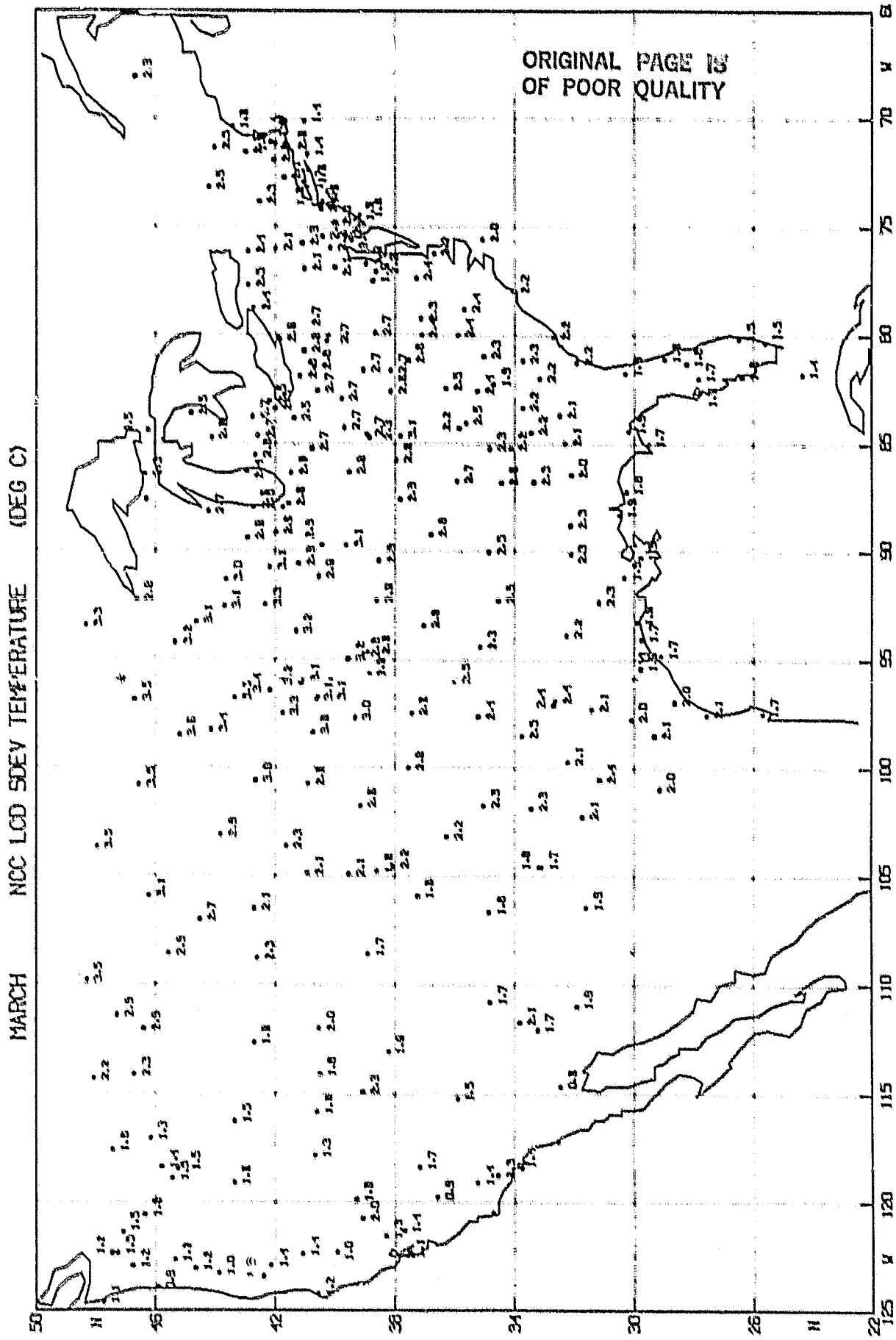


Fig. 3.b.4

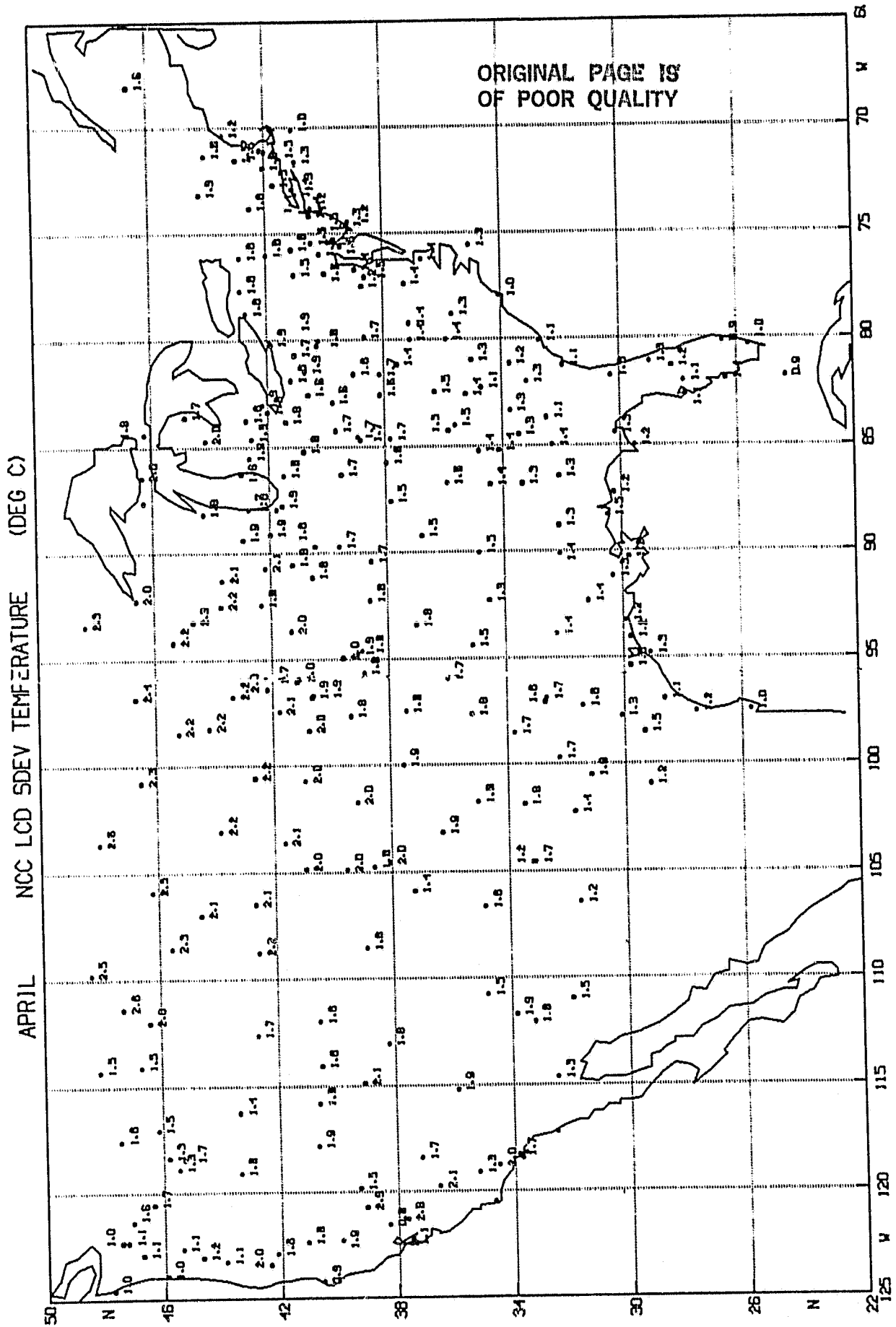


Fig. 3.b.5

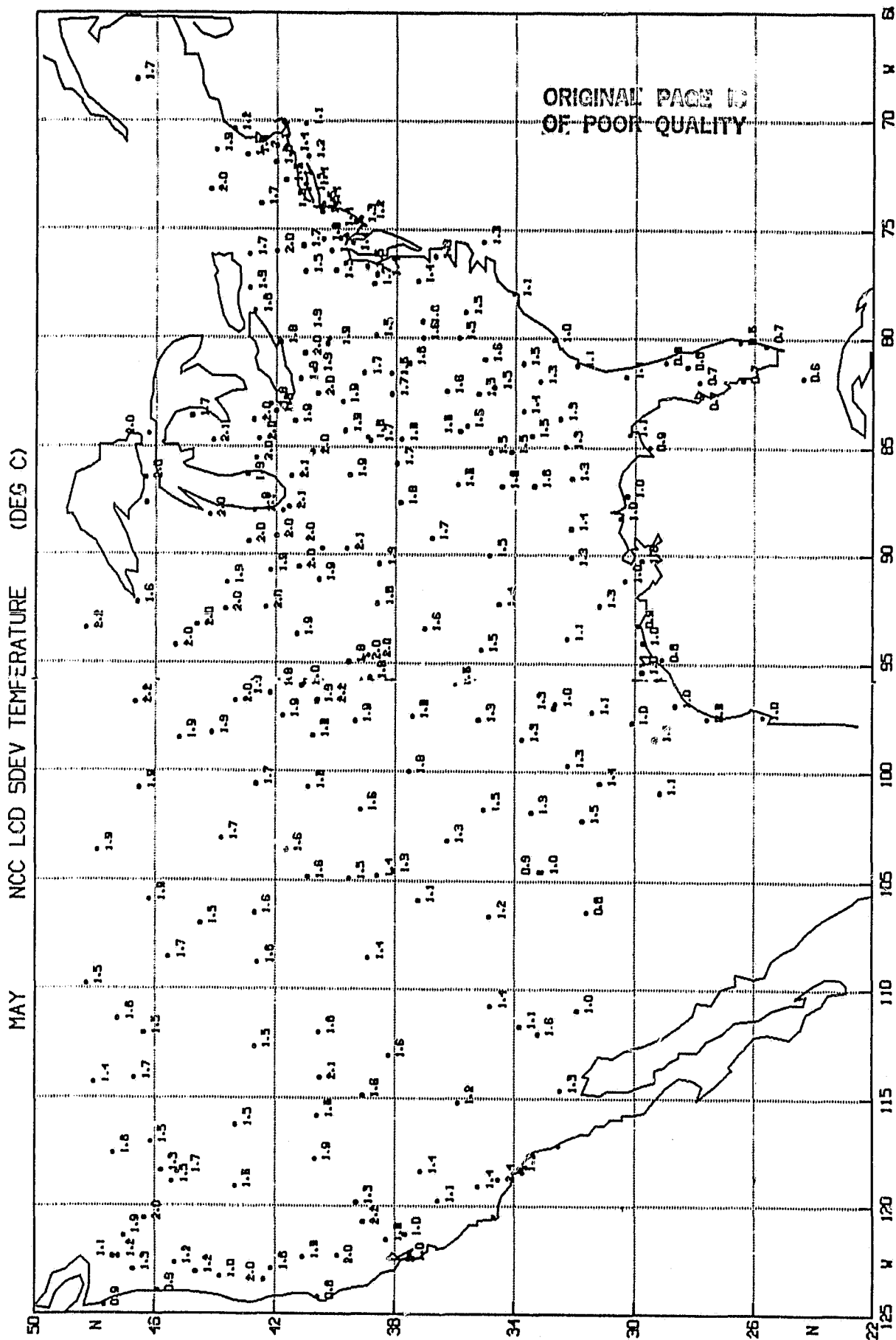


Fig. 3.b.6

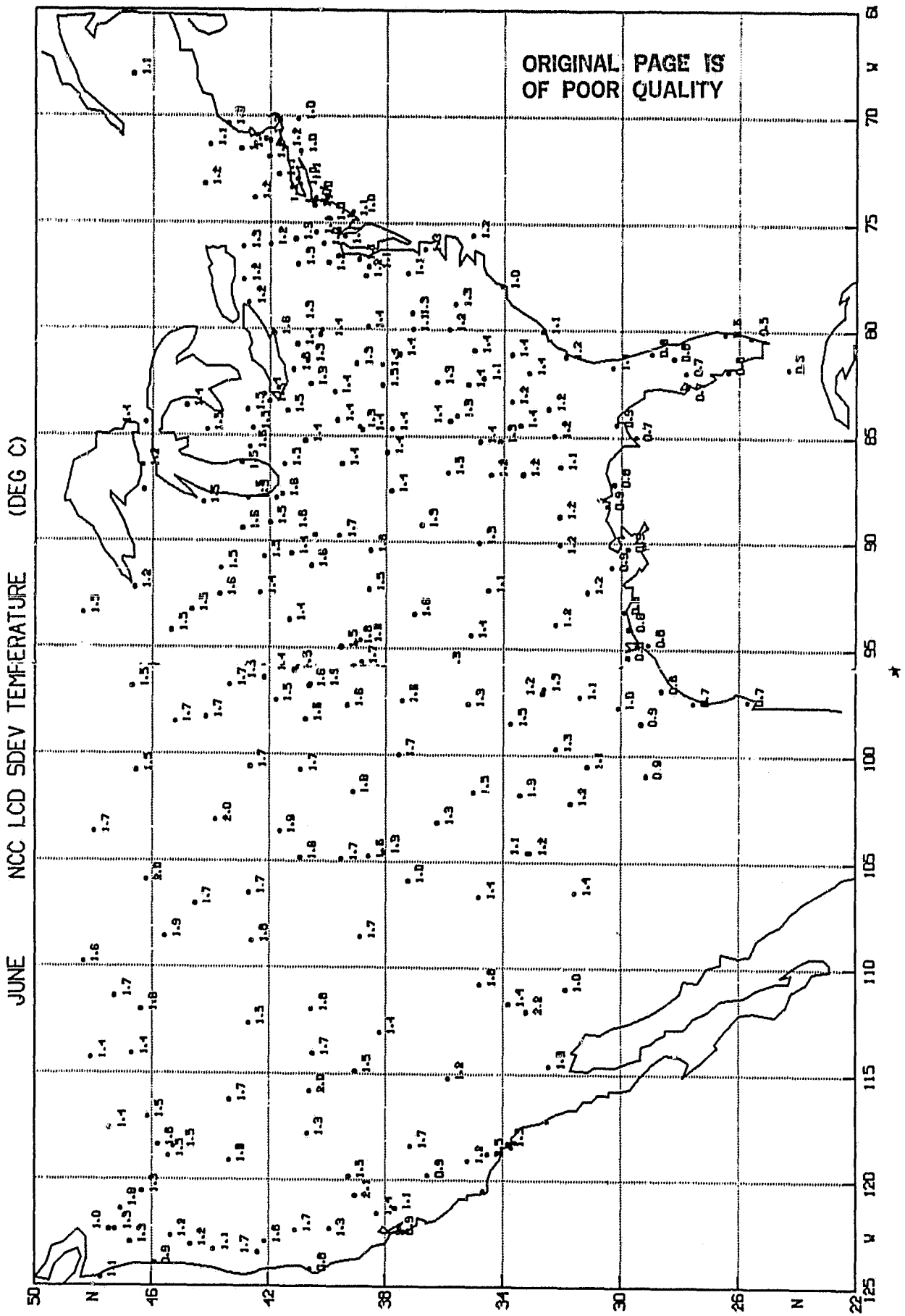


Fig. 3.b.7

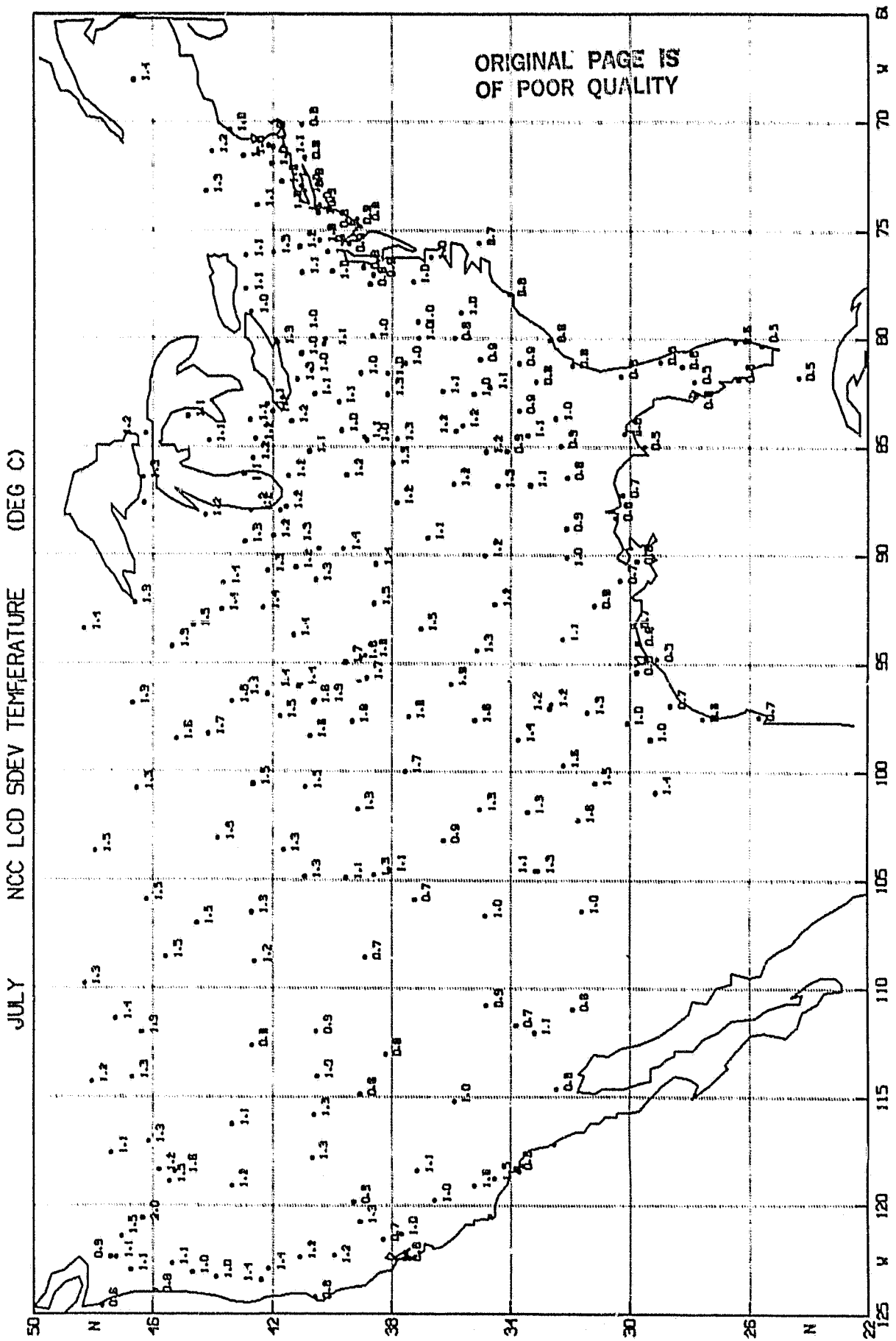


Fig. 3.b.8

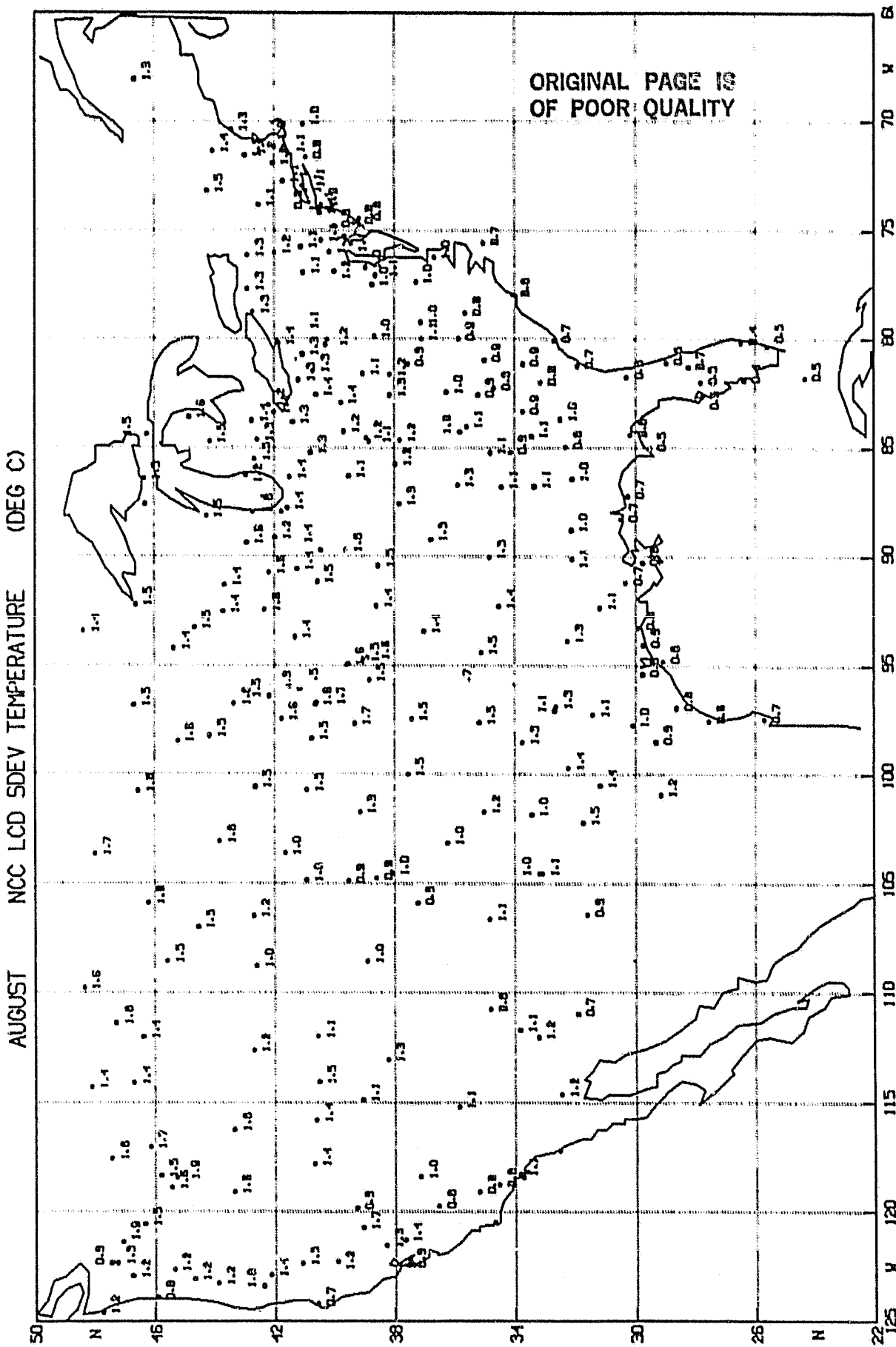


Fig. 3.b.9

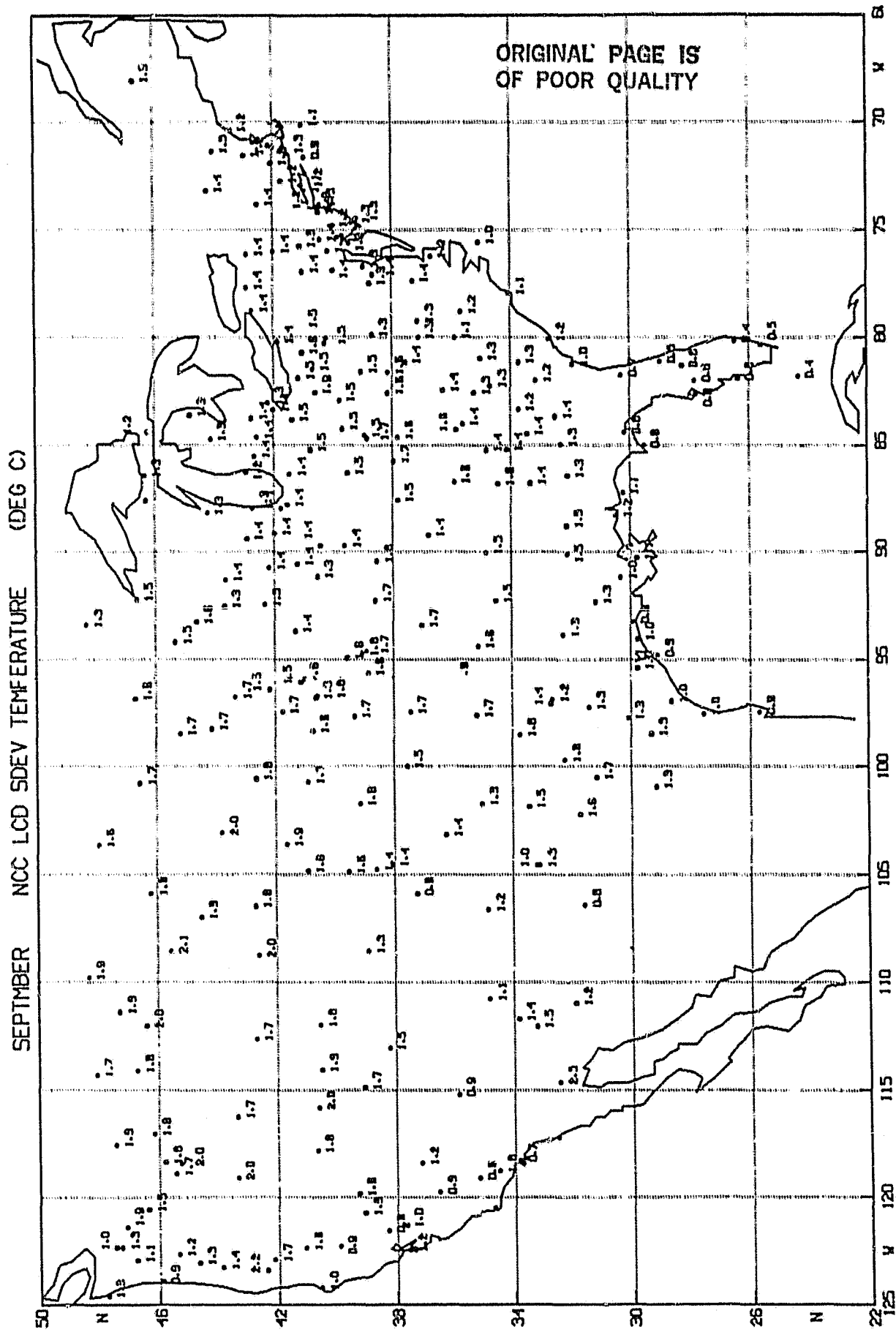


Fig. 3.b.10

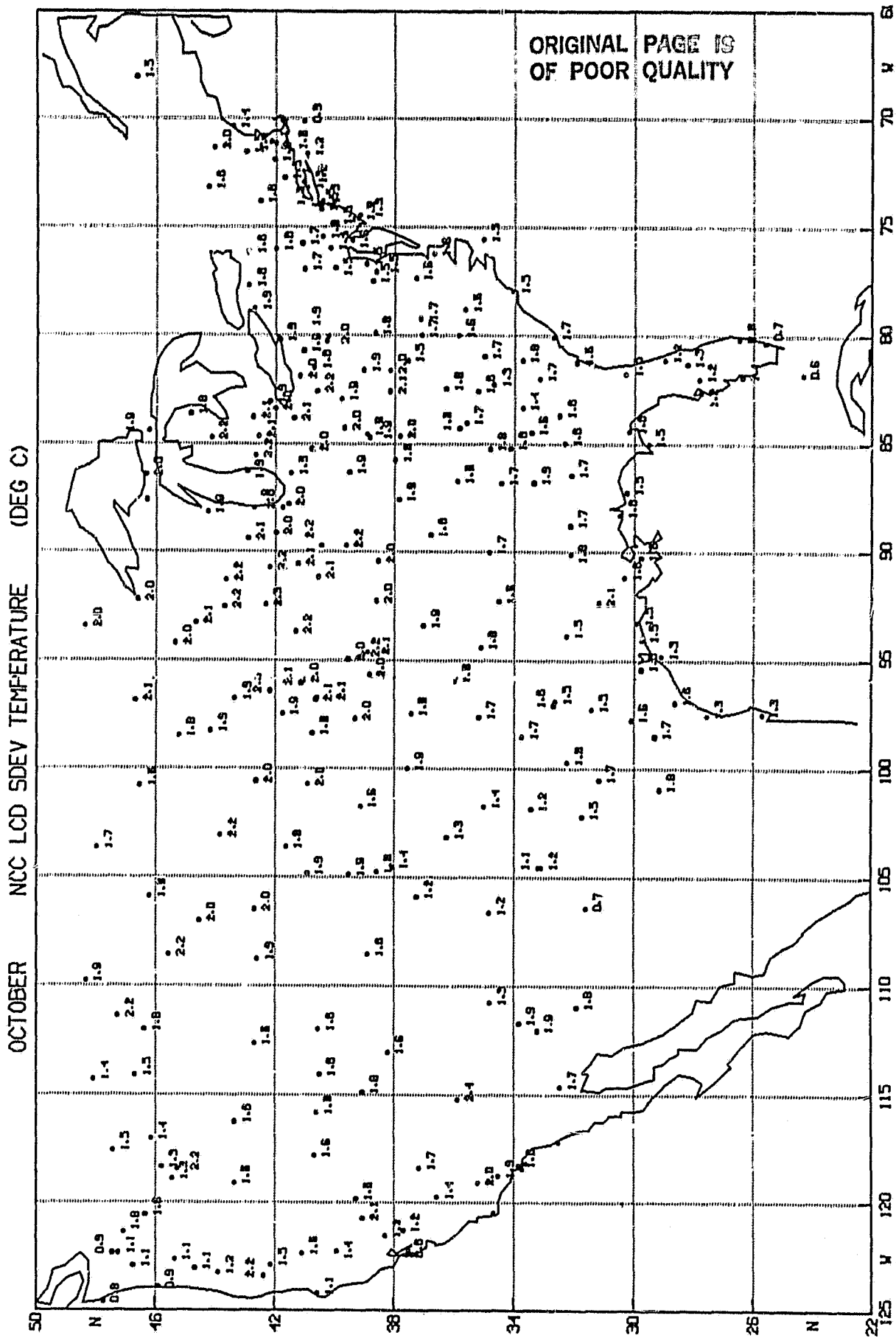


Fig. 3.b.11

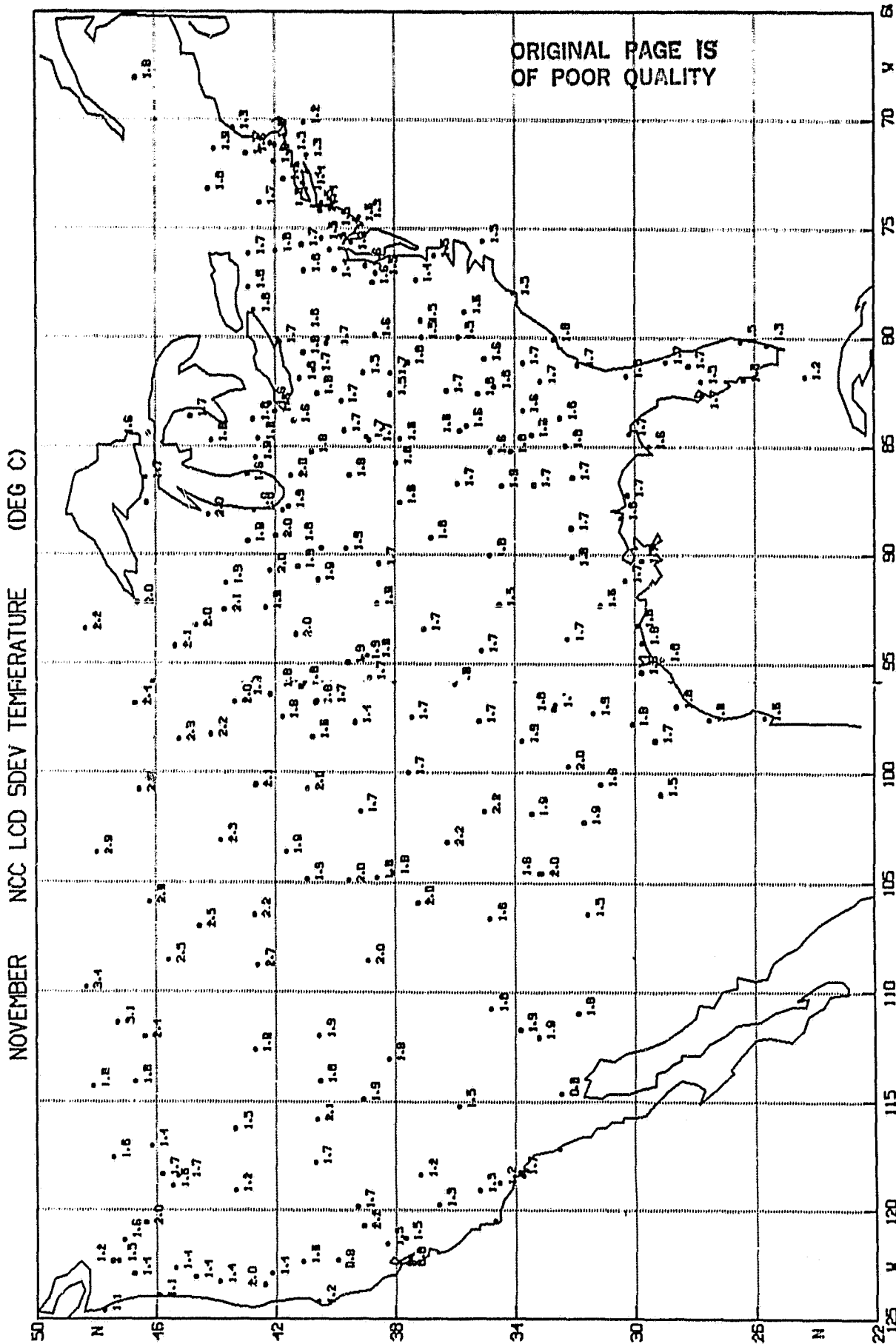


Fig. 3.b.12

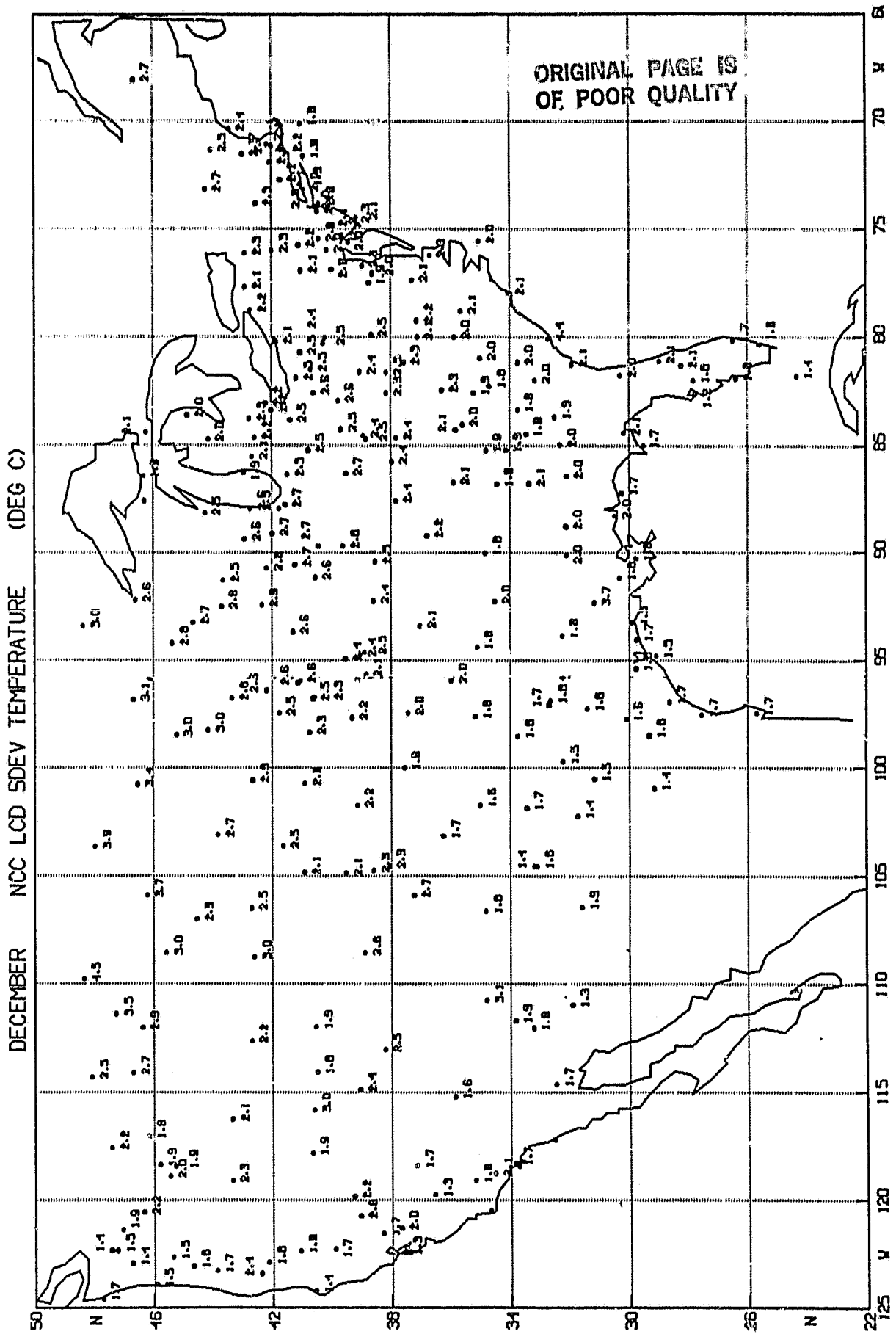


Fig. 4.a.1

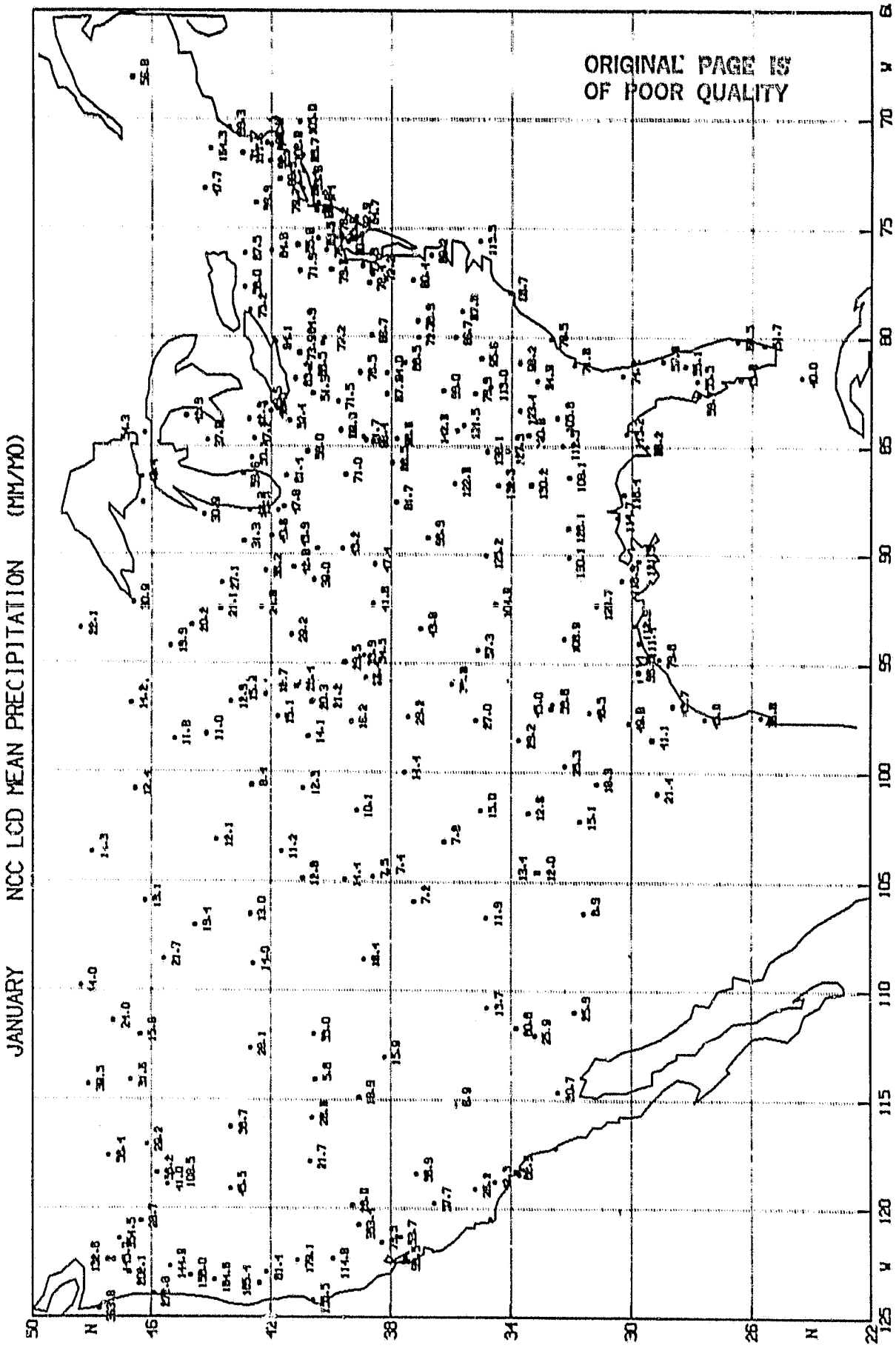


Fig. 4.a.3

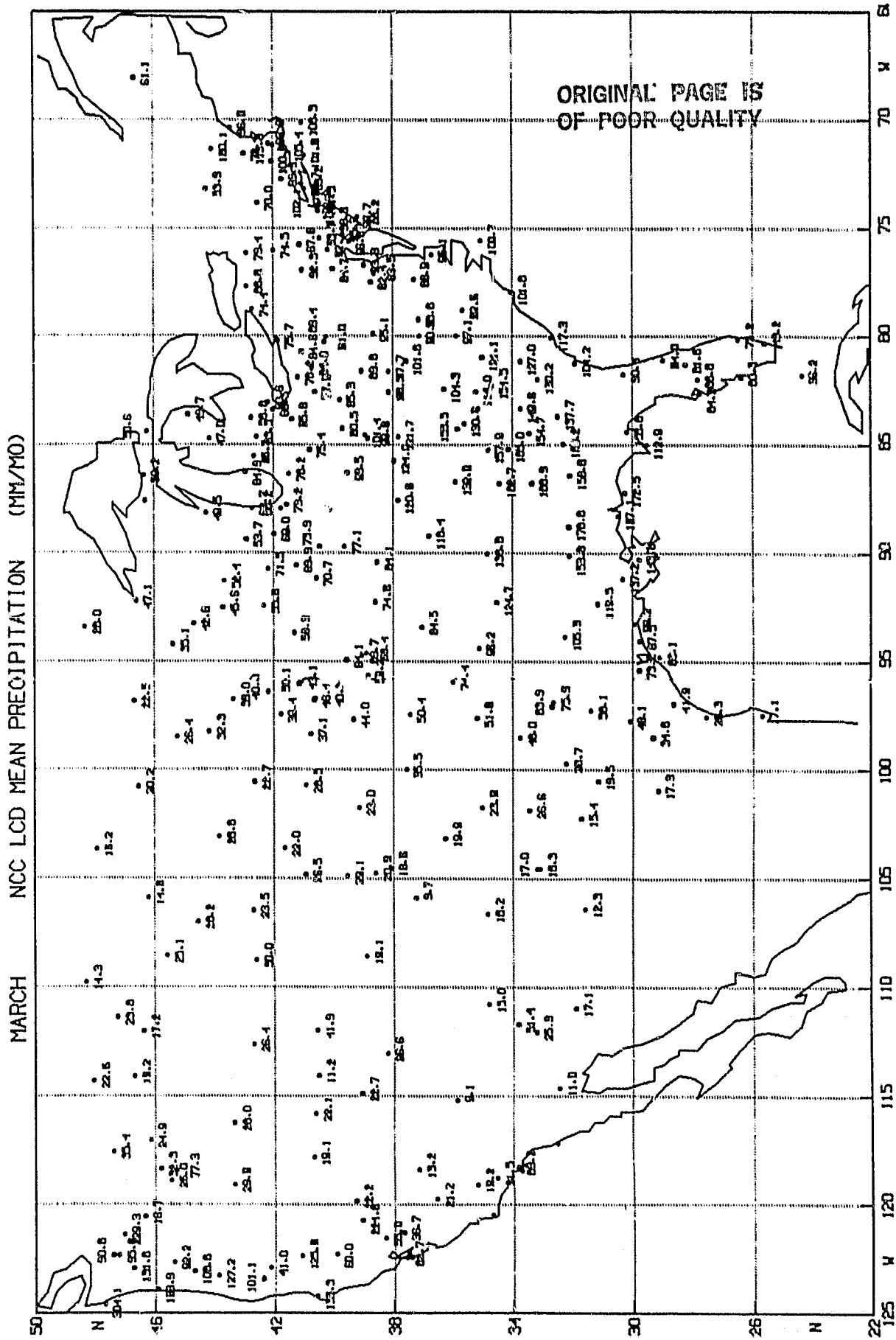


Fig. 4.a.4

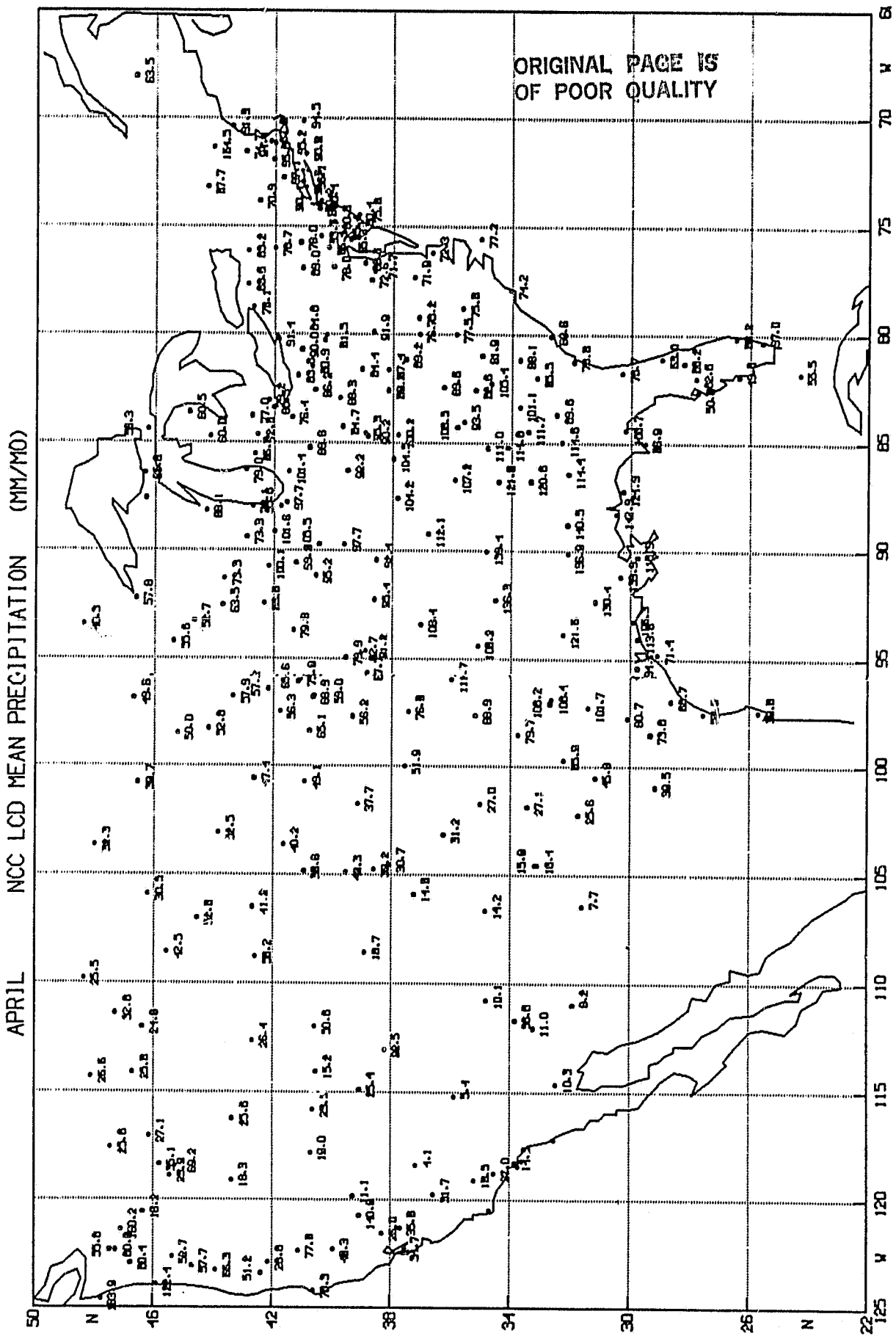


Fig. 4.a.5

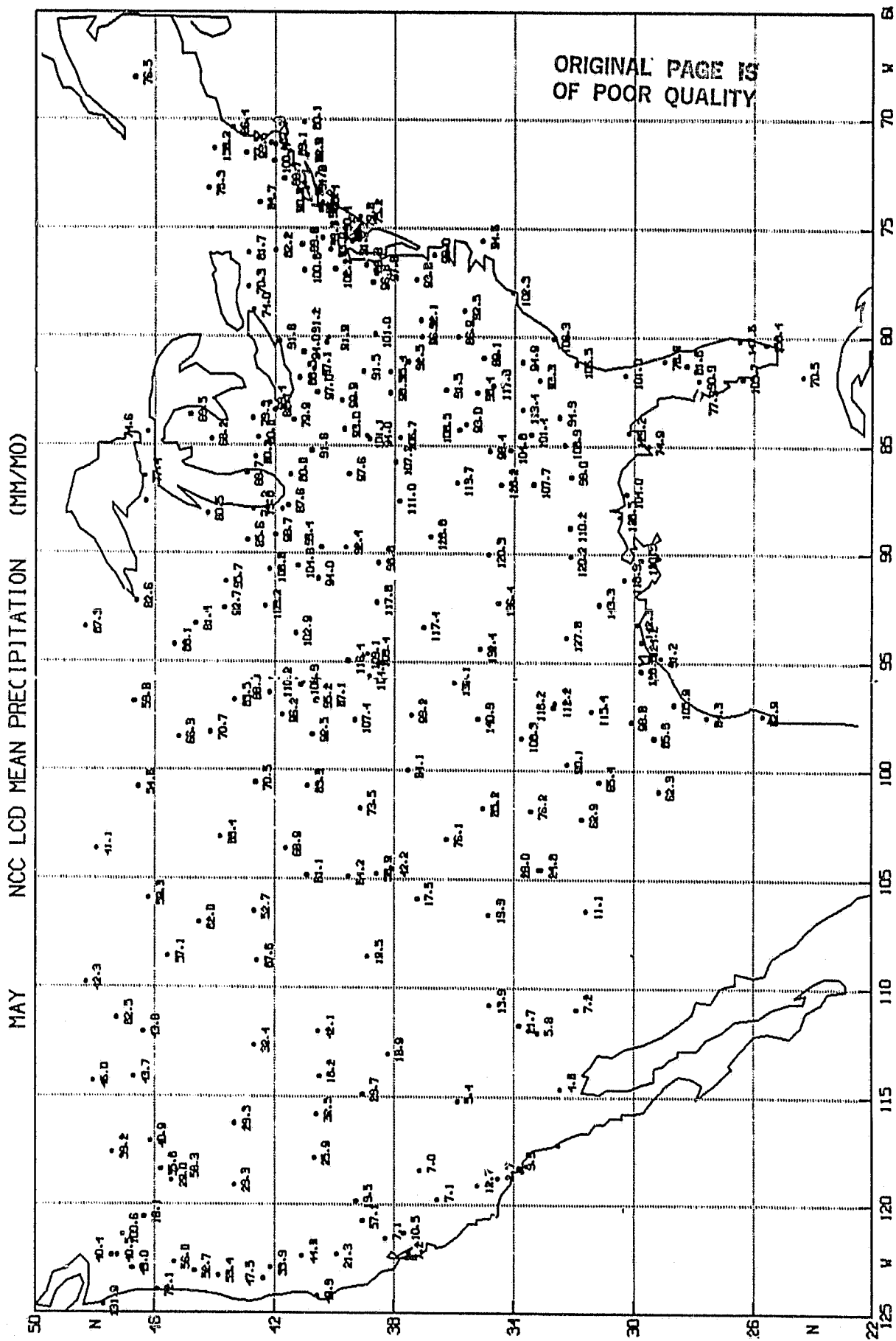


Fig. 4.a.6

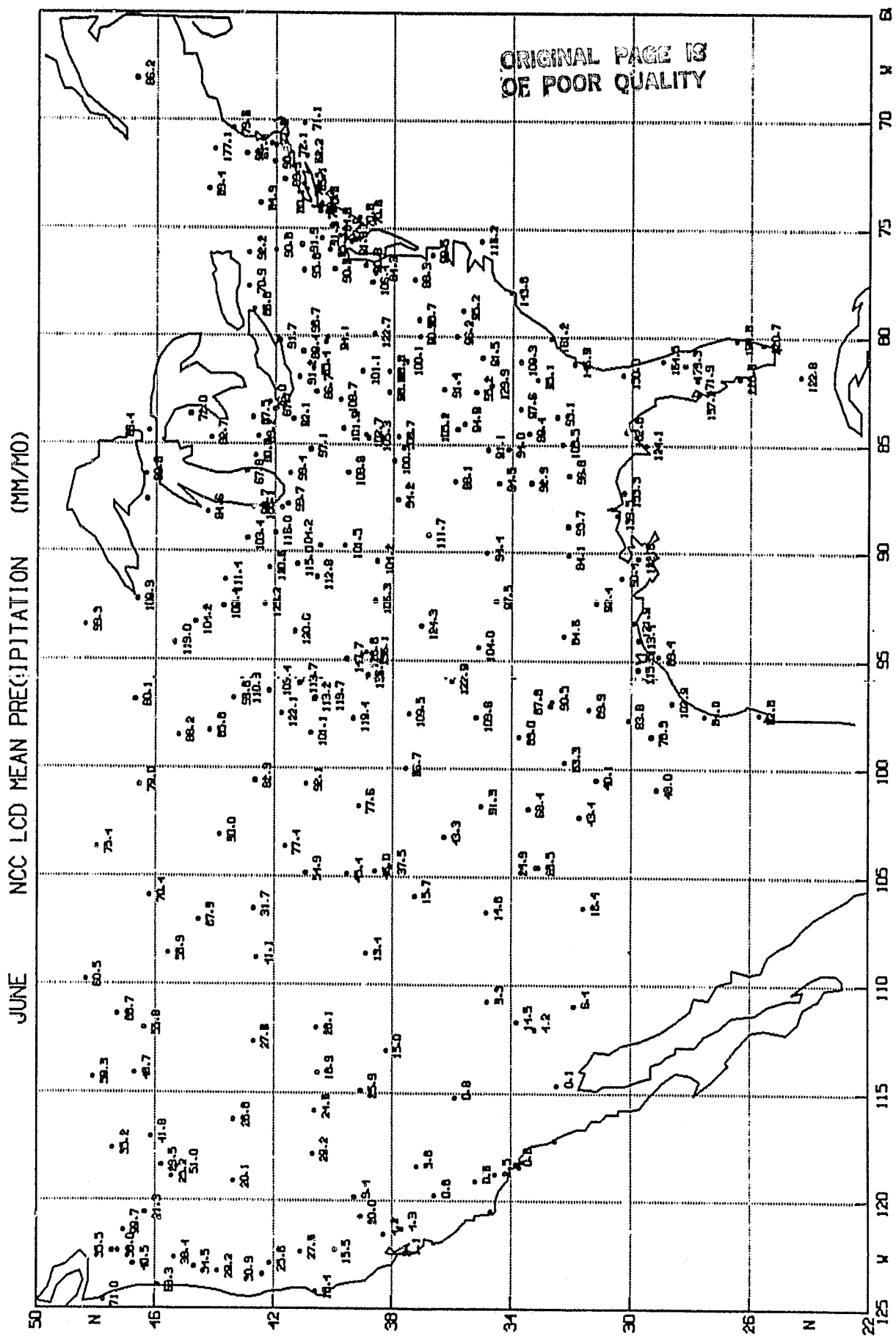


Fig. 4.a.7

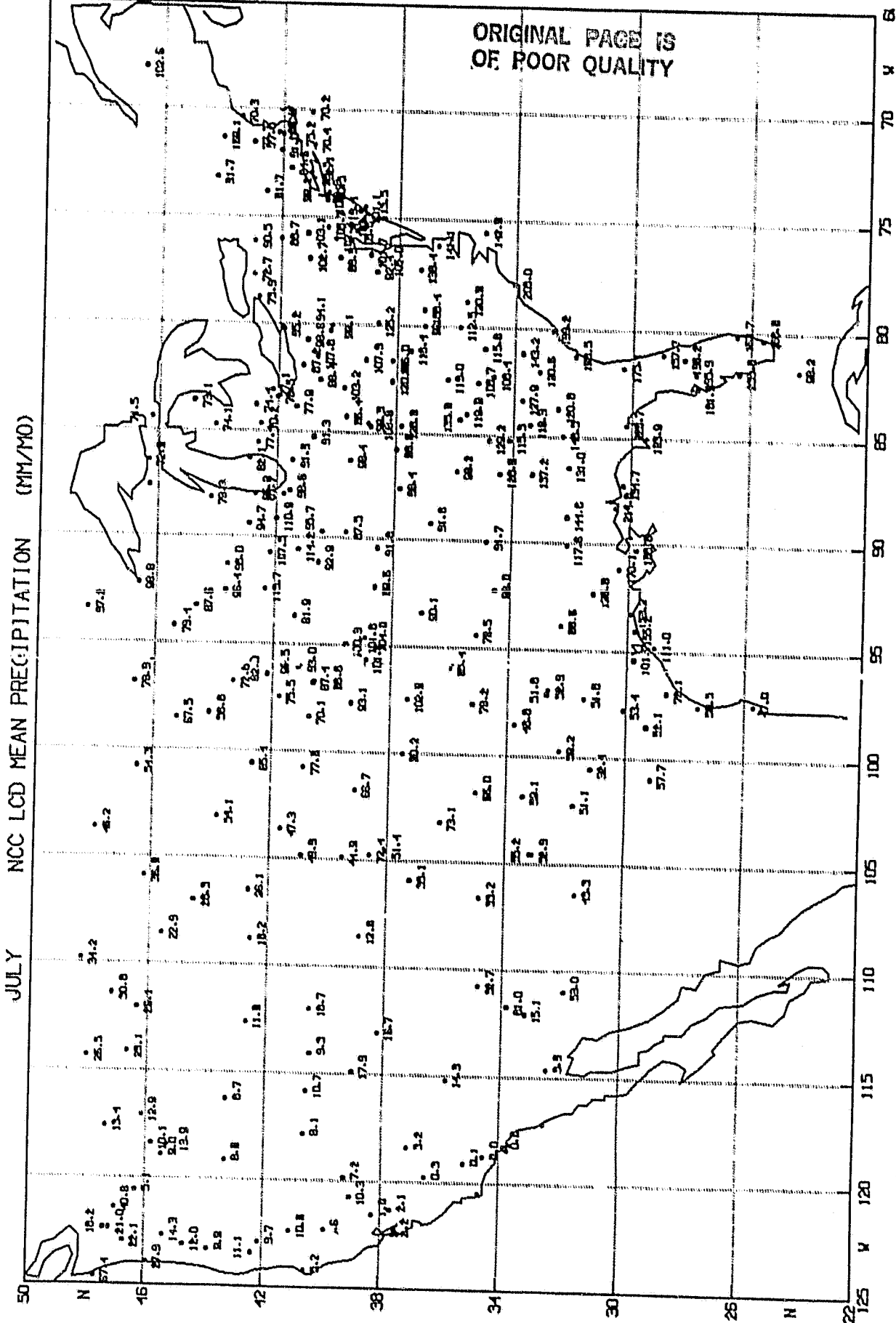


Fig. 4.a.9

SEPTEMBER NCC LCD MEAN PRECIPITATION (MM/MO)

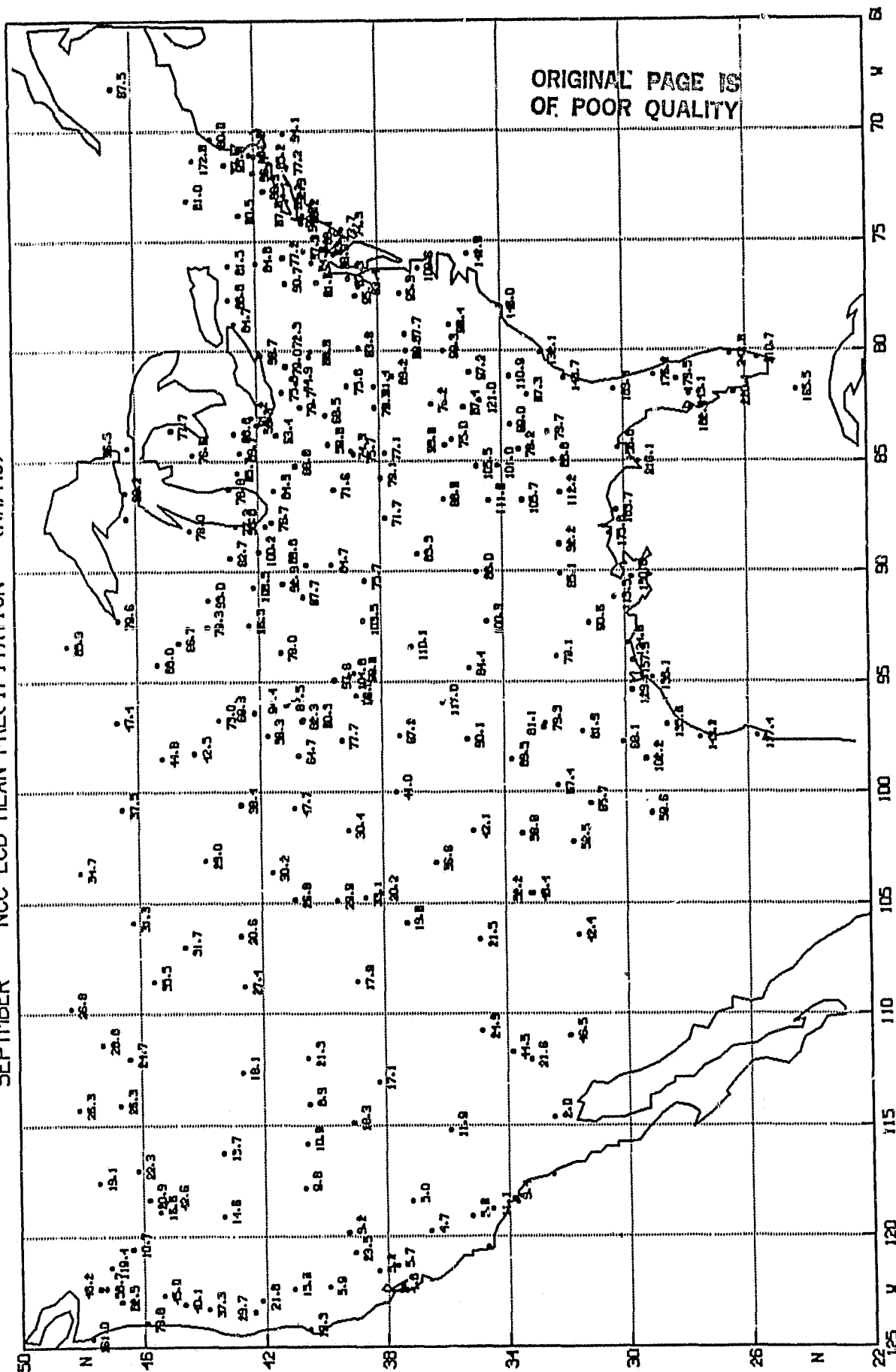


Fig. 4.a.10

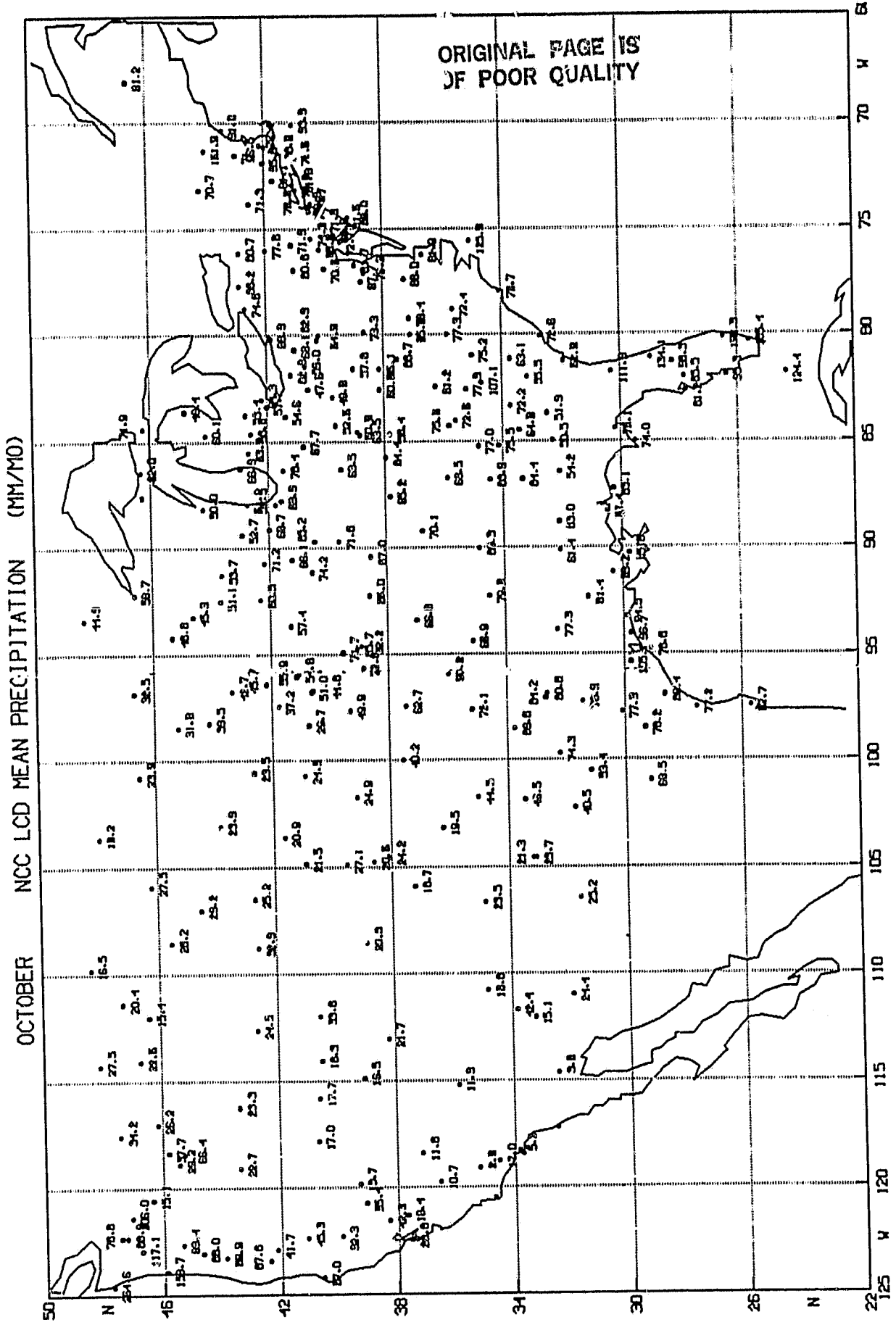


Fig. 4.a.11

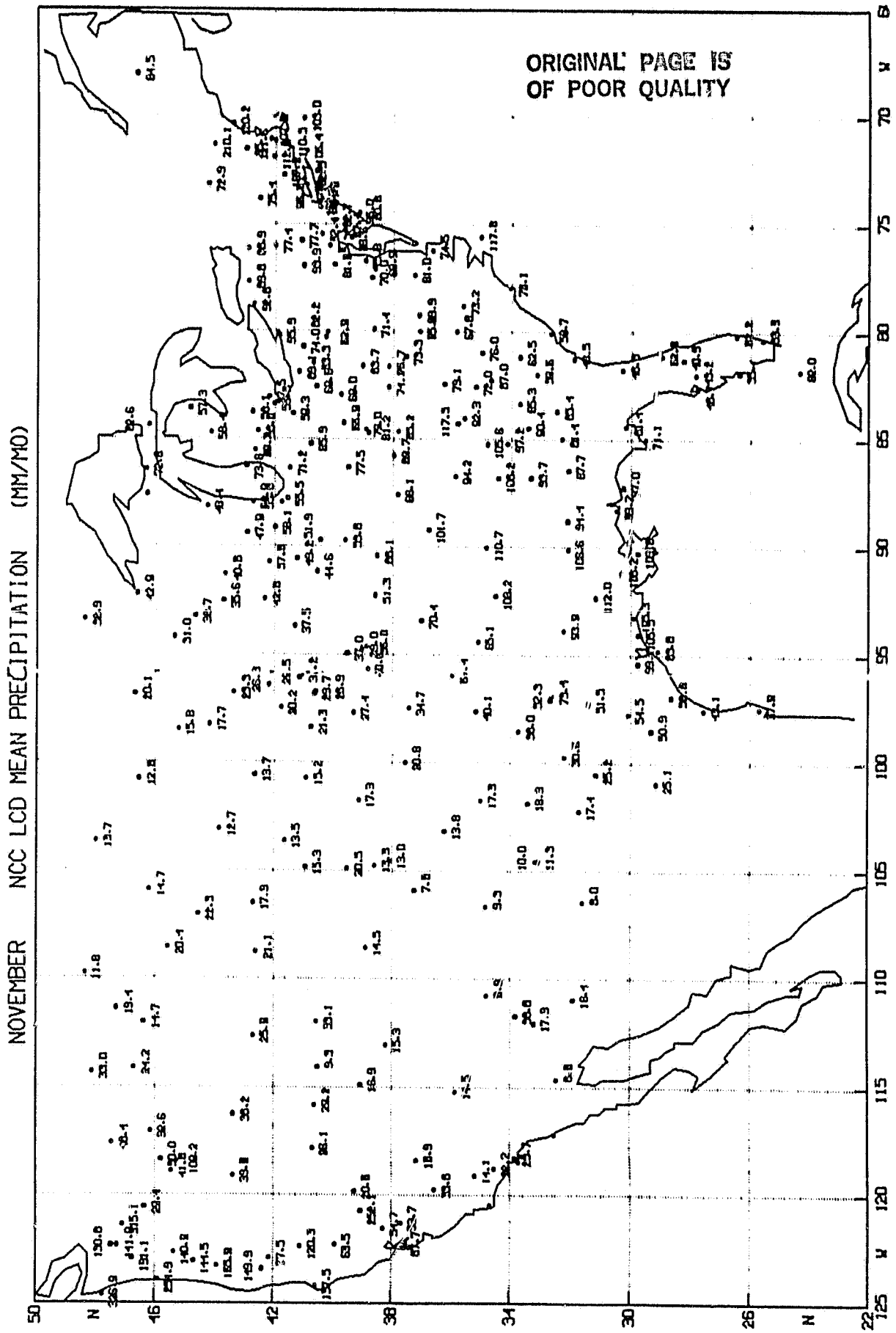


Fig. 4.b.1

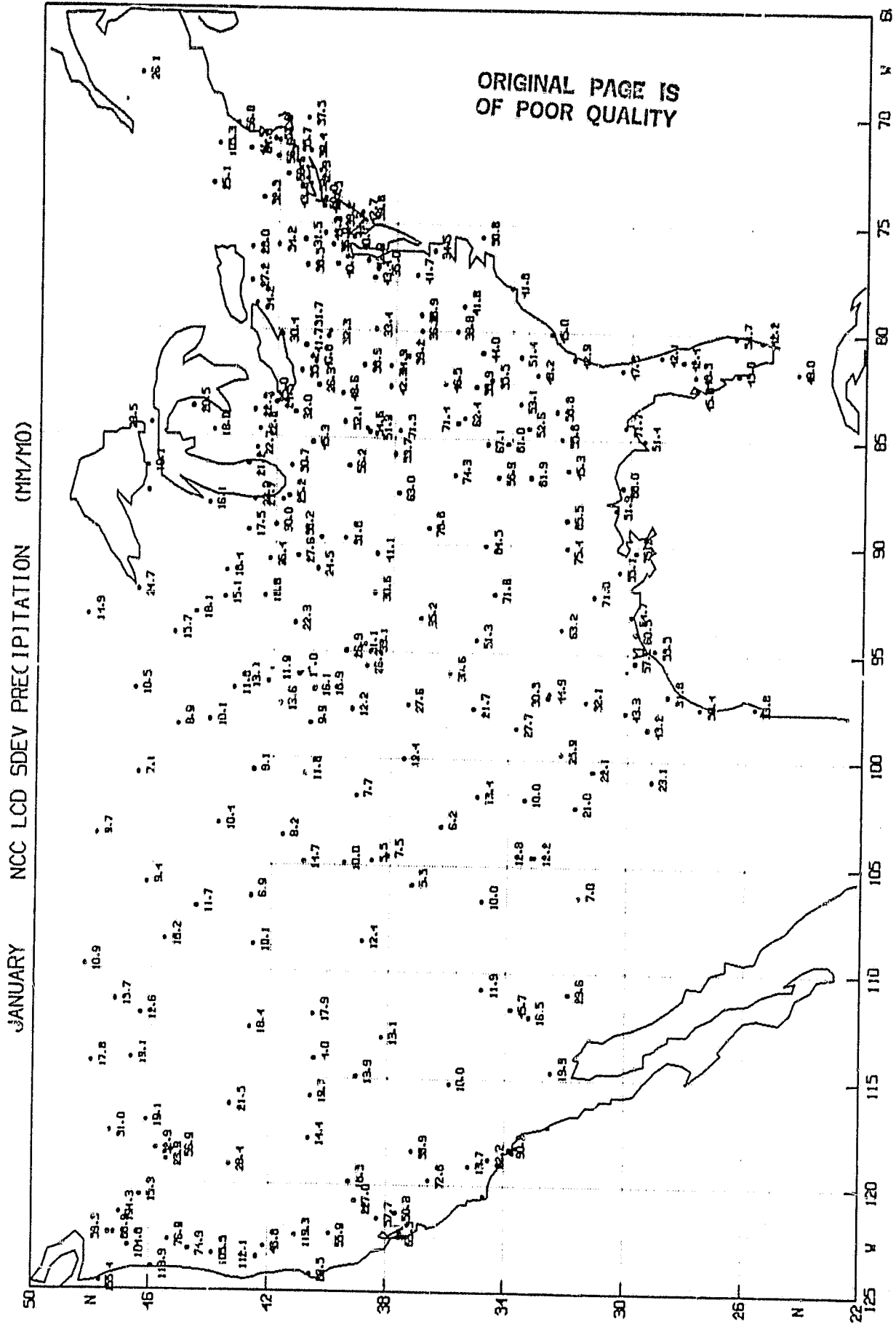


Fig. 4.b.2

FEBRUARY NCC LCD SDEV PRECIPITATION (MM/MO)

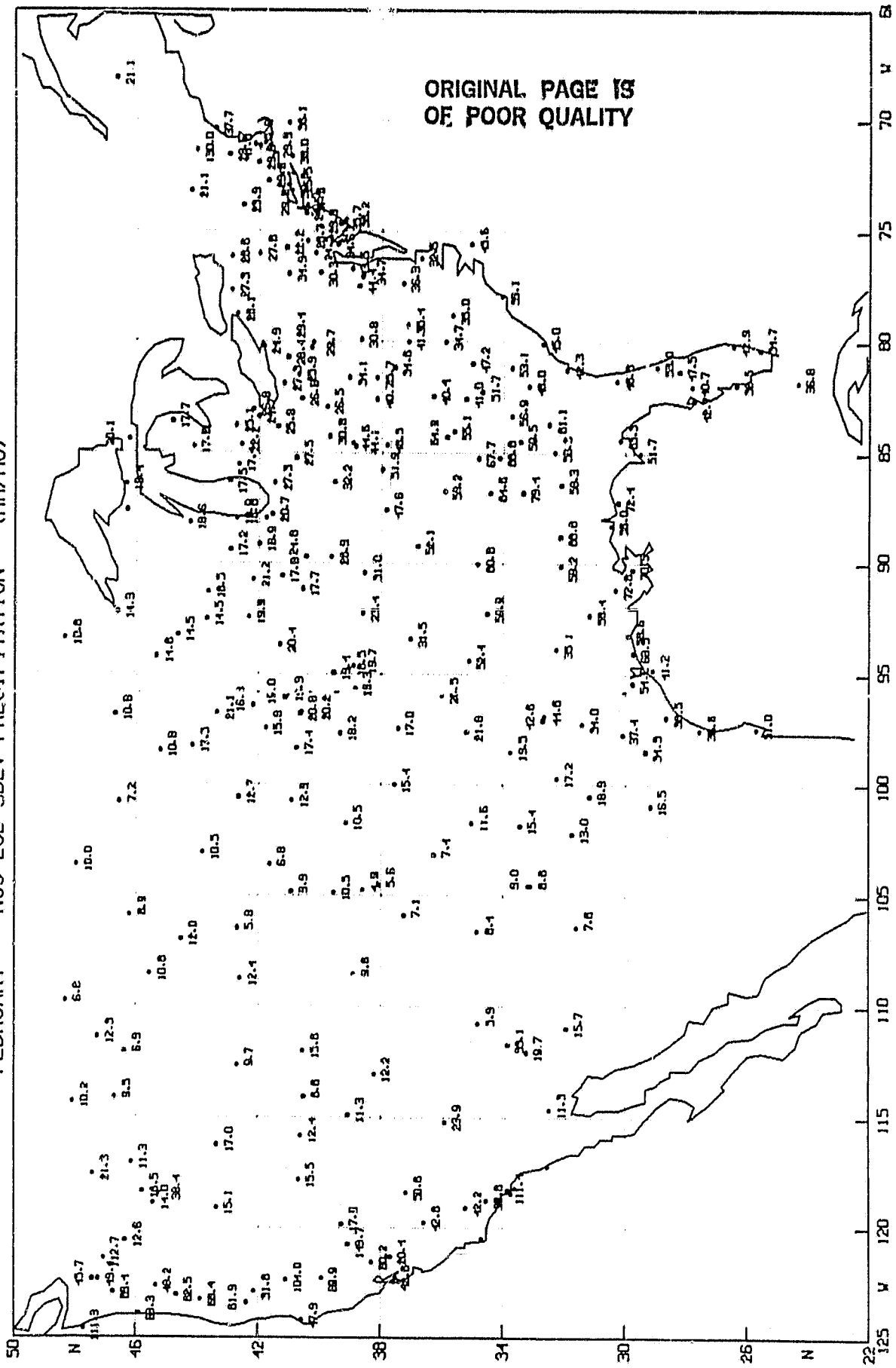


Fig. 4.b.3

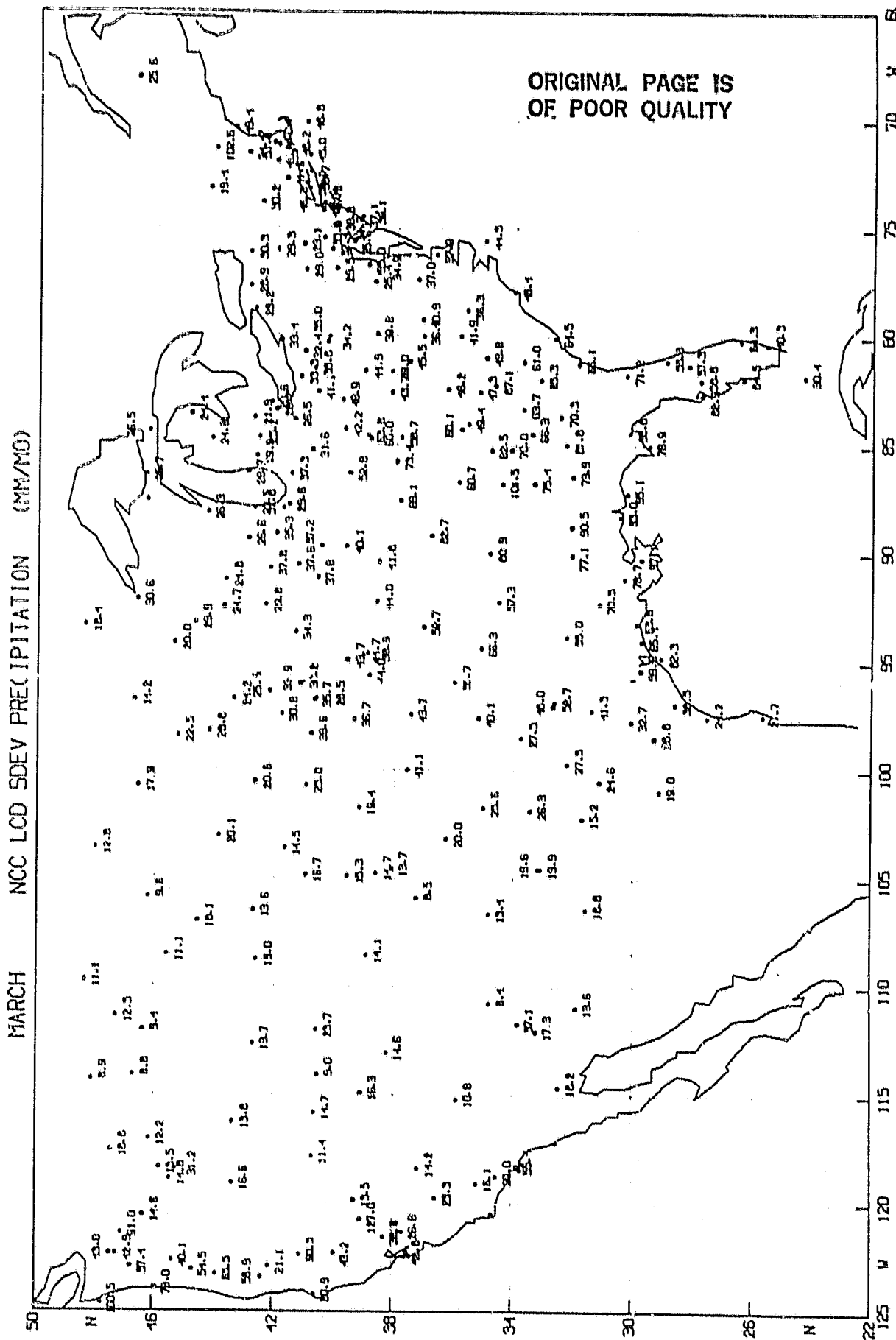


Fig. 4.b.4

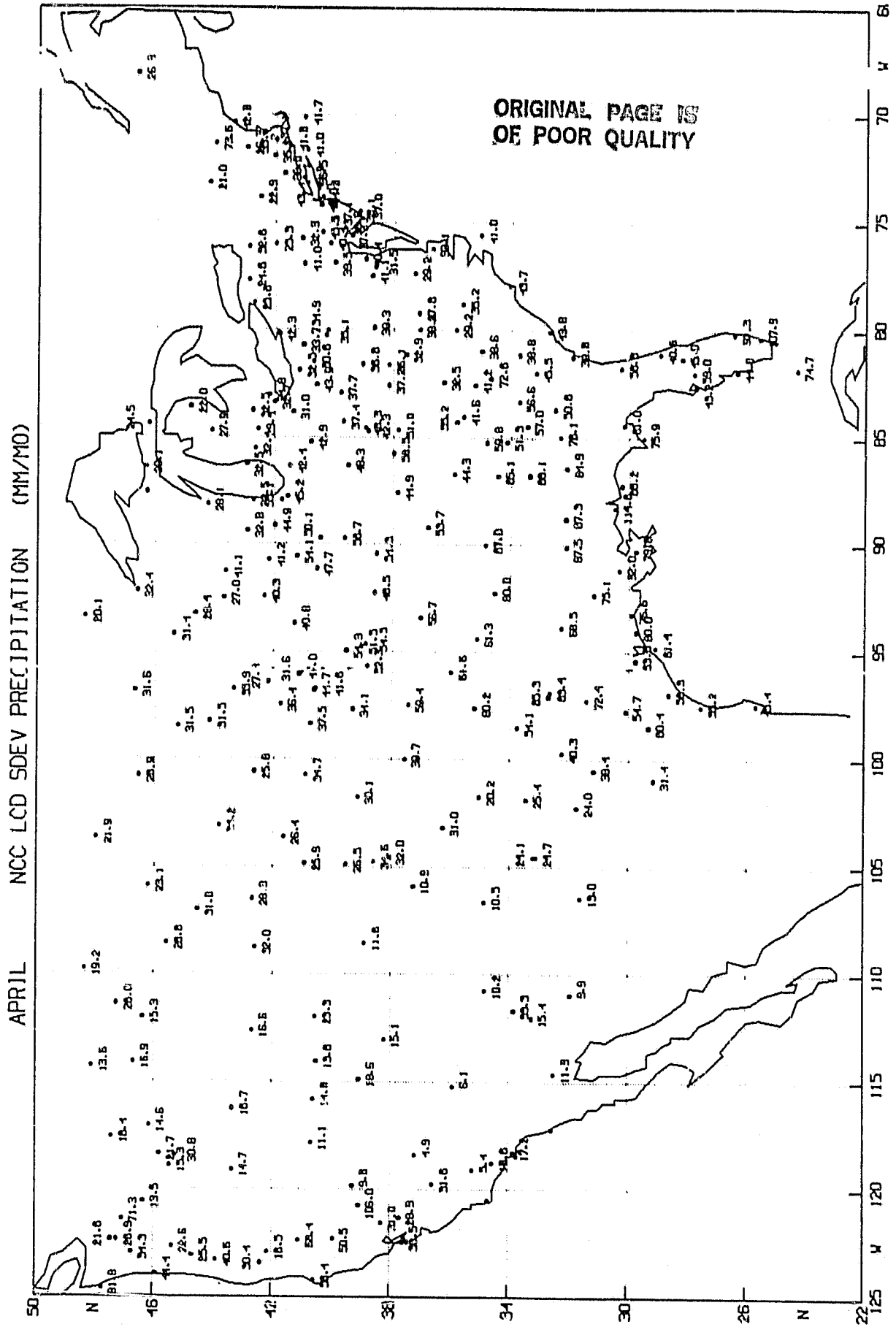


Fig. 4.b.5

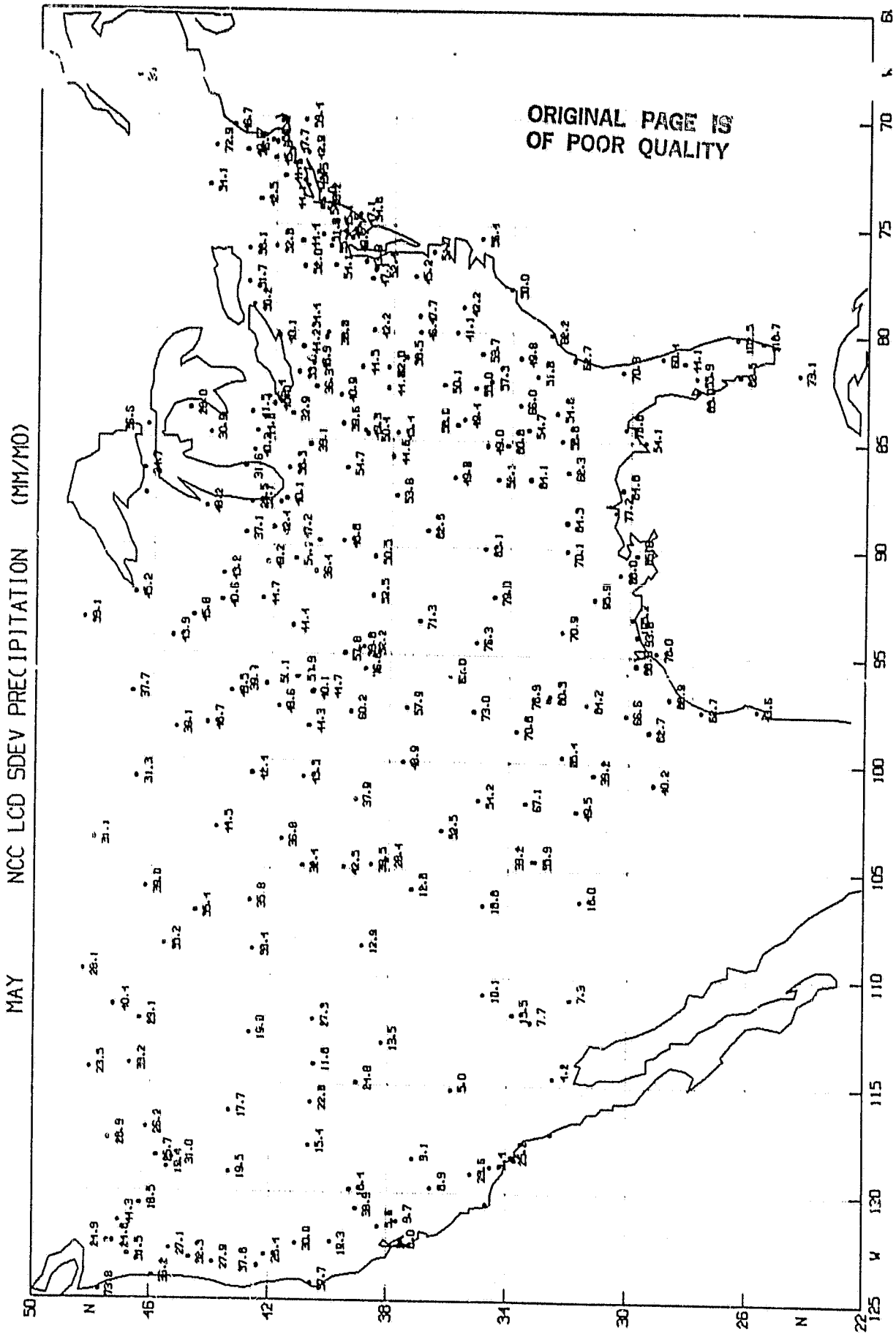


Fig. 4.b.6

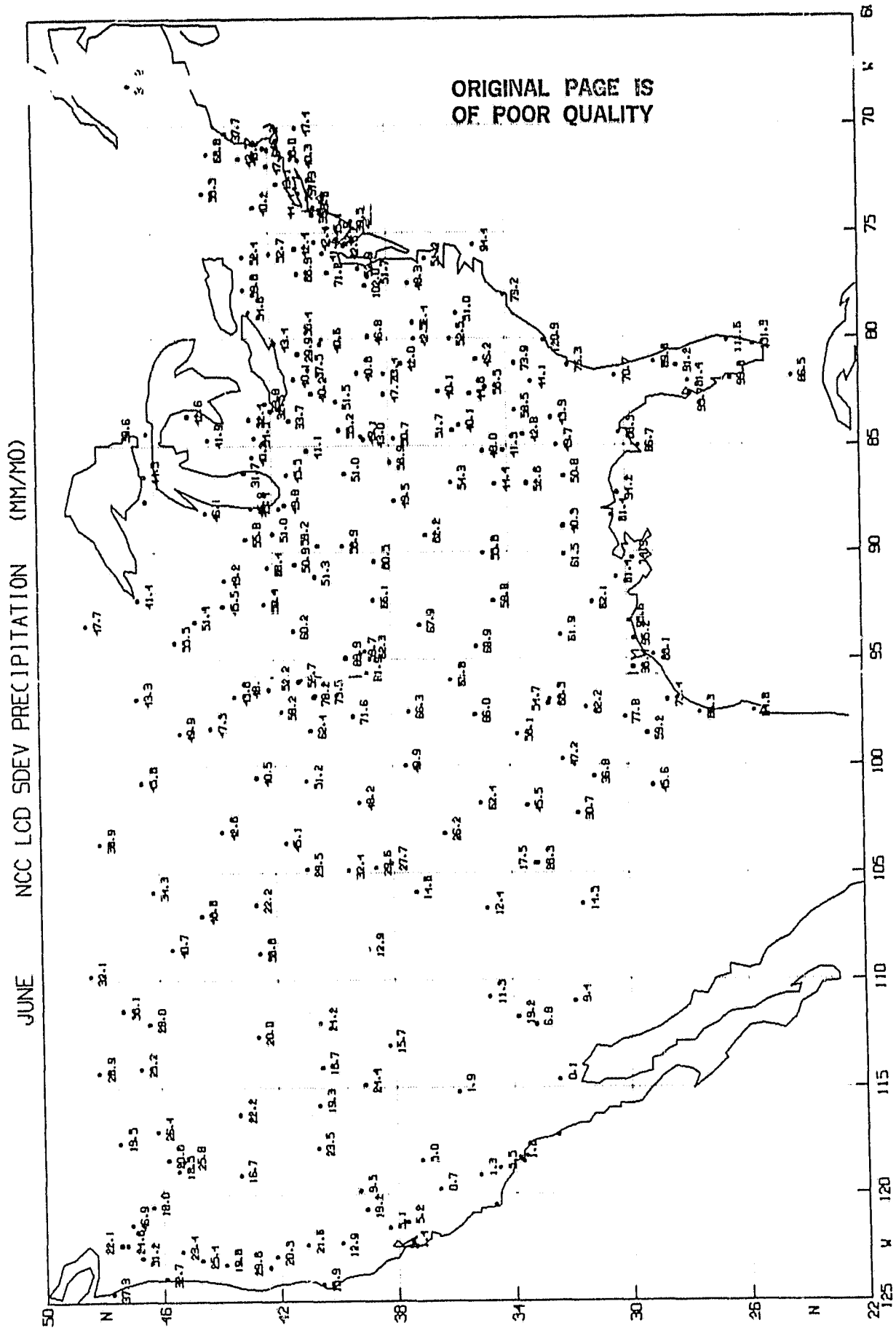


Fig. 4.b.7

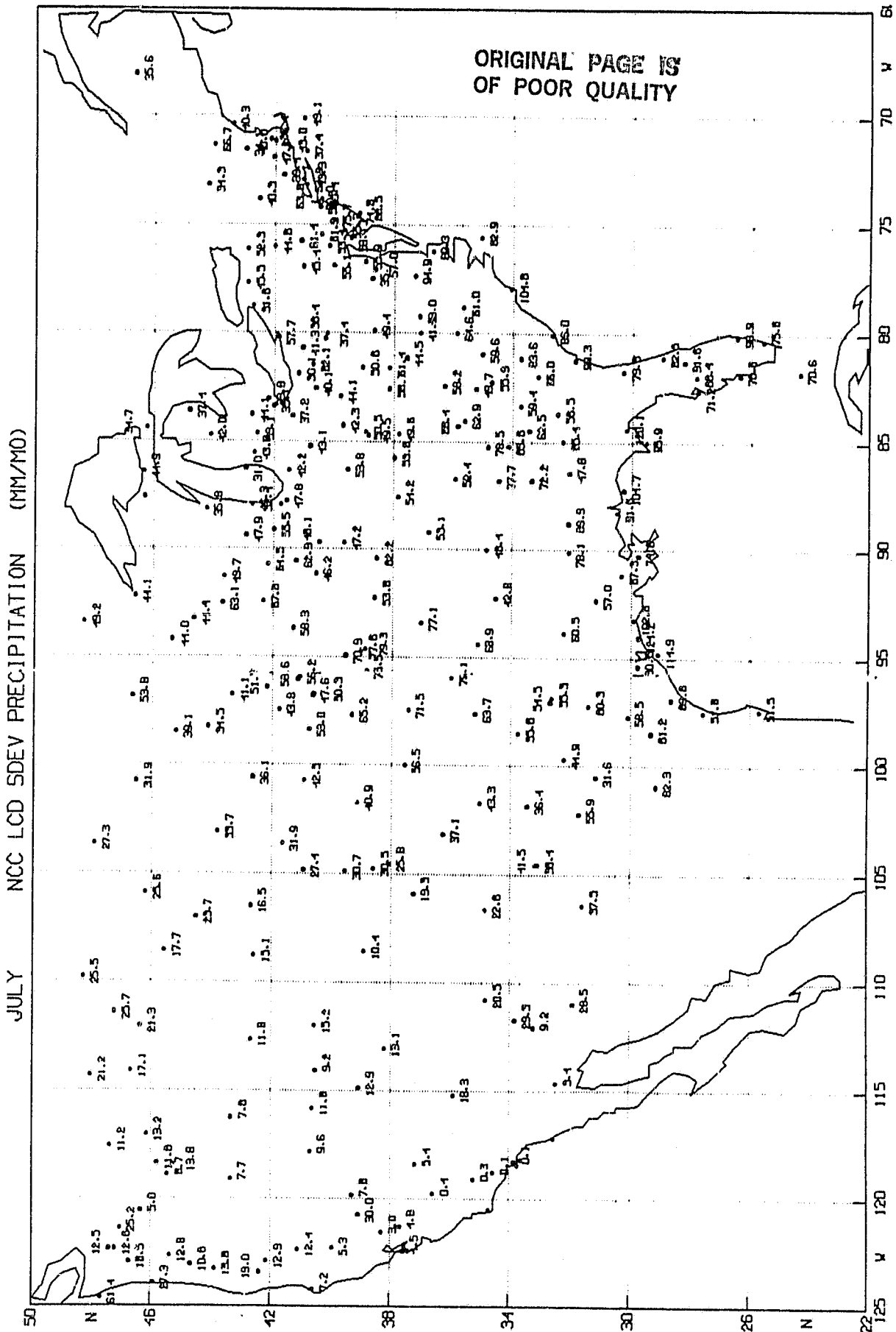


Fig. 4.b.8

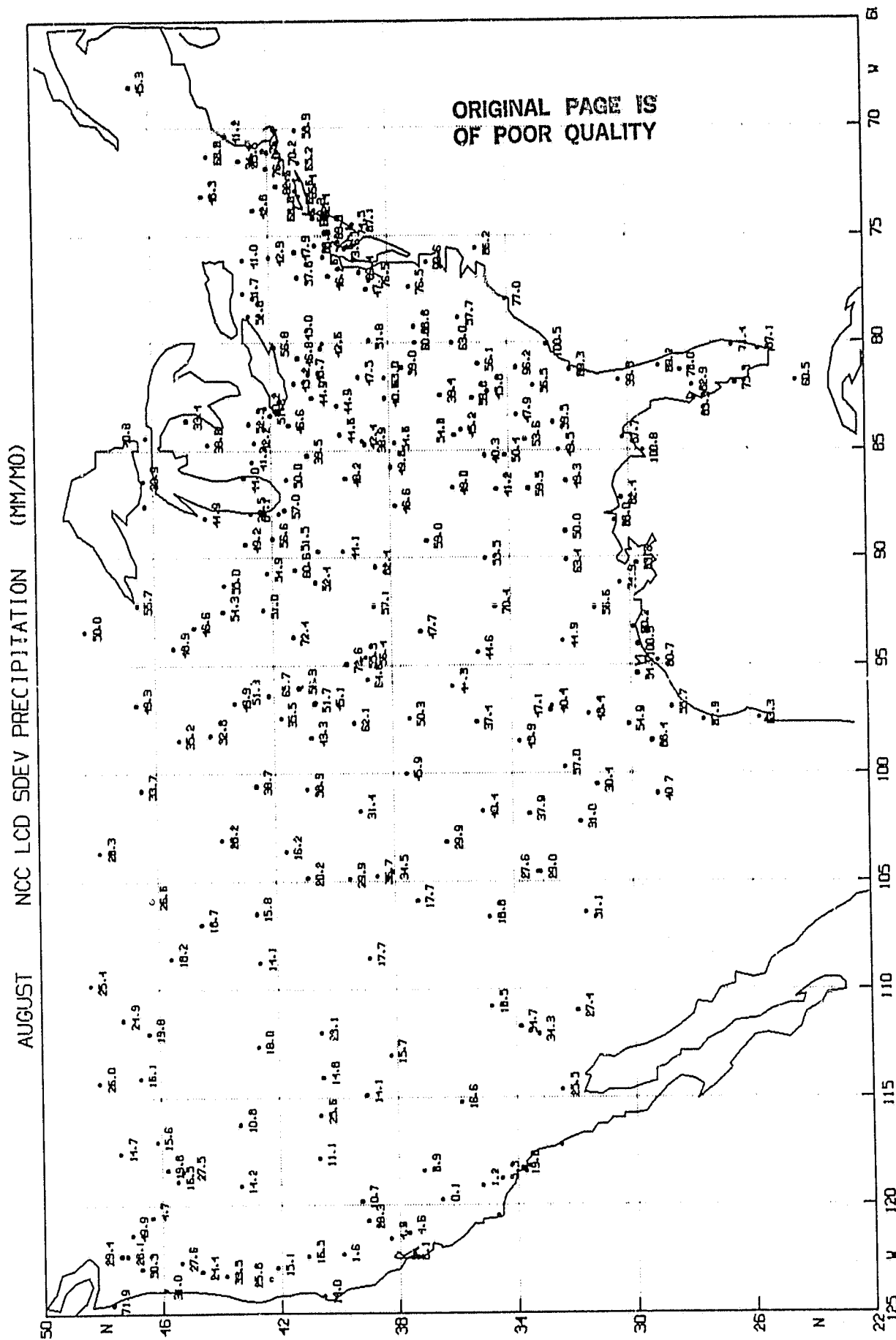


Fig. 4.b.9

SEPTEMBER NCC LCD SDEV PRECIPITATION (MM/MO)

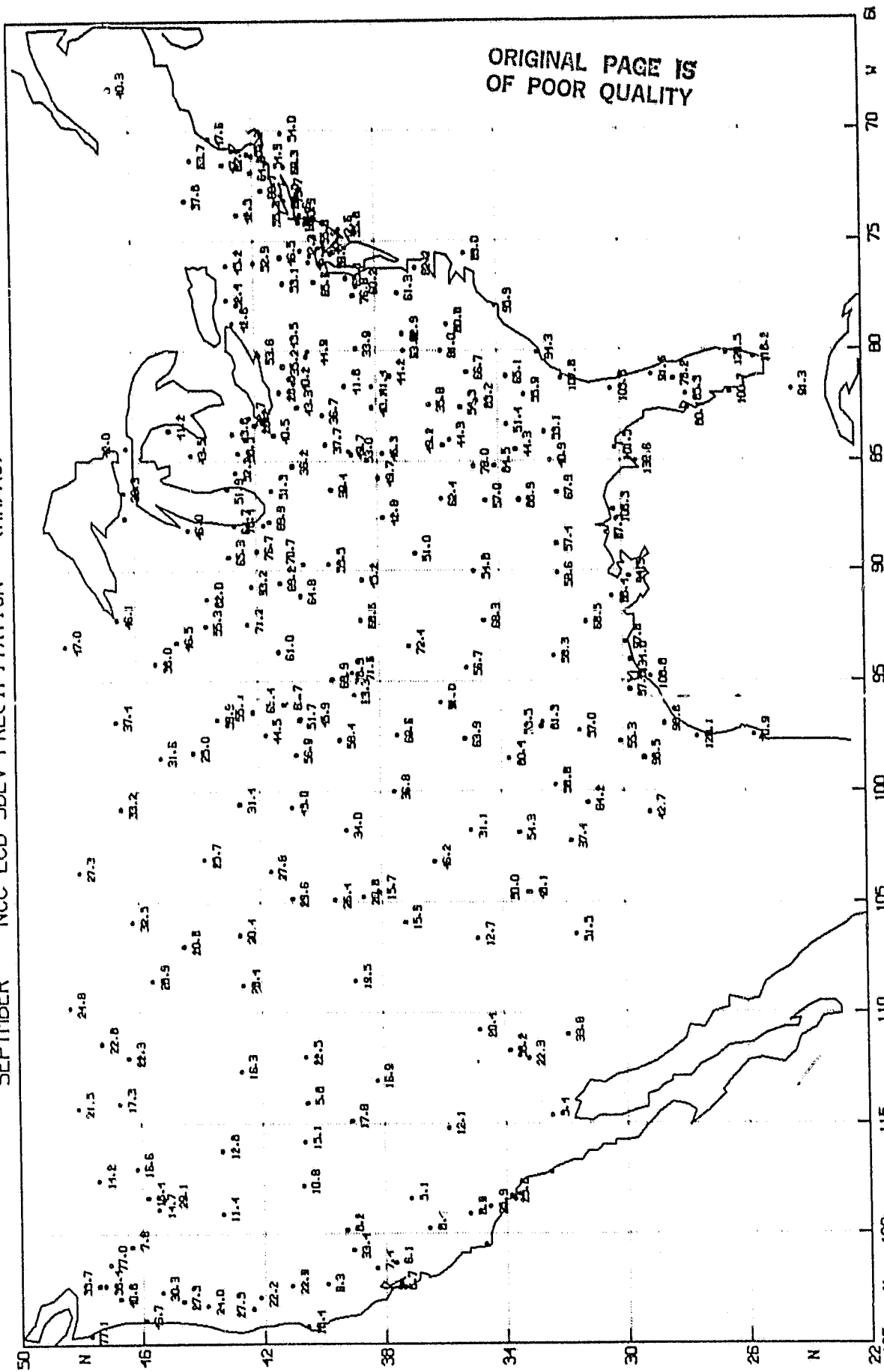


Fig. 4.b.10

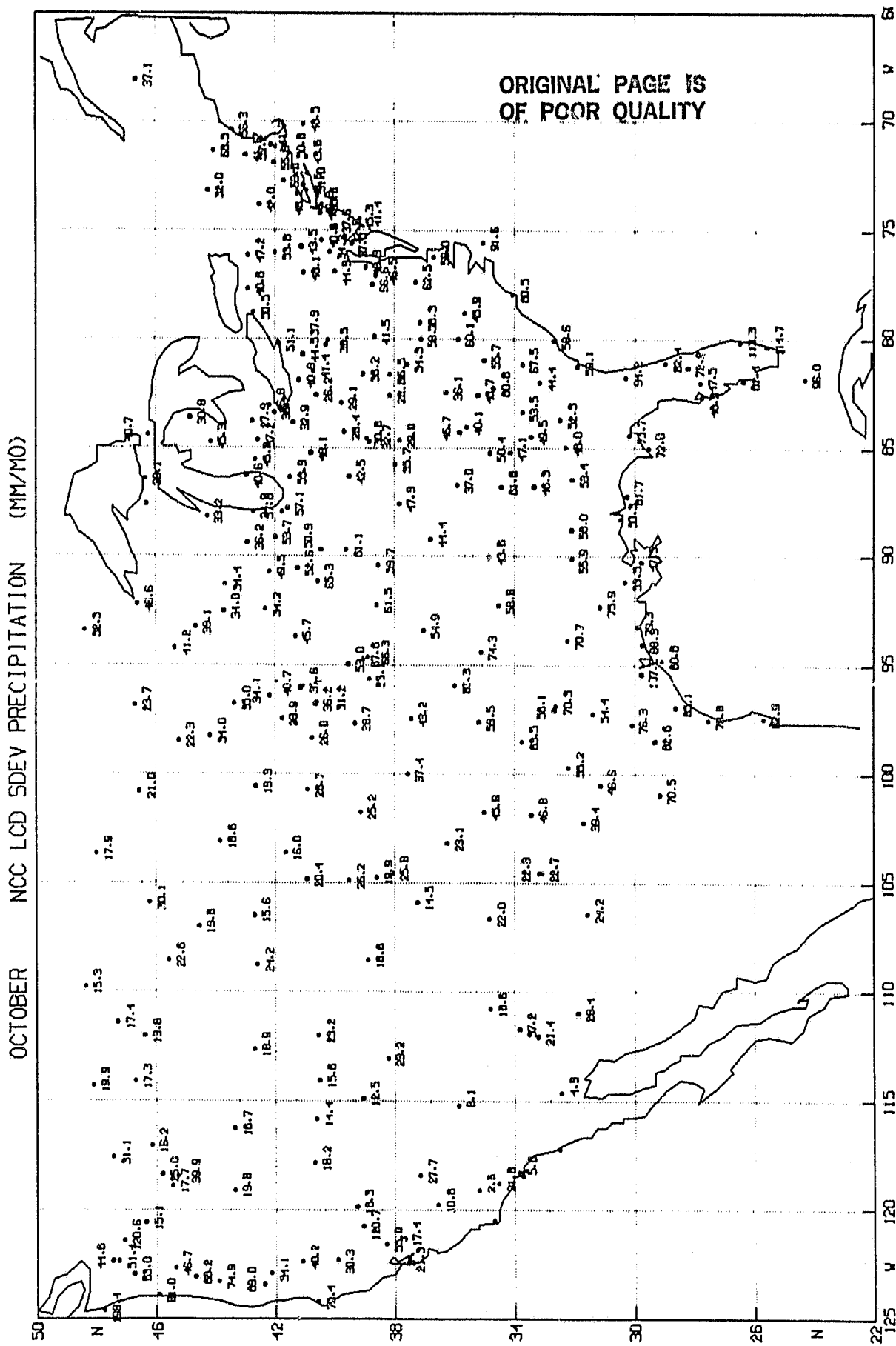


Fig. 4.b.11

NOVEMBER NCC LCD SDEV PRECIPITATION (MM/MO)

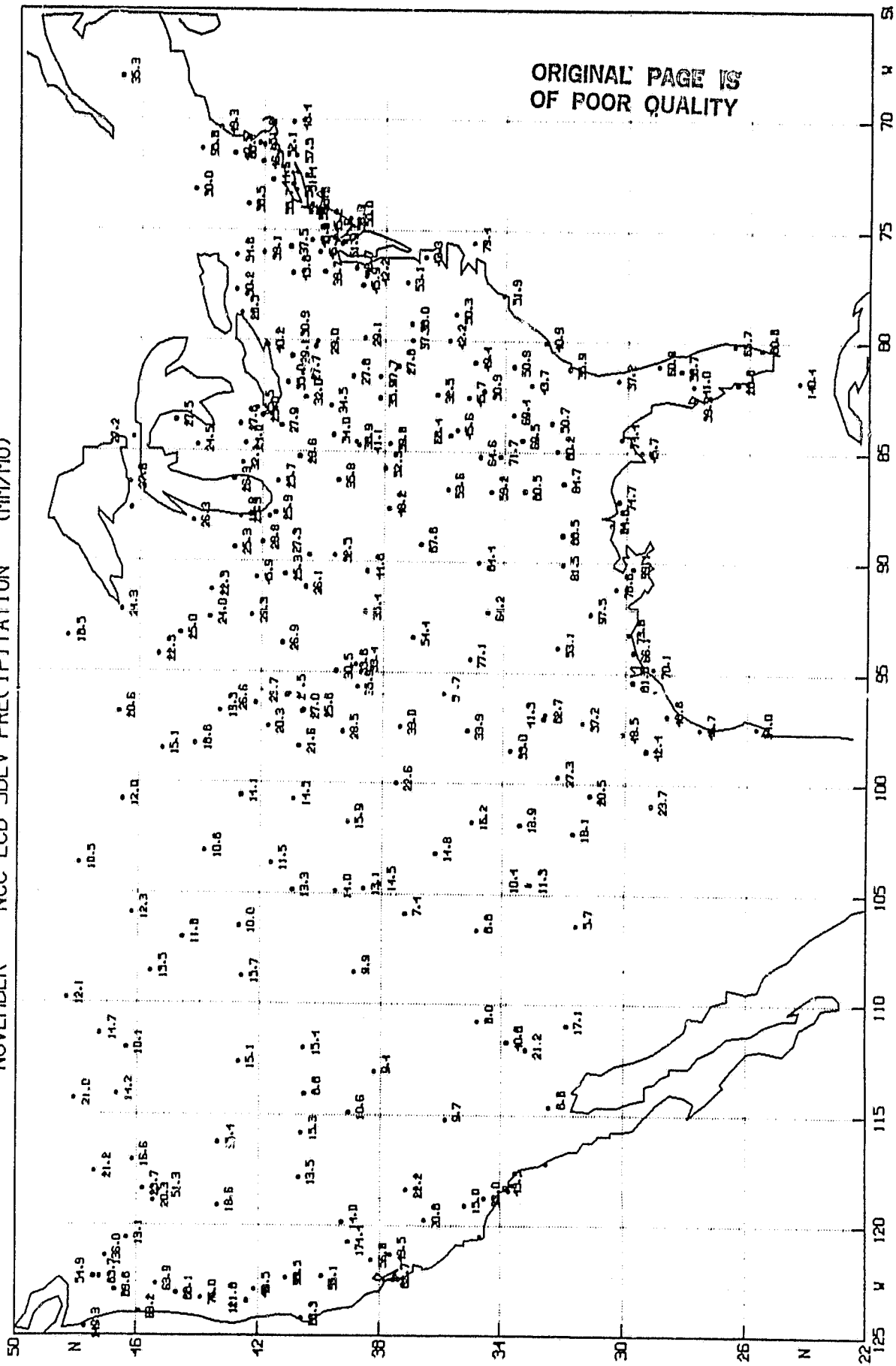


Fig. 4.b.12

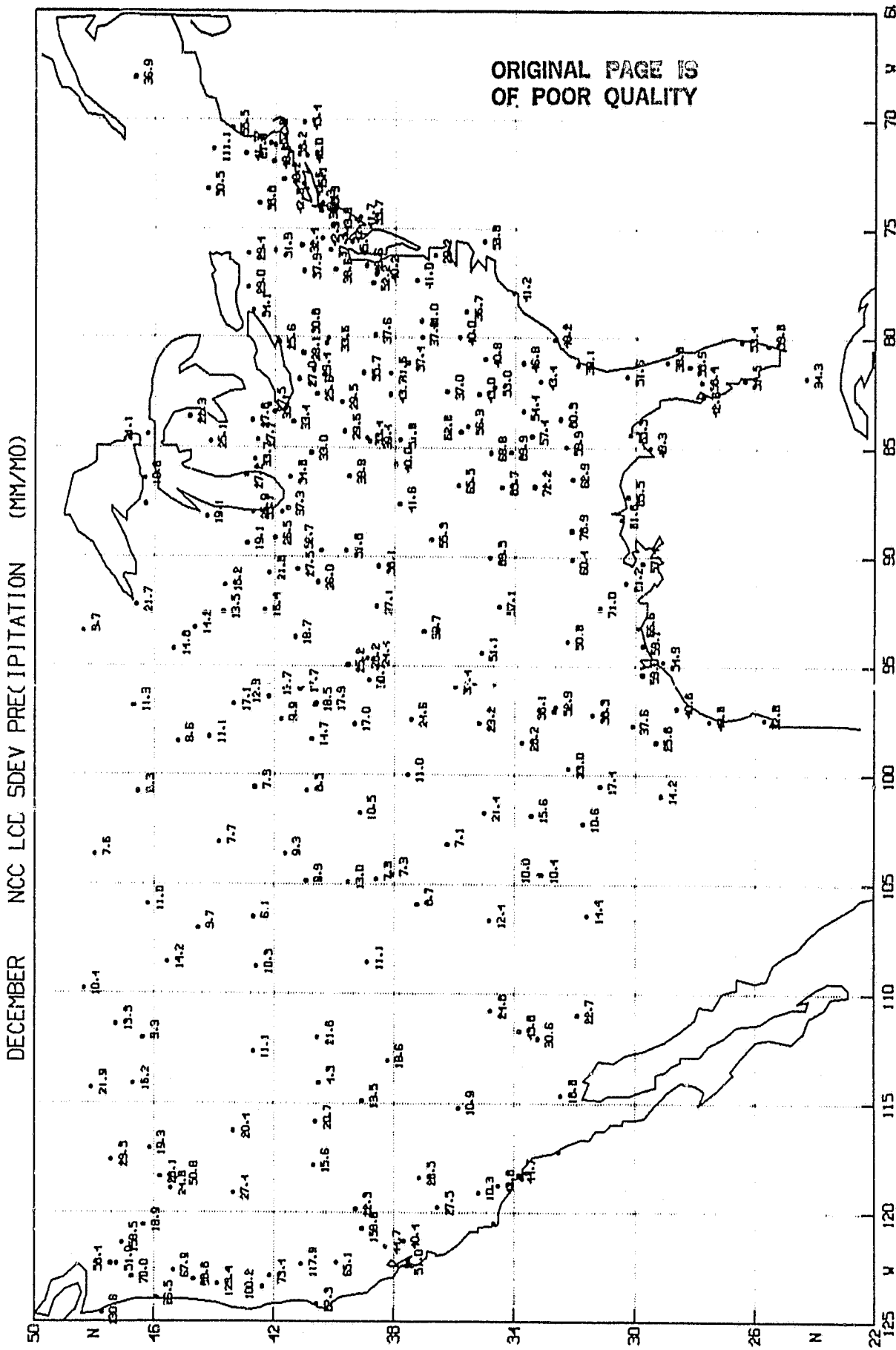


Fig. 5.a.2

FEBRUARY NCC LCD MEAN SOIL MOISTURE FRACTION

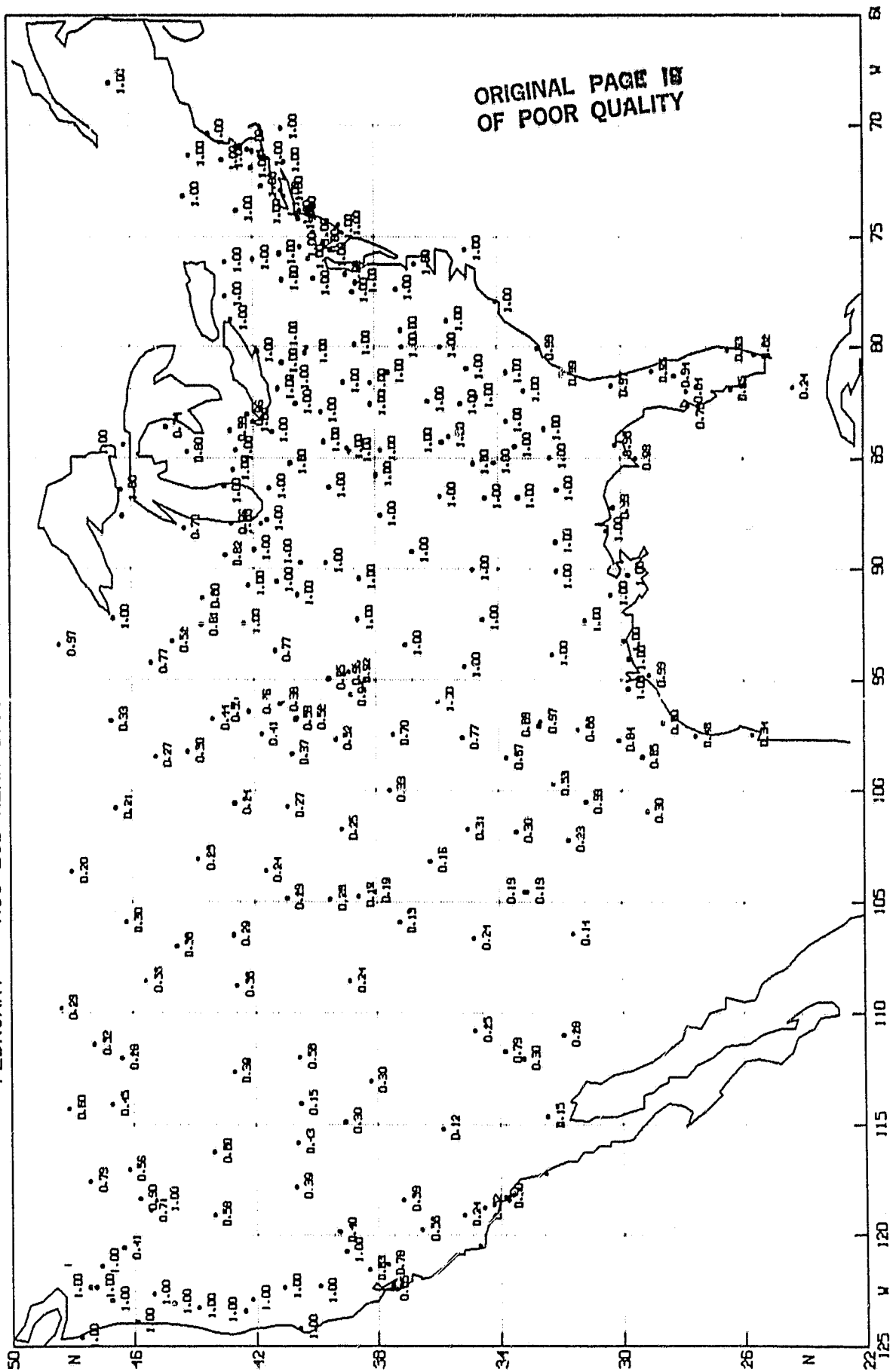


Fig. 5.a.3

MARCH
NCC LCD MEAN SOIL MOISTURE FRACTION

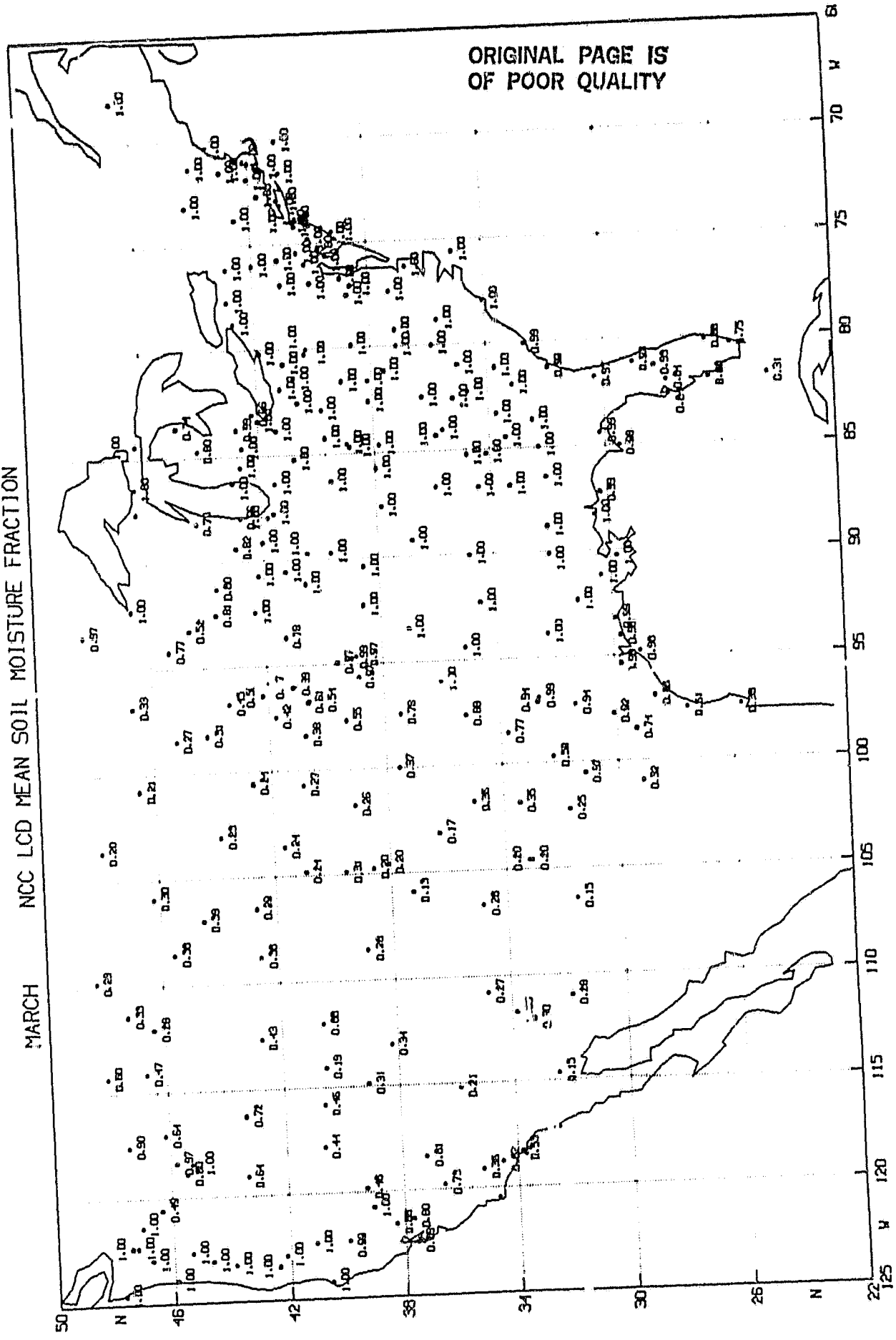


Fig. 5.a.4

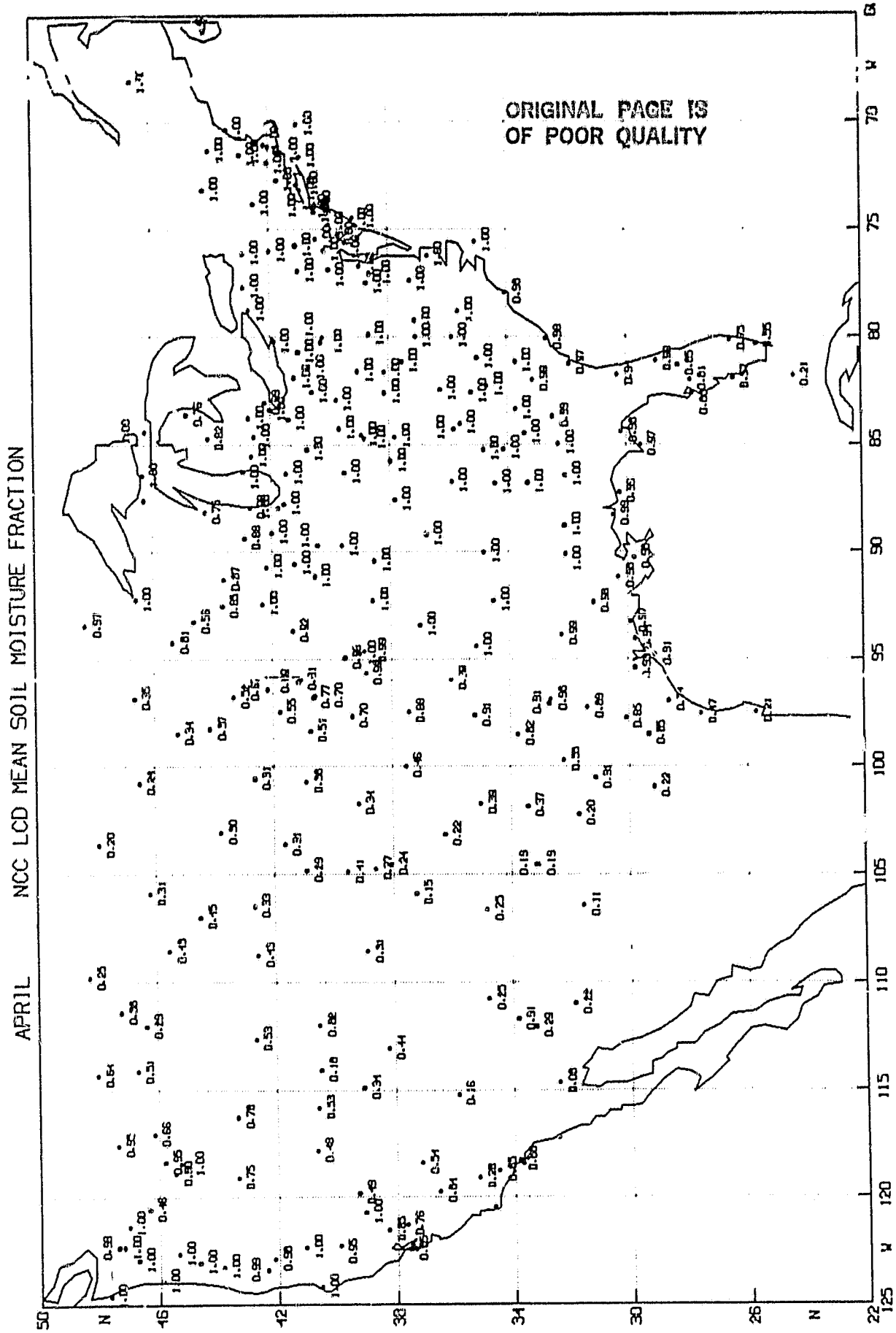


Fig. 5.a.6

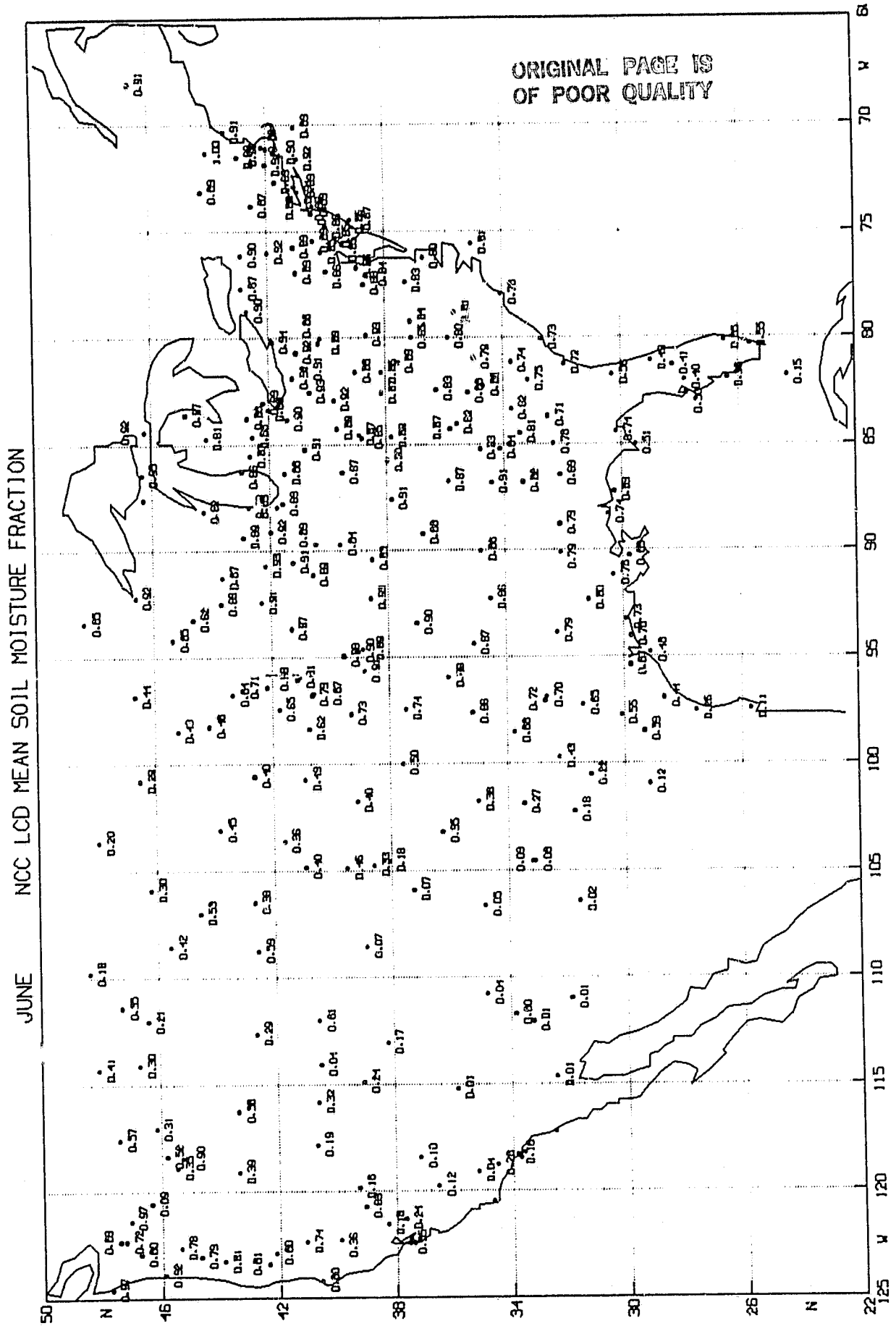


Fig. 5.a.7

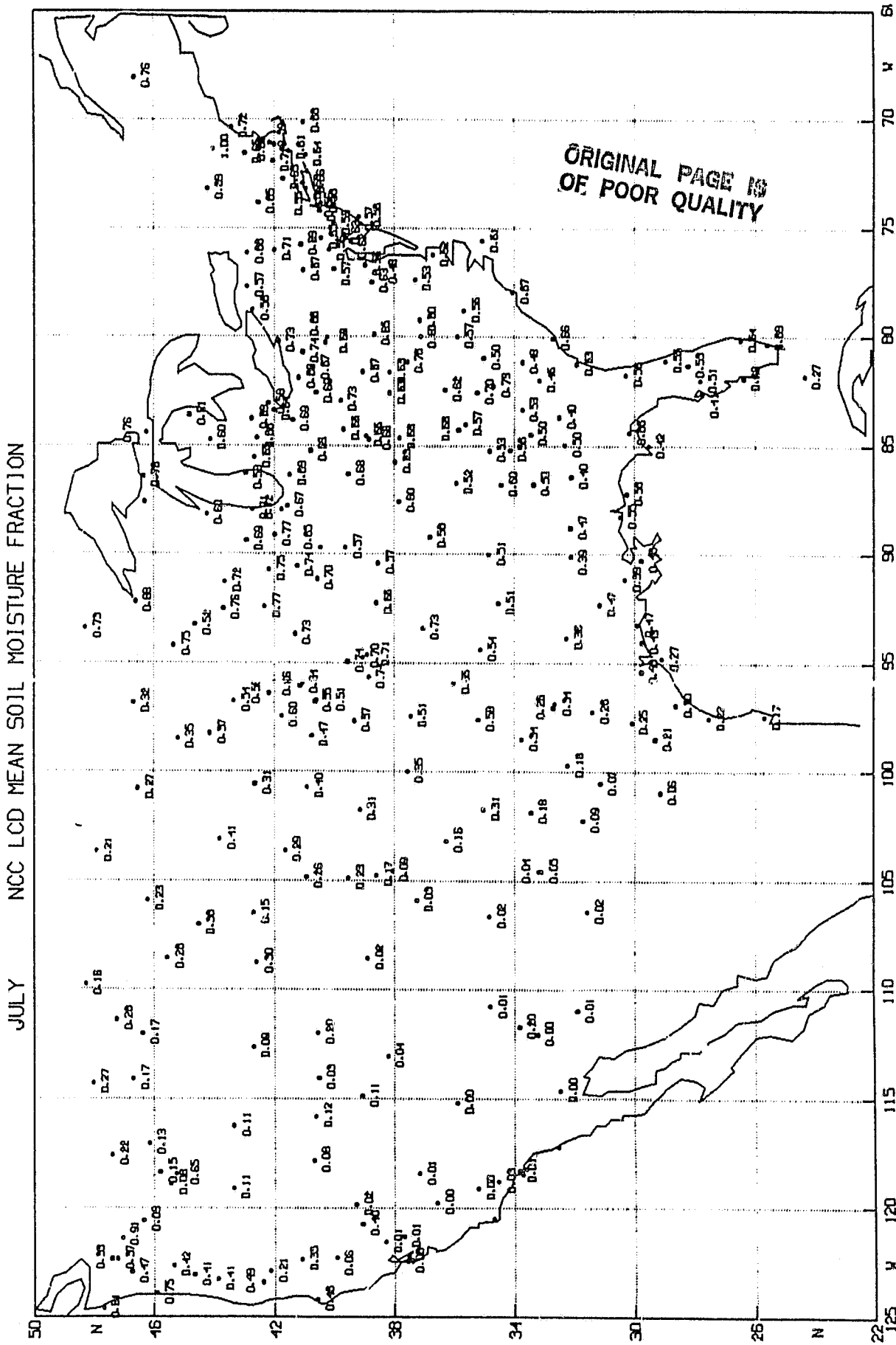


Fig. 5.a.8

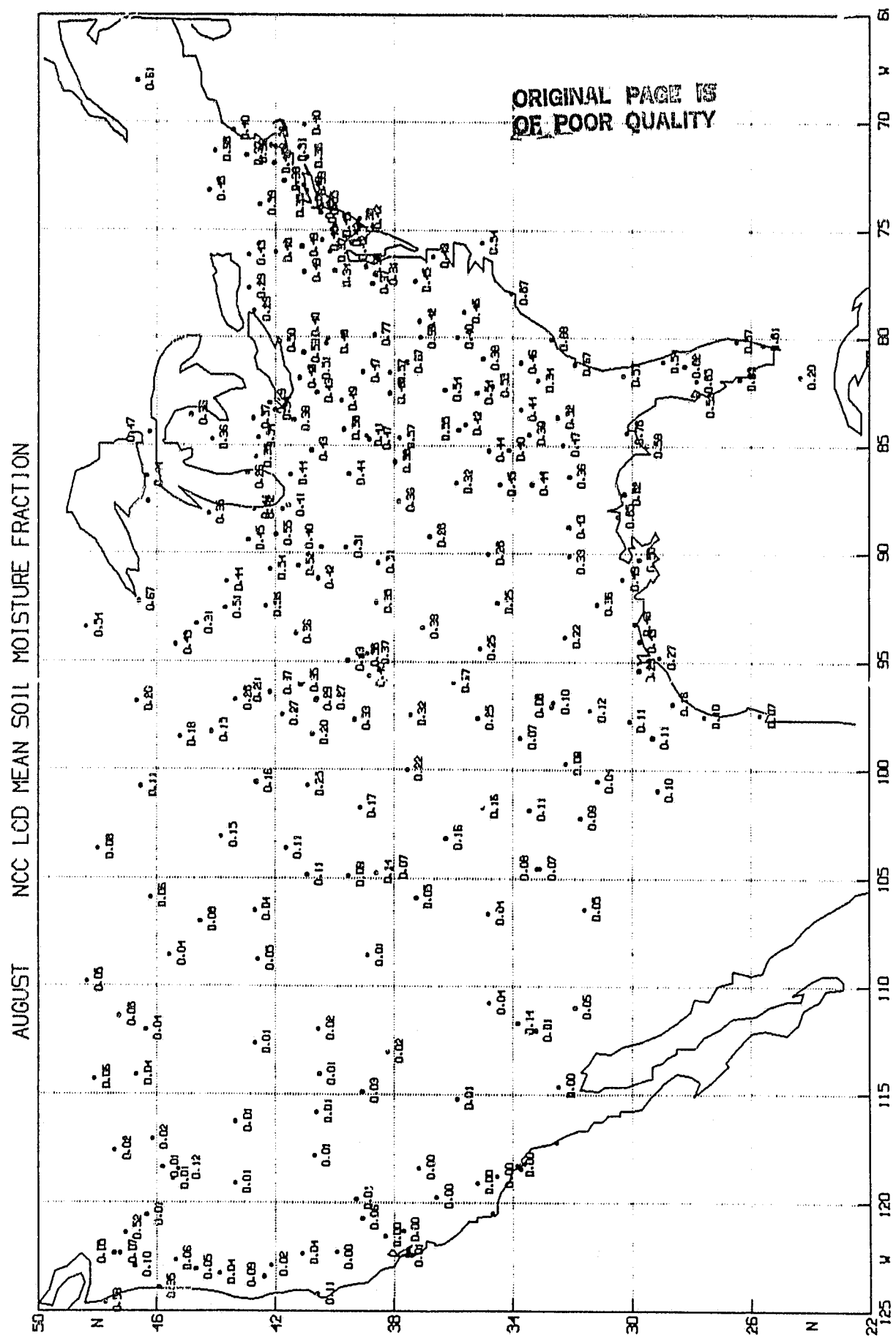


Fig. 5.a.9

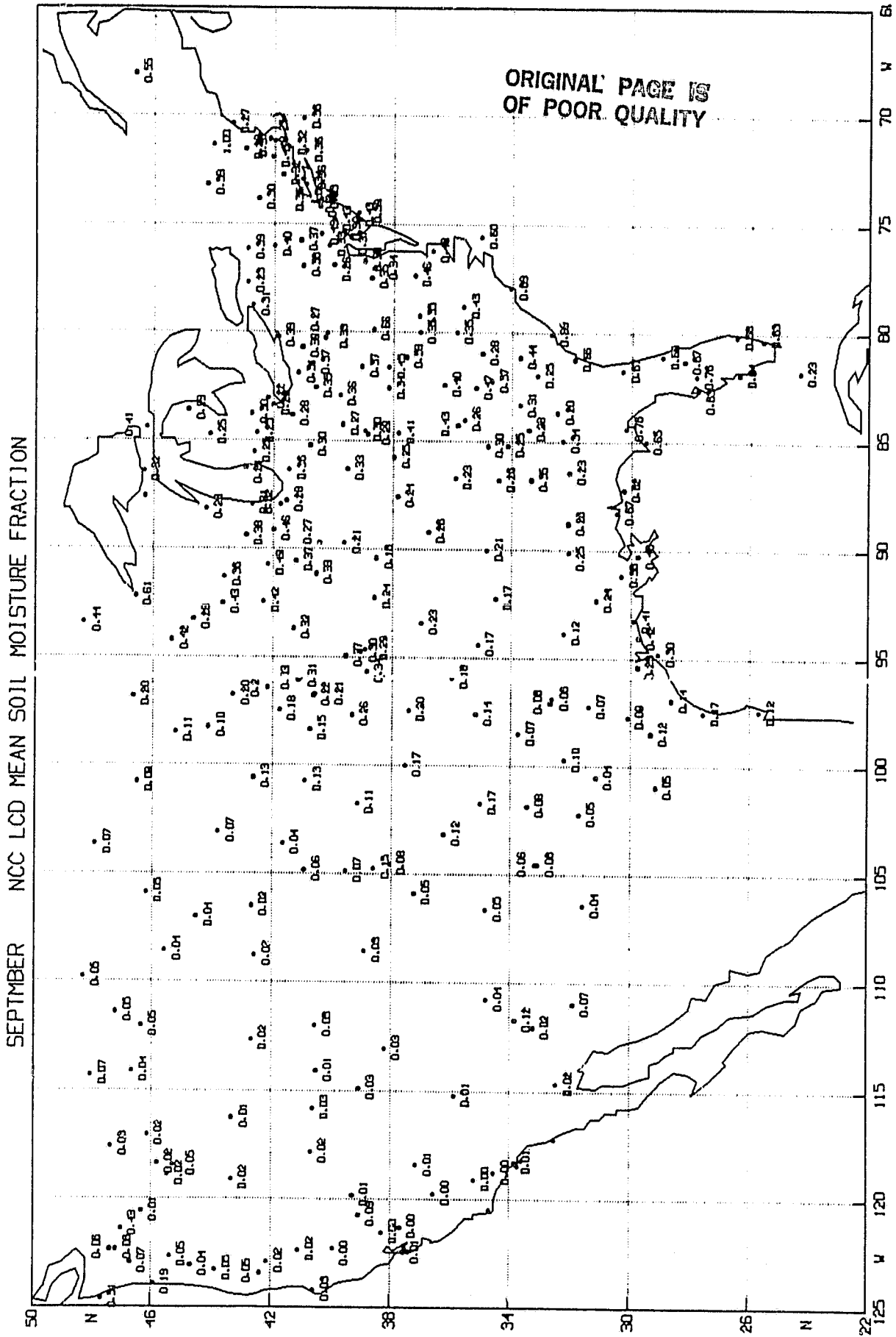


Fig. 5.a.10

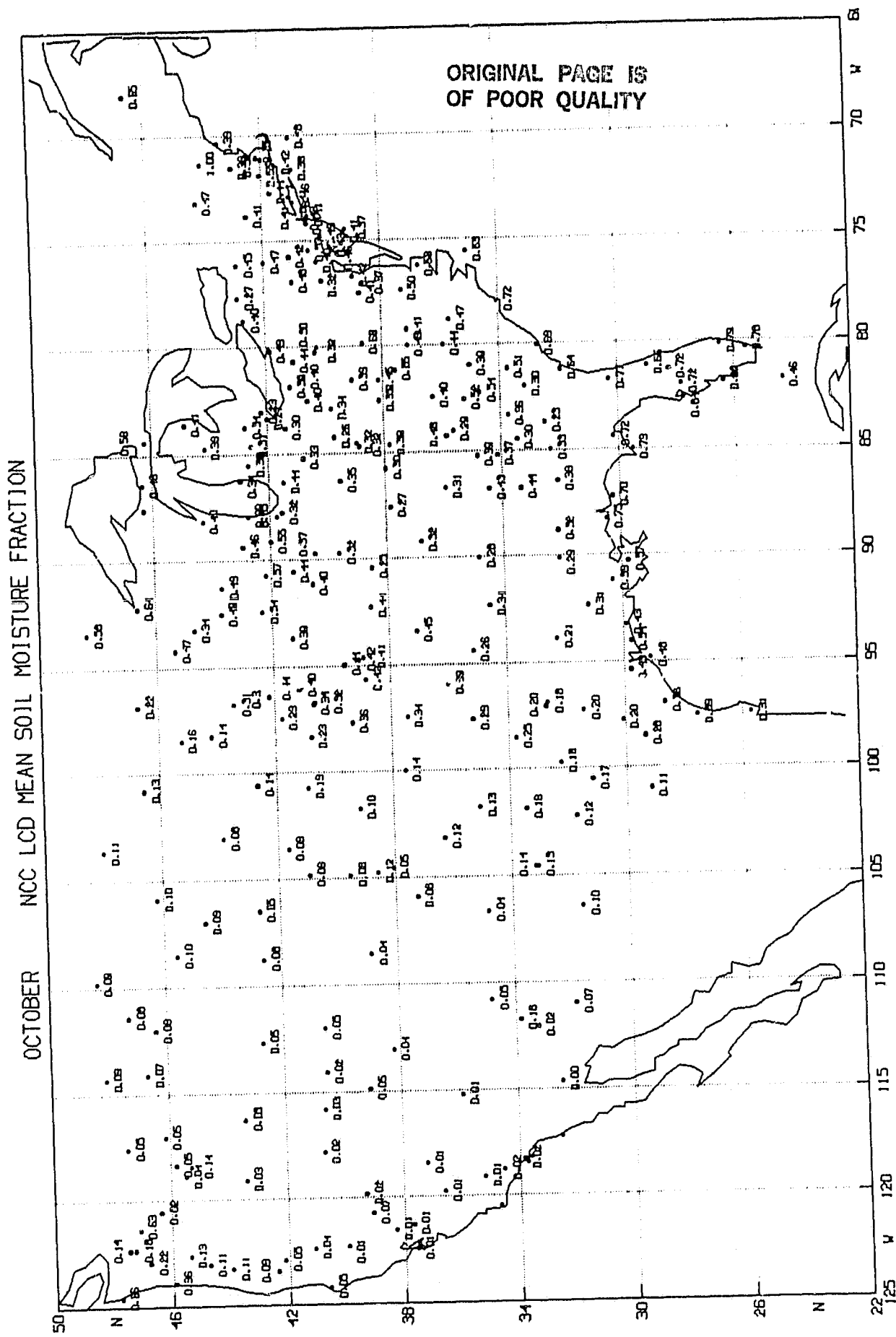


Fig. 5.a.12

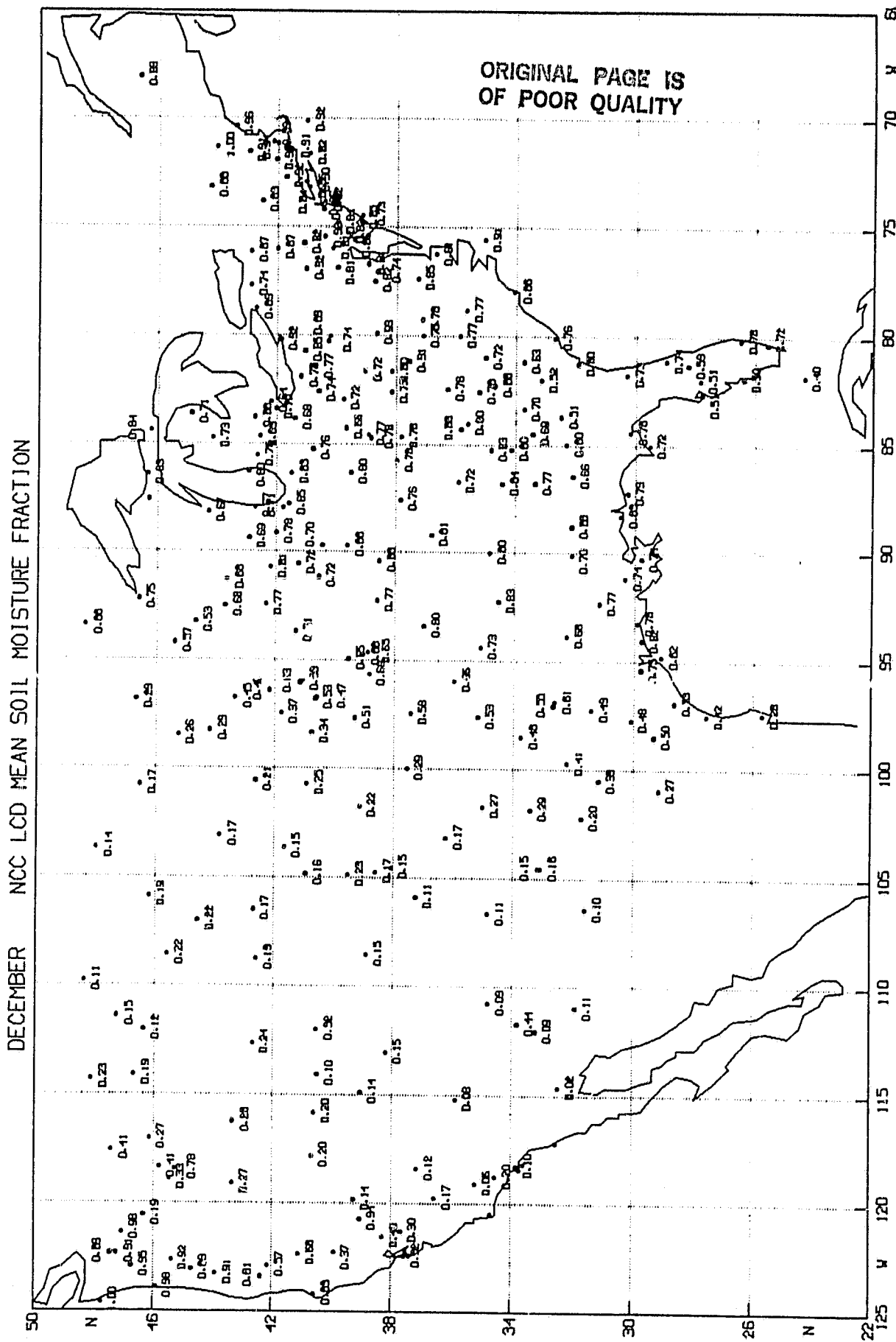


Fig. 5.b.1

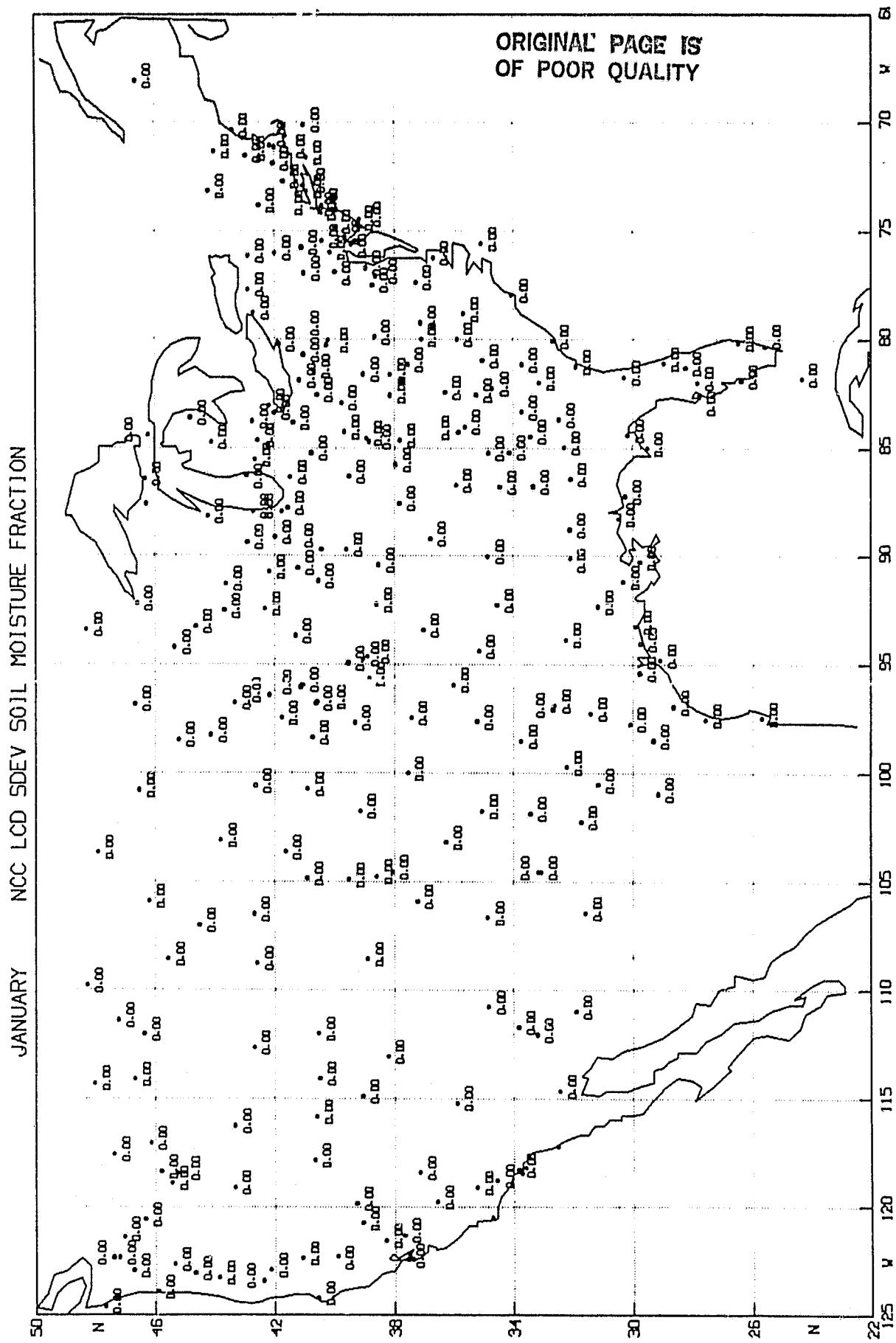


Fig. 5.b.3

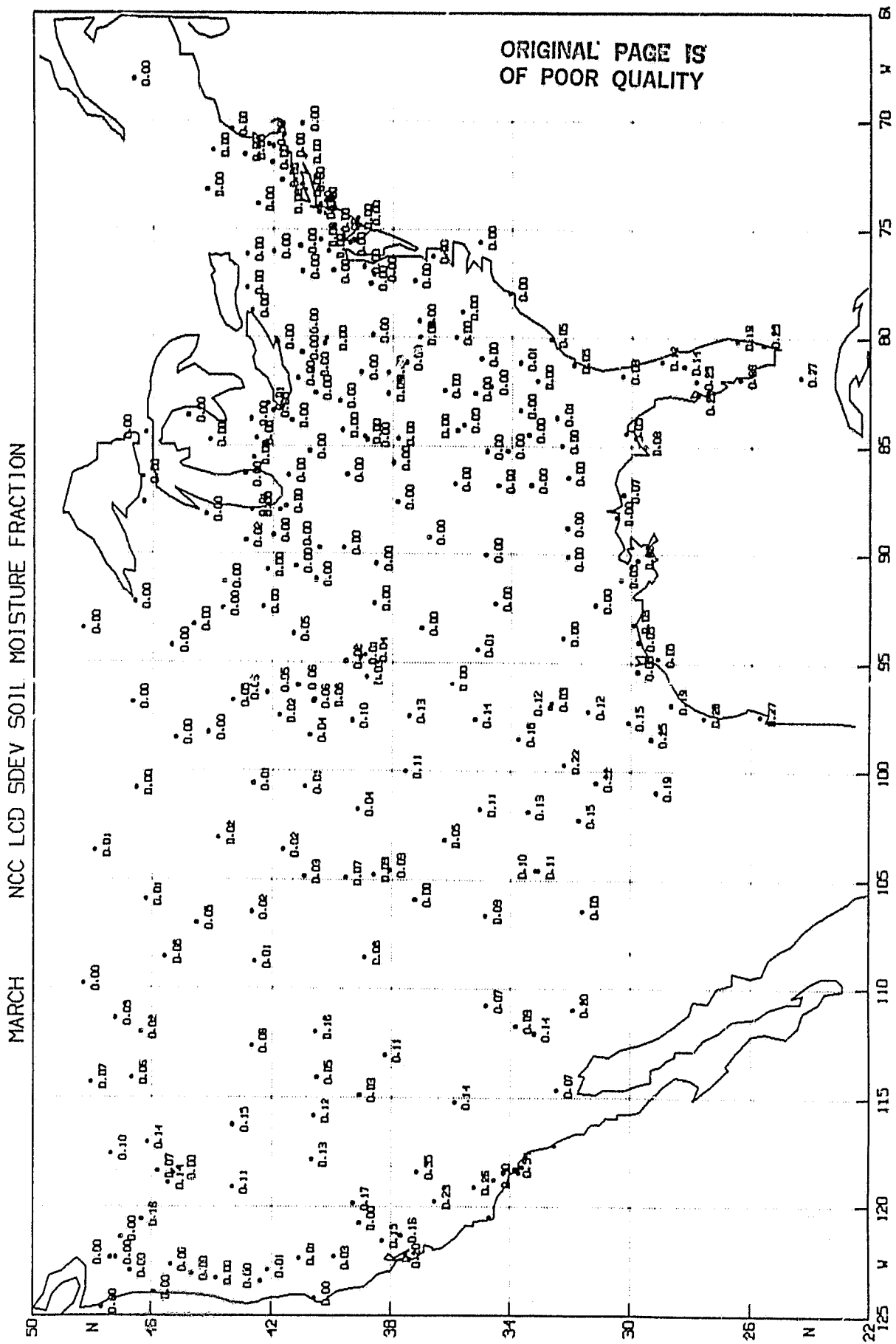


Fig. 5.b.4

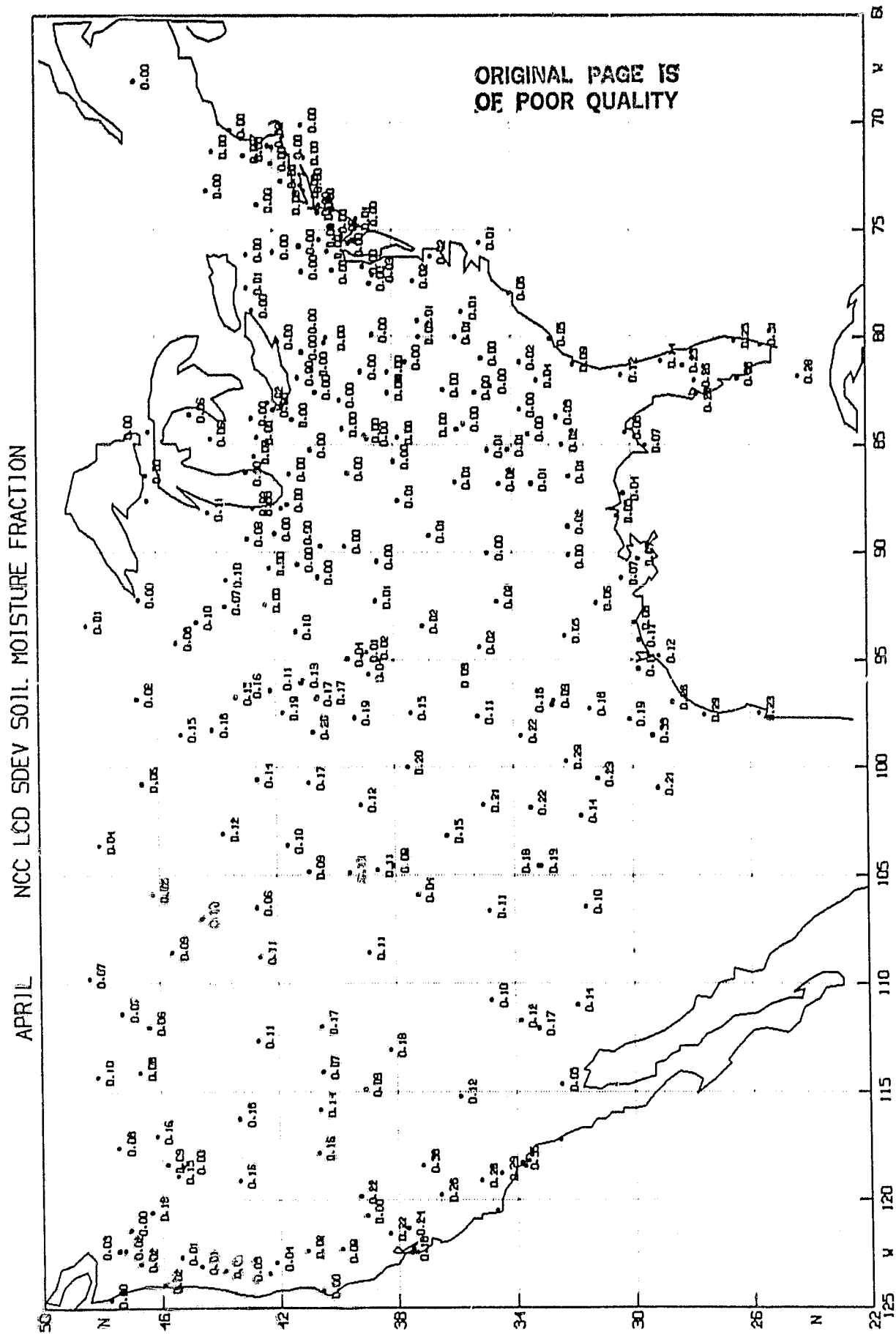


Fig. 5.b.6

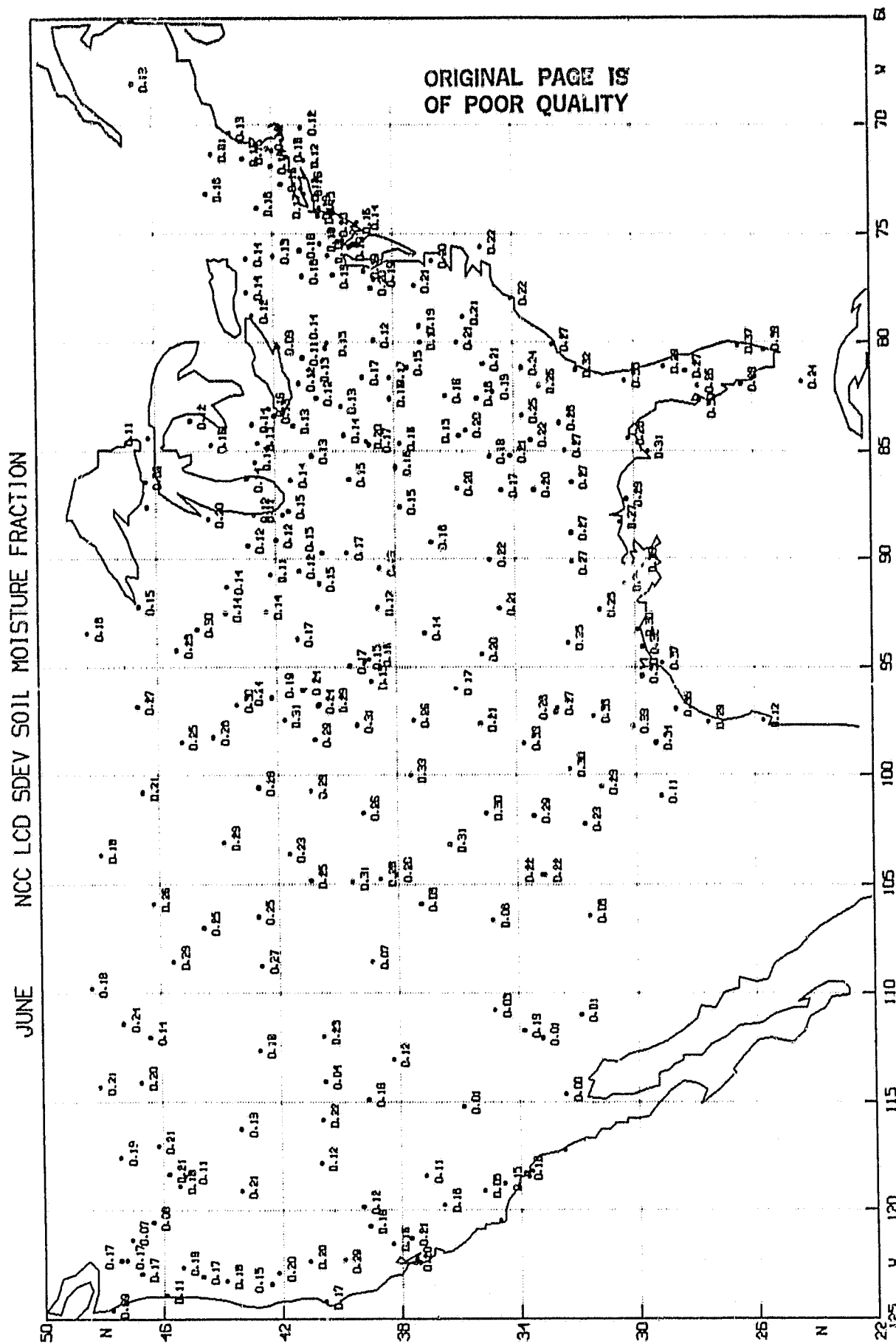


Fig. 5.b.7

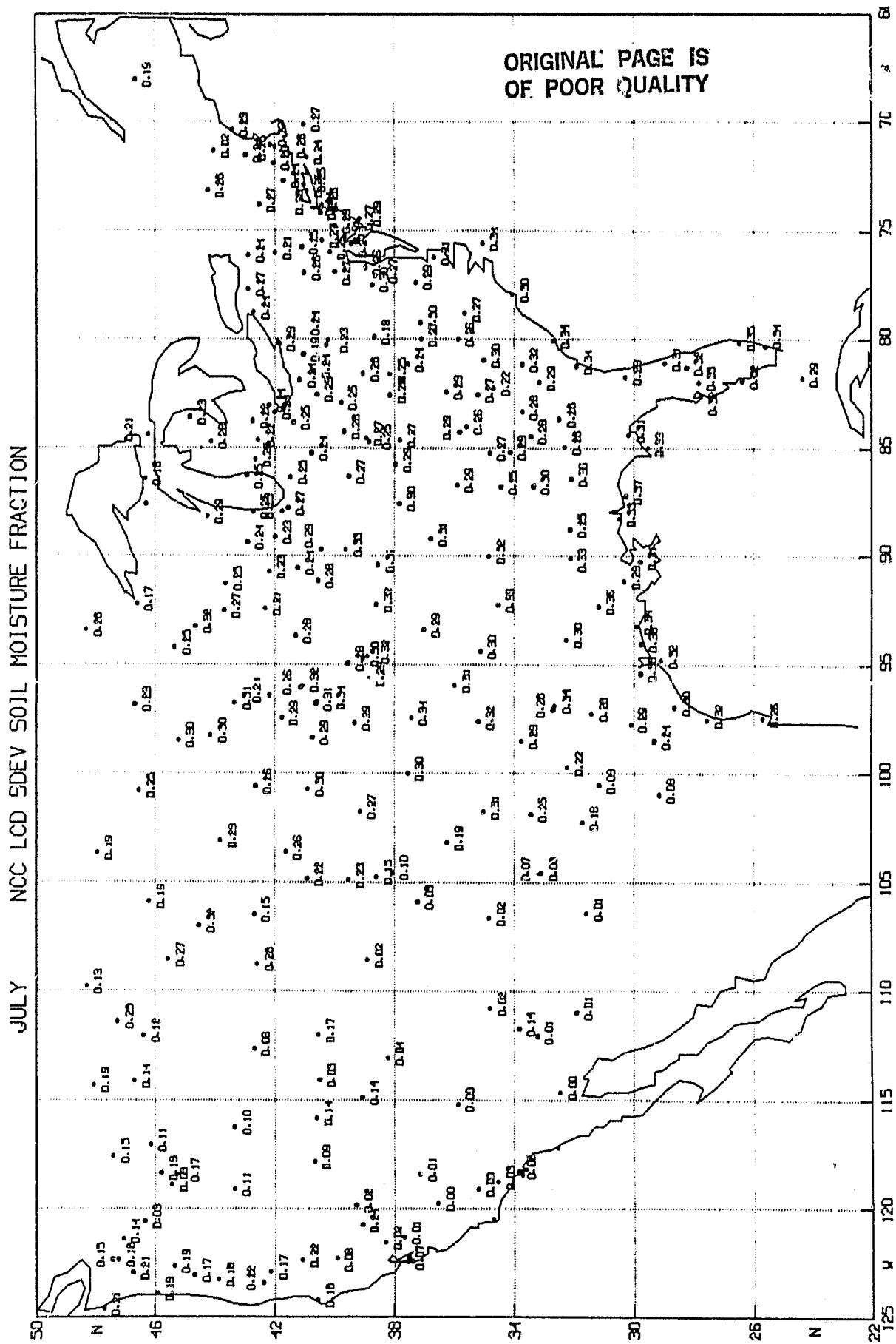


Fig. 5.b.9

SEPTEMBER NCC LCD SDEV SOIL MOISTURE FRACTION

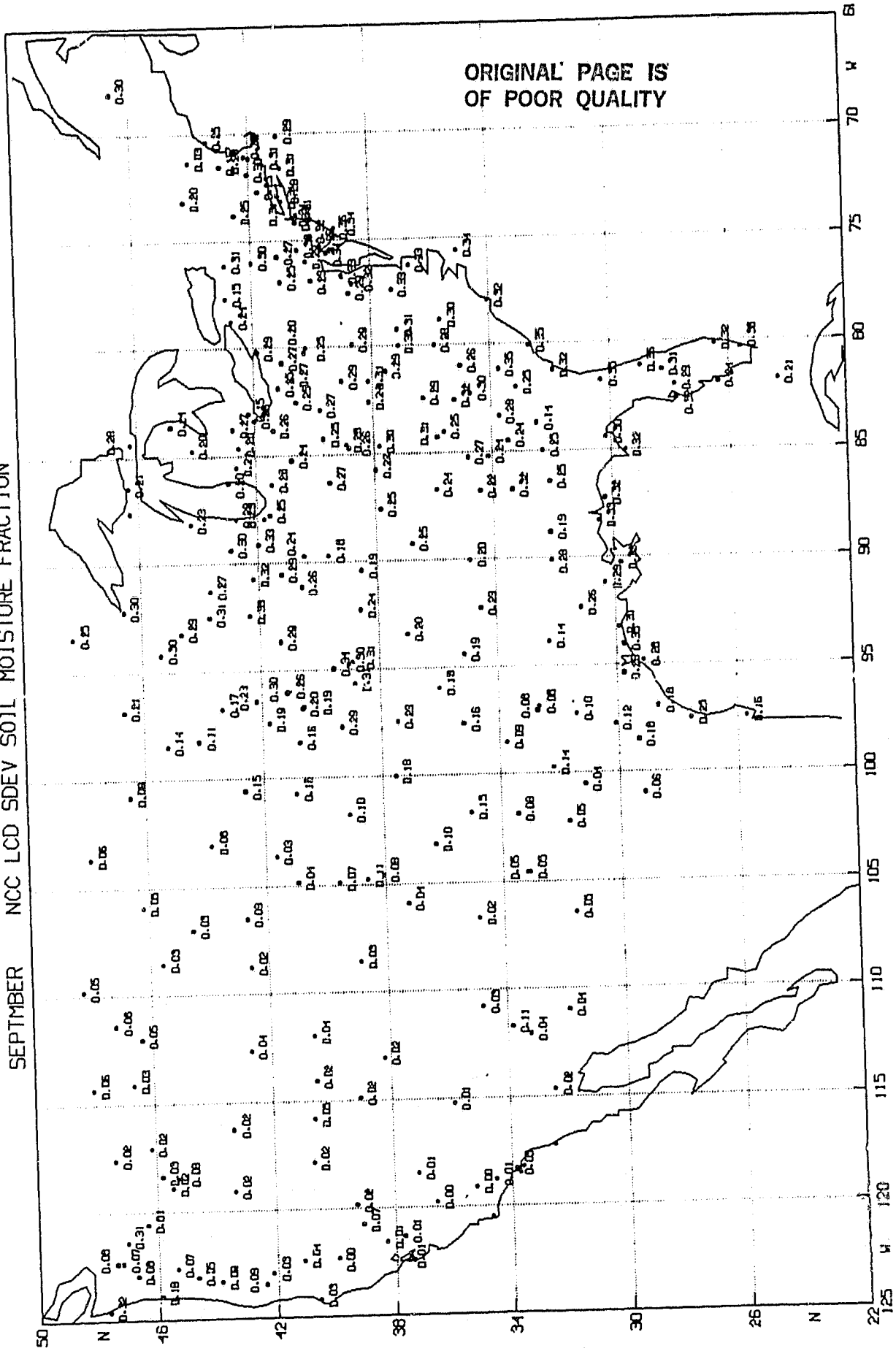


Fig. 5.b.10

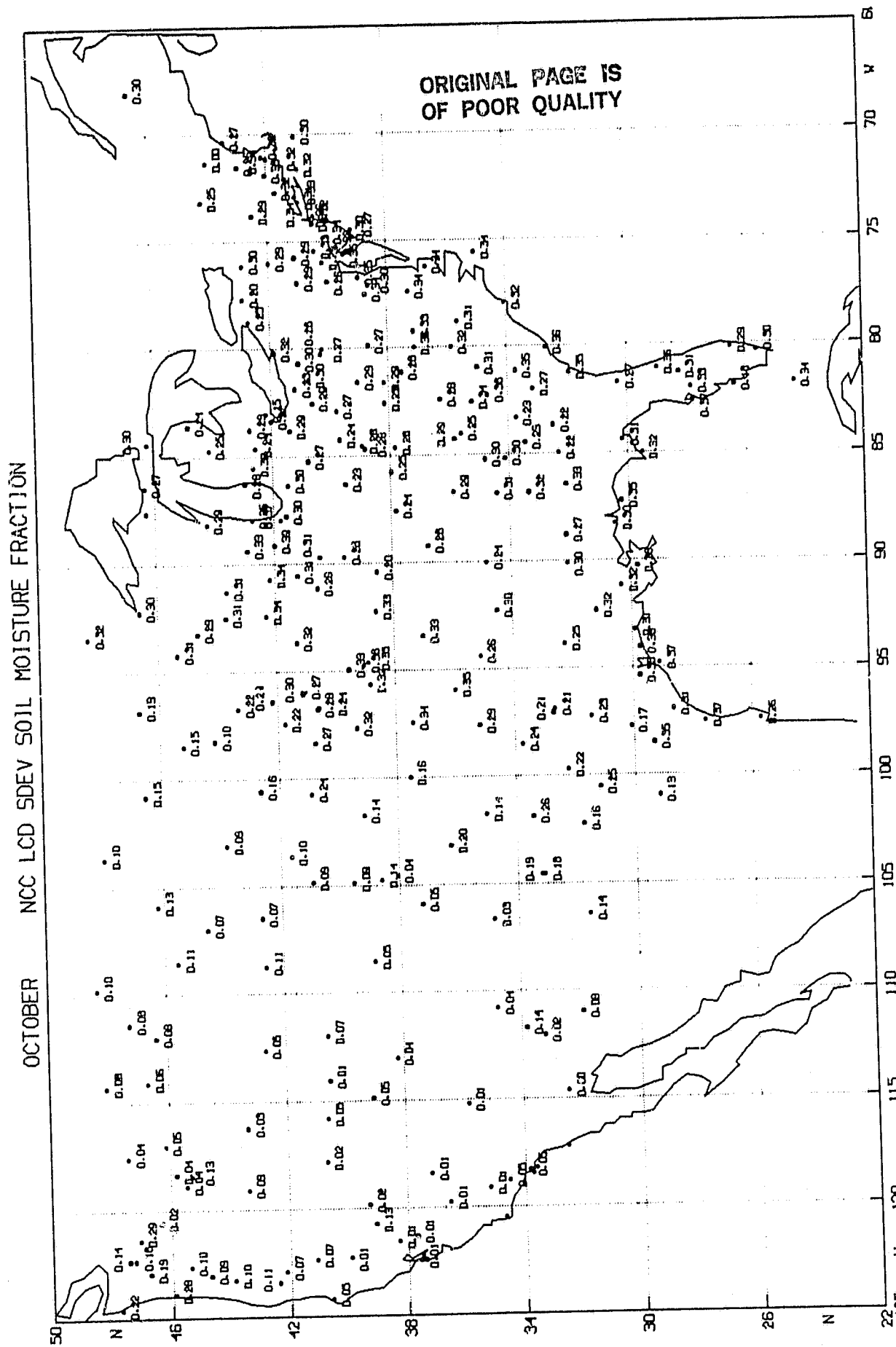


Fig. 5.b.11

NOVEMBER NCC LCD SDEV SOIL MOISTURE FRACTION

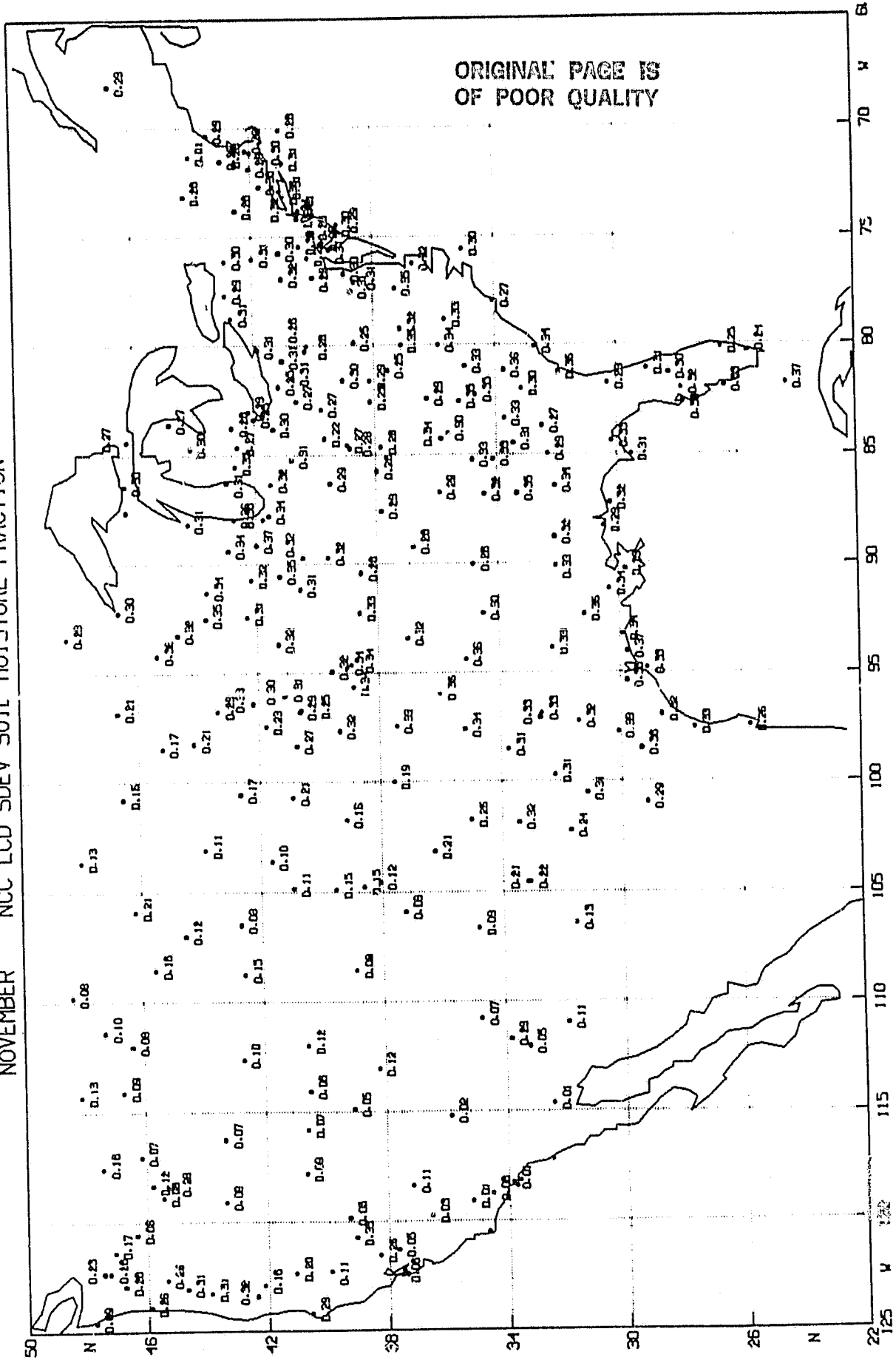
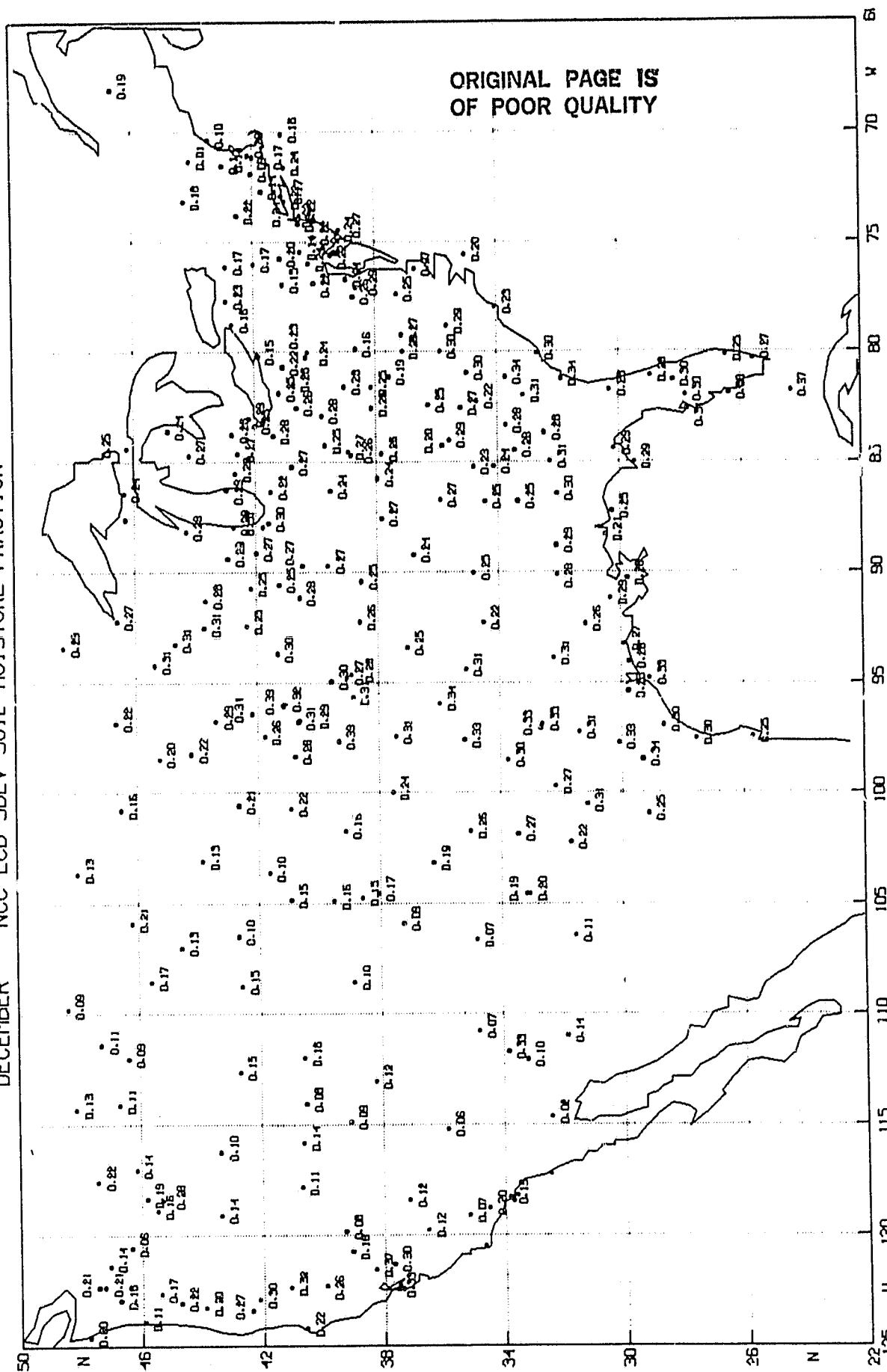


Fig. 5.b.12

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.

PRECEDING PAGE BLANK NOT FILMED

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:

$$P = E + C_m \quad (1)$$

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 anomalies (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:

$$h = C_p T + gz + Lq \quad (2)$$

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 $C_p T$ term. The increase in the $C_p T$ 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 calculated antecedent soil moisture and evapotranspiration fields do not use the future precipitation or surface temperature data. This ensures that the correlations are truly 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.

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:

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

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,

ORIGINAL PAGE IS
OF POOR QUALITY

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 χ^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 ($w^* \approx 150$ 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.

ORIGINAL PAGE IS
OF POOR QUALITY

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

ORIGINAL PAGE IS
OF POOR QUALITY

- 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.

ORIGINAL PAGE IS
OF POOR QUALITY

- Thorntwaite, 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.

FIGURE LEGENDS

ORIGINAL PAGE IS
OF POOR QUALITY

- 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

PRECEDING PAGE BLANK NOT FILMED

ORIGINAL PAGE IS
OF POOR QUALITY

TABLE II.A

NORMALIZED CONTINGENCY TABLES FOR C48S

MONTHLY PRECIPITATION WITH ANTECEDENT PRECIPITATION

MAY

100	93	100	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

ORIGINAL PAGE IS
OF POOR QUALITY

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 C485

MONTHLY PRECIPITATION WITH ANTECEDENT EVAPOTRANSPIRATION

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

GHISQ= 38.5

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

GHISQ= 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

GHISQ= 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

GHISQ= 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

GHISQ= 14.0

OCTOBER

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

GHISQ= 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

GHISQ= 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	91	99	108	112

GHISQ= 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

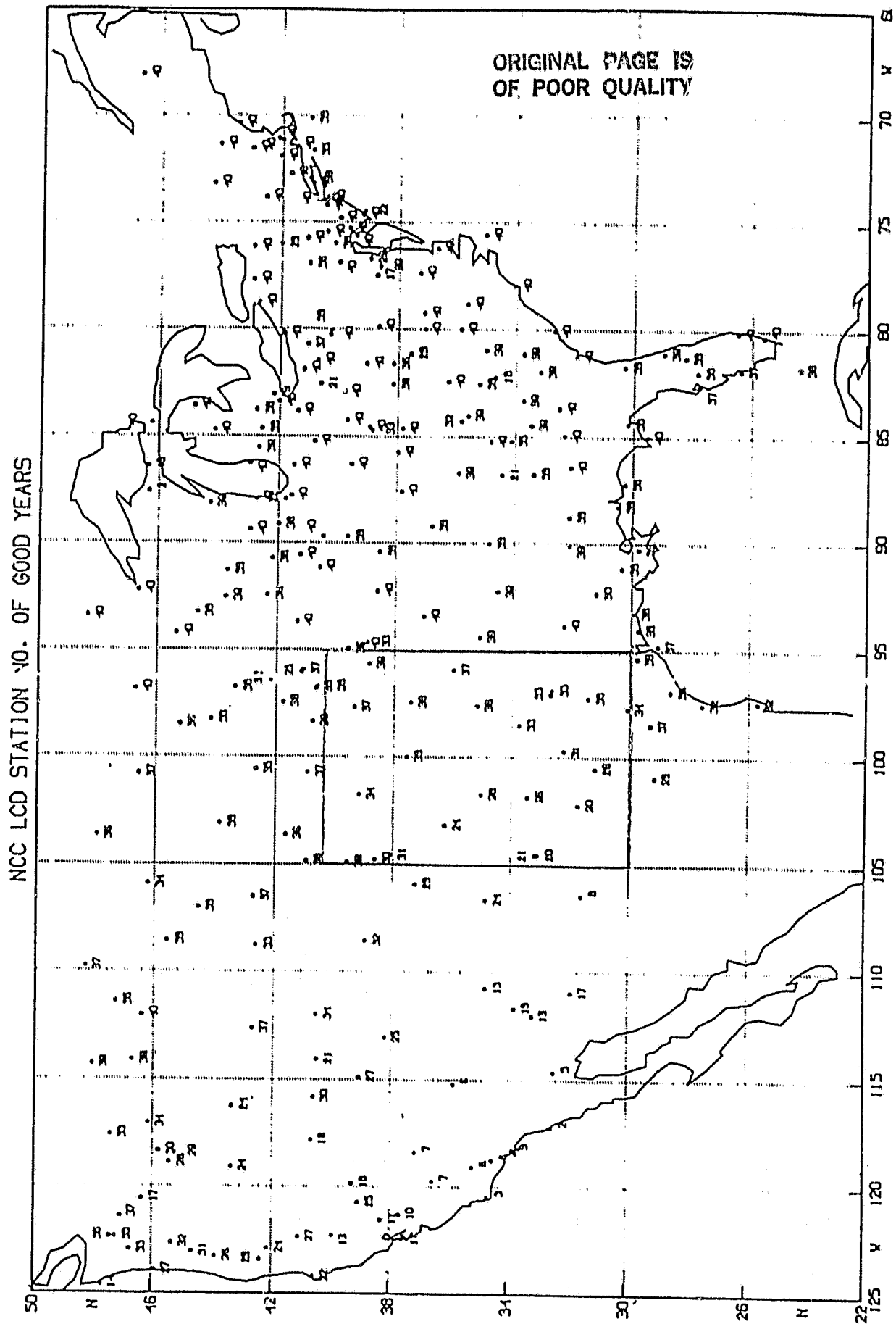
CHISQ= 23.4

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



SEPTMBER NCC LCD MEAN SOIL MOISTURE FRACTION

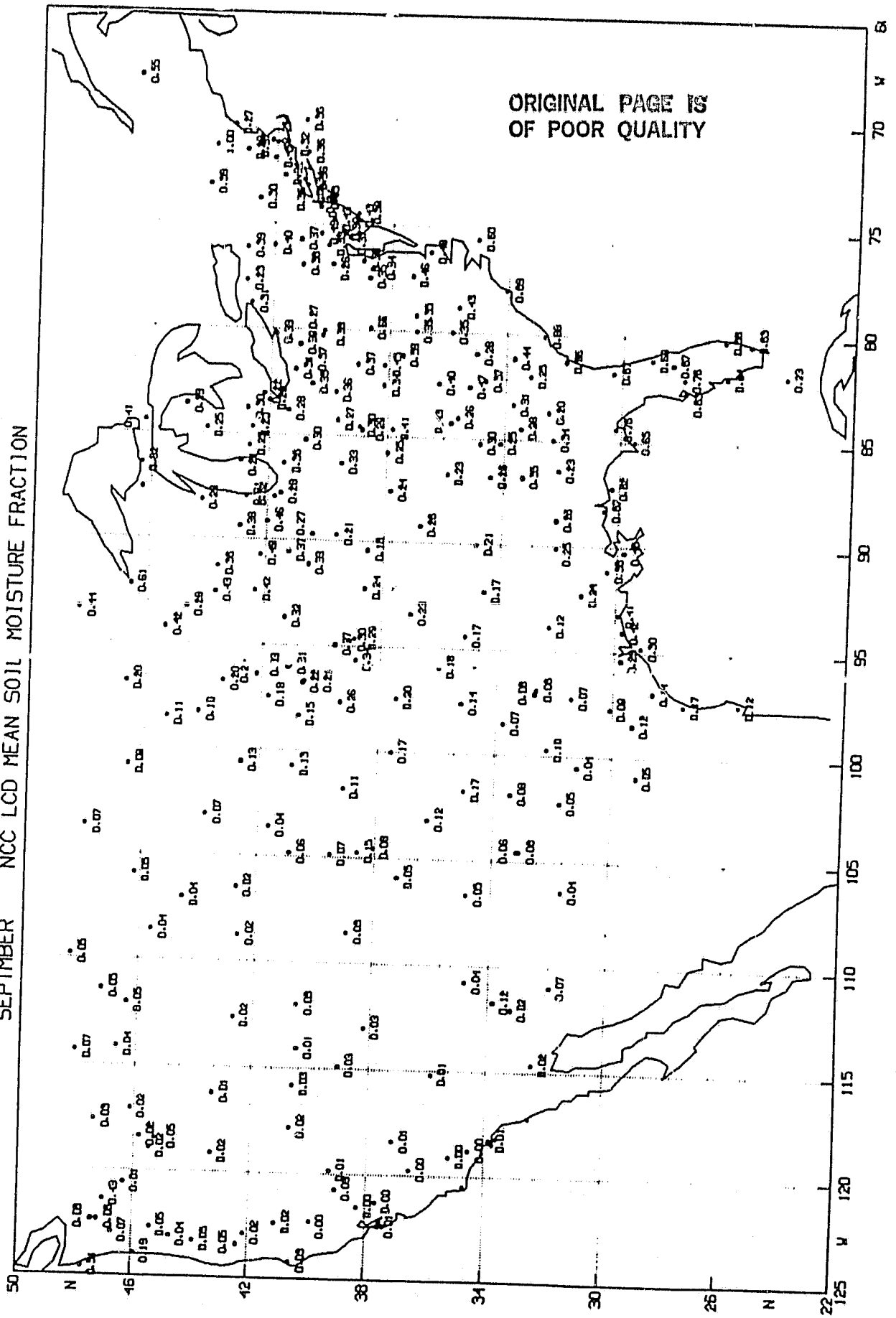


Fig. 2b

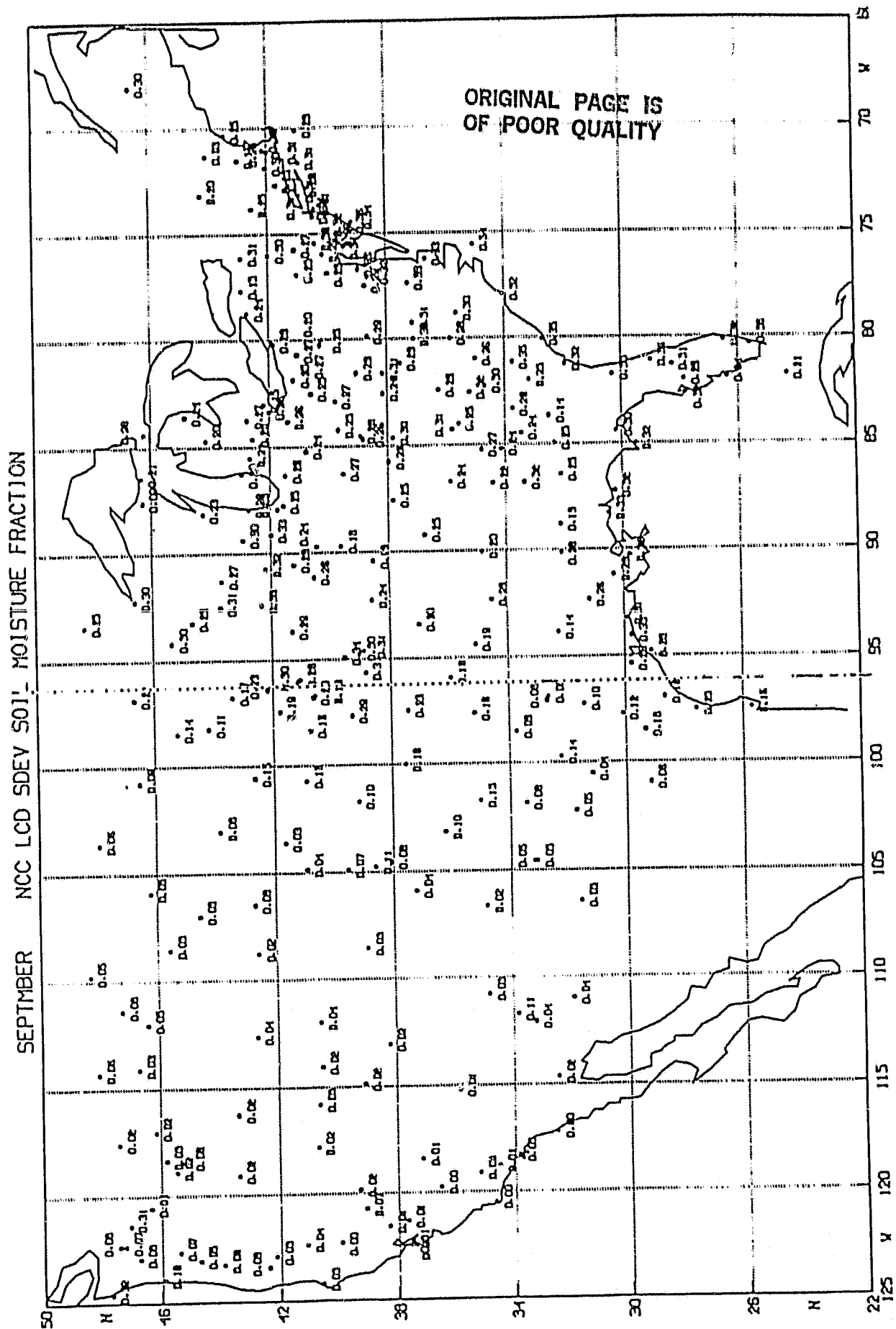


Fig. 3a

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

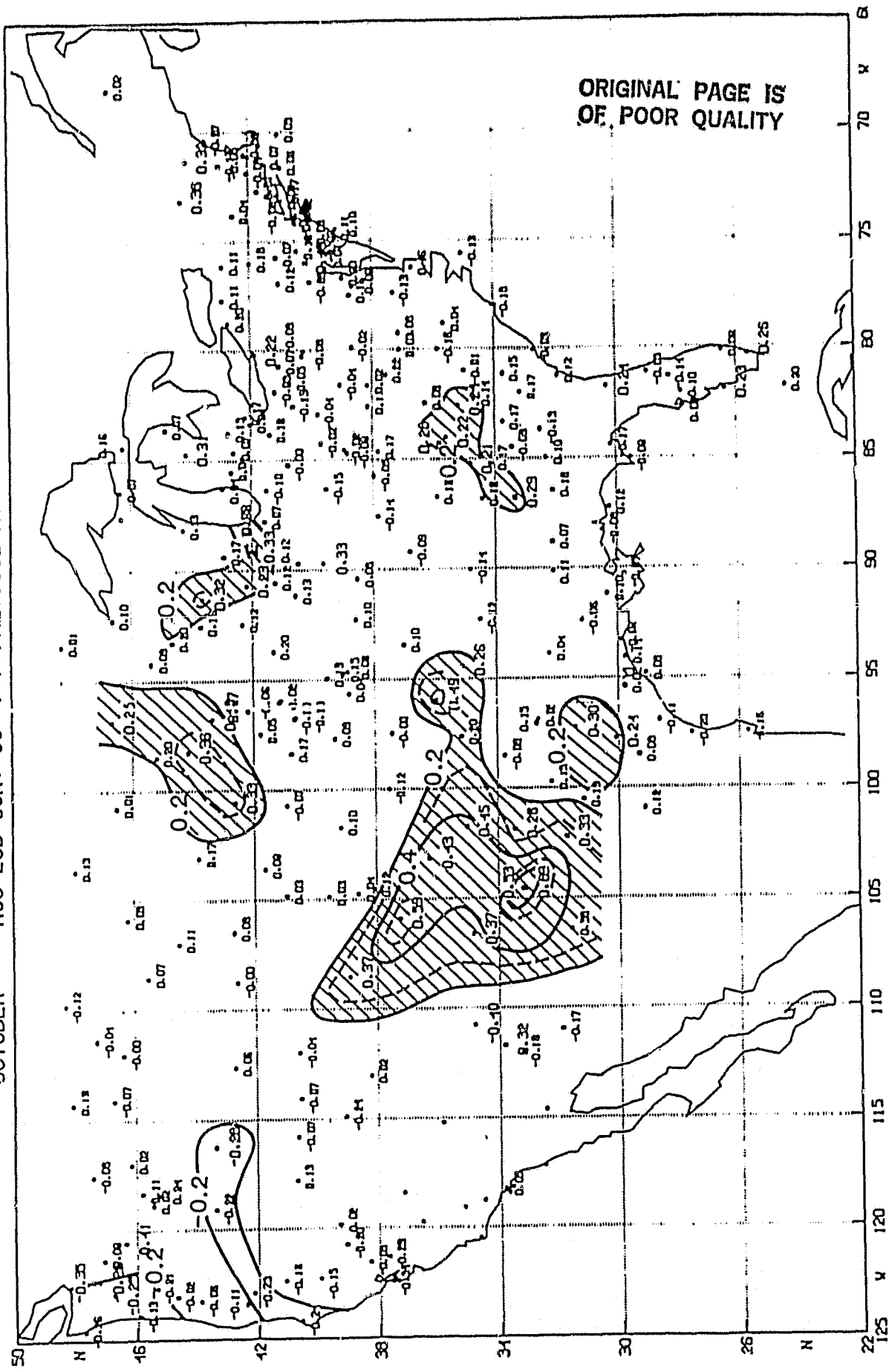


Fig. 3C

OCTOBER NCC LCD COR. CO. PRECIP. - EVAPORATION

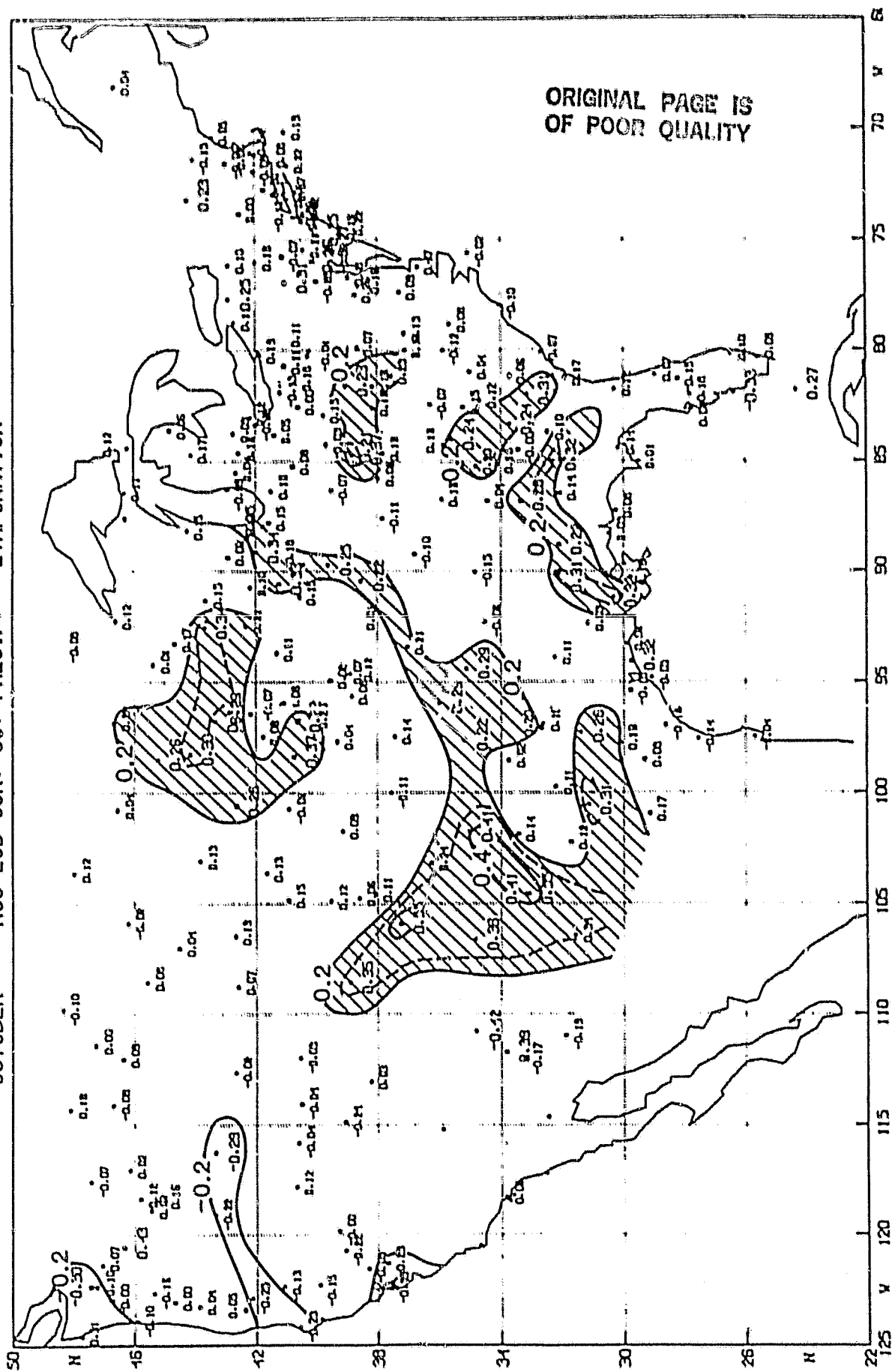


Fig. 4a

ORIGINAL PAGE IS
OF POOR QUALITY

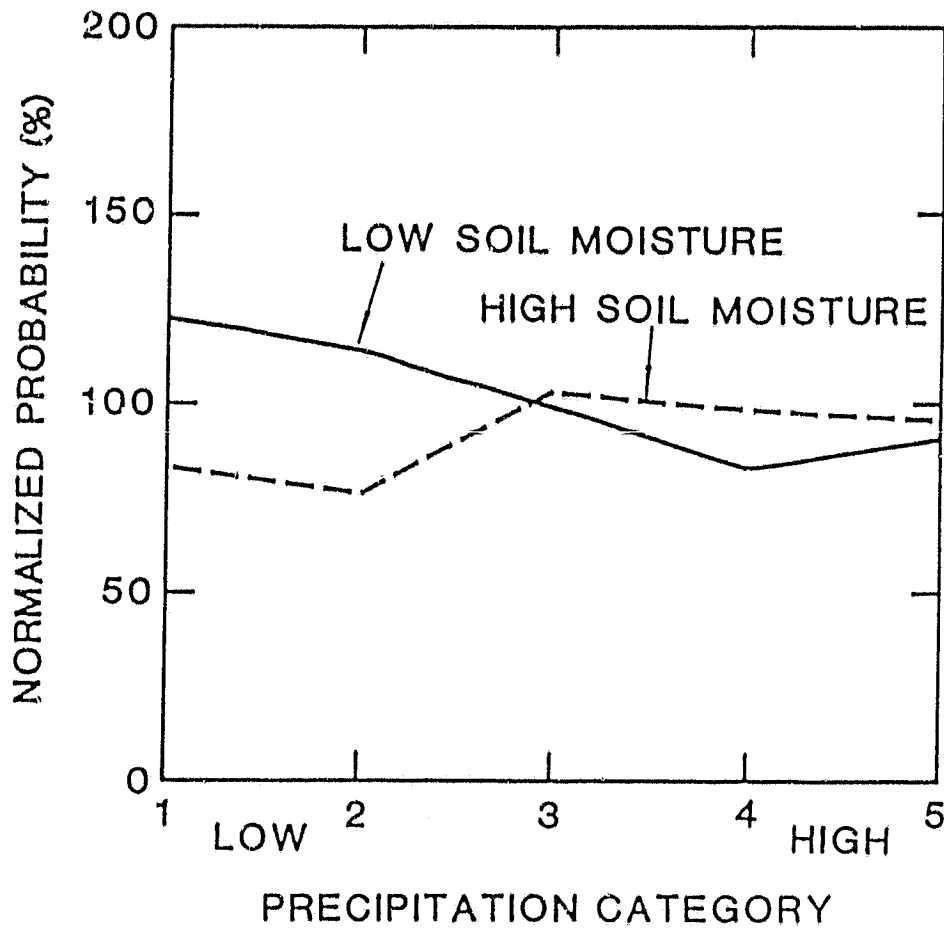


Fig. 4b

ORIGINAL PAGE IS
OF POOR QUALITY

