AFCRL - 67 - 0471

AD661598

THUNDERSTORM PENETRATIONS OF THE TROPOPAUSE, A CLIMATOLOGY AND A METHOD OF ESTIMATION

Michael J. Long

ATMOSPHERIC RESEARCH & DEVELOPMENT CORP.
1600 GENESEE ST., RM. 856
KANSAS CITY, MO. 64102

CONTRACT NO. AF19(628)-5189

Project No. 8624
Task No. 862401
Work Unit No. 86240202

FINAL REPORT

PERIOD COVERED: AUGUST 1965 THROUGH JULY 1967

AUGUST 1967

CONTRACT MONITOR: Arthur J. Kantor
AEROSPACE INSTRUMENTATION LABORATORY

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED. IT MAY BE RELEASED TO THE CLEARINGHOUSE, DEPARTMENT OF COMMERCE, FOR SALE TO THE GENERAL PUBLIC

Prepared for:

AIR FORCE CAMBRIDGE RESEARCH LABORATORIES
OFFICE OF AEROSPACE RESEARCH
UNITED STATES AIR FORCE
BEDFORD, MASSACHUSETTS 01730

87

AFCRL-67-0471

THUNDERSTORM PENETRATIONS OF THE TROPOPAUSE, A CLIMATOLOGY AND A METHOD OF ESTIMATION

Michael J. Long

Atmospheric Research & Development Corp.
1600 Genesee S.. Rm. 856
Kansas City, Mo. 64102

Contract No. AF19(628)-5189

Project No. 8624

Task No. 862401

Work Unit No. 86240101

FINAL REPORT

Period Covered: August 1965 through July 1967

August 1967

Contract Monitor: Arthur J. Kantor

Aerospace Instrumentation Laboratory

Distribution of this document is unlimited. It may be released to the Clearinghouse, Department of Commerce, for sale to the general public.

Prepared for:

AIR FORCE CAMBRIDGE RESEARCH LABORATORIES

OFFICE OF AEROSPACE RESEARCH

UNITED STATES AIR FORCE

BEDFORD, MASSACHUSETTS 01730

Abstract

Data sources for radar measurement of thunderstorm penetrations of the tropopause level outside the United States are listed, and a climatology for North America is presented. Important features are a double maximum over the central and southern United States, a decrease in penetrations around the great lakes, and a few penetrations north of 50 N. Although few penetrations were found outside North America, northeastern China is listed as the next most likely area for large numbers of penetrations.

Two studies suggest that the sole use of low level moisture or the maximum amount of energy available to a storm will not be successful in estimating penetration amounts. An equation of the form $Y=Ae^{-bX}$ was found to fit the cumulative distribution of penetrations at ten United States stations. A method of estimating the cumulative frequency distribution of penetrations based on a determination of the highest penetration and the above equation gave good results. A computer program is included which will determine the highest penetration likely from a sounding.

Table of Contents

Illustrations

Tables

I. Introduction

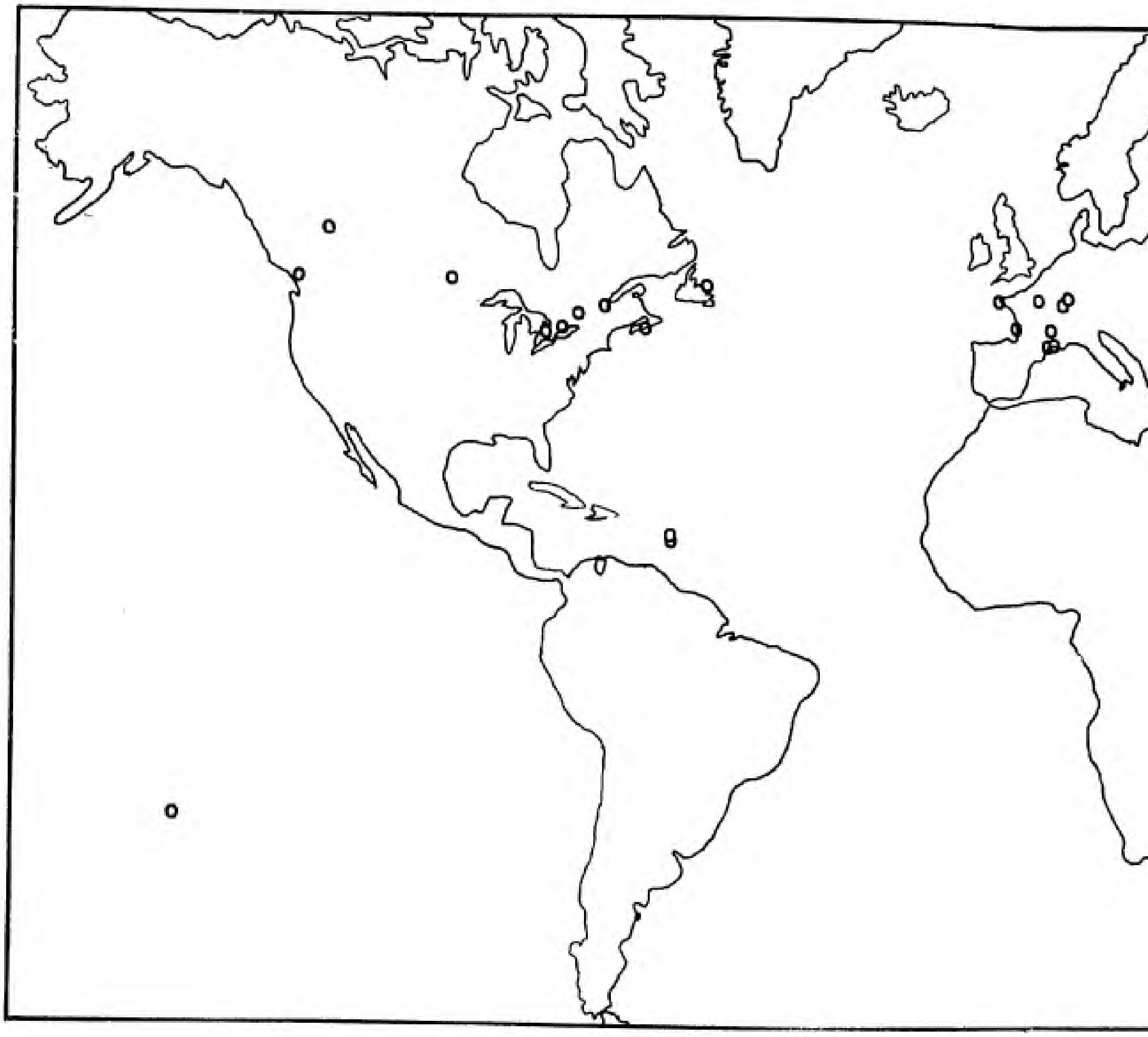
The study of the interaction of strong convection and the tropopause has had a short history, beginning with the developement of continuous radar coverage in the United States five to ten years ago. Information on this problem has been brought up to date by Long et al (1965). The interest in convection-tropopause problems is not confined to the United States, however, and ther is a need for information on the world-wide distribution of thunderstorm penetrations of the tropopause.

This is the final report on this contract and is an extension of the results obtained for the United States by Long (1965), and Long et al (1965). Previous results showed a preliminary climatology of penetrations of the tropopause for ten stations in the United States using a four year data period. Results were summarized on a geographical basis, by months and on an hourly basis. Other studies were done on the number of cloud tops above 60,000 feet, the number of consecutive hours of penetrations, and the number of penetrations outside the United States over a short period of time at a few stations. This report presents similar information from radar stations outside the United States, as well as a method of estimating the vertical distribution of penetrations from a sounding, and a computer program for this type of sounding analysis.

II. Radar Information Outside the United States

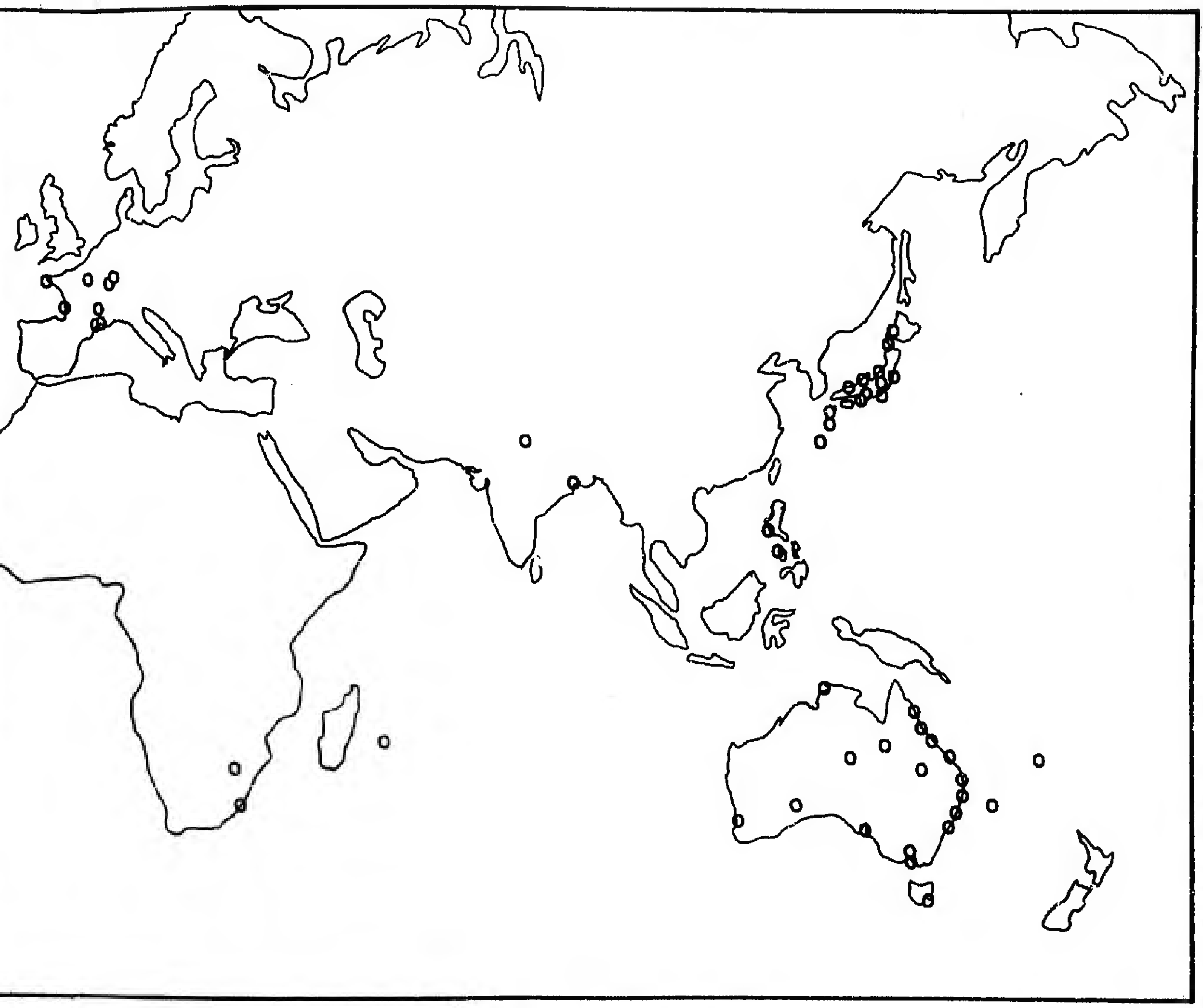
At the beginning of this contract, letters were sent to the meteorological or geophysical agencies of 115 countries throughout the world. A second mailing, smaller than the first, was sent in April and May 1966 to the more important countries that did not answer the first letter. The letter sent in each of the mailings requested information on the existence of original data sheets or logs from routinely operating radar sets with RHI capability. In addition, each country was asked to list the best reference on thunderstorm climatology that was available.

Replies were received from 50 countries. Of these, seven gave positive answers about the radar data sheets. The radar stations in these countries and their dependencies are shown in Fig. 1. The radar locations are also listed in Table 1, with the countries which seemed to have the best data listed first. The Philippines were one of the few countries which sent information to AR & DC, while the French stations may not routinely measure the tops of clouds. There are minor problems with each of the countries, such as the Japanese data being in Japanese, the radar sets in some of the countries having large beam widths, and the possibility that some of the countries take only infrequent or irregular observations. In spite of these difficulties, Table 1 and Fig. 1 represent the only sources of data outside the United States.



A

FIGURE I RADAR DATA SOURCES FOR CLOUD TOP HEIGHTS (o)



B

TS (o)

Table 1: Radar Locations and Types. Locations have been either supplied by the countries involved, or have been estimated (*)

Station Name	Latitude (degrees)	Longitude (degrees)	Set Type	Observations per Day
Philippines				
Manila	14.6N	120.95E	Not Mentioned	Not Mentioned
Baras	13.7N	124.25E	" "	" "
Australia				
Cloncurry	20.67S	140.50E	277	6
Eagle Farm	27.43S	153.08E	277	6
Gladstome	23.85S	151.27E	277	7
Mackay	21.12S	149.17E	277	7
Townsville	19.25S	146.77E	277	9
Cape Byron Isl.	28.63S	153.63E	Marconi SNW51	7
Lord Howe Isl.	31.52S	159.07E	277	8
Sydney	33.87S	151.03E	Marconi SNW51	6
Williamstown	32.82S	151.83E	277	6
Laverton	37.87S	144.75E	277	5
Melbourne	37.80S	144.97E	RC 33	5
Hobart Apt.	42.83S	147.50E	277	3
Forrest	30.85S	128.10E	277	no routine RAREPS
Guildford	31.93S	115.95E	277	6
Adelaide Apt.	34.95S	138.53E	277	4
Alice Springs	23.80S	133.88E	277	3, plus extras
Darwin	12.43S	130.87E	277	8
Cairns	16.87S	145.70E	Cossor Radar	6
Charleville	26.42S	146.28E	277	6
Canada				
Halifax	44.6N*	63.6W*	Curtiss-Wright C-Band	Hourly
Toronto	43.7N*	79.5W*	same	same
Winnipeg	49.9N*	97.0W*	same	same
Edmonton	53.3N*	113.5W*	same	same
Gander	49.0N*	54.5W*	Decca 41	same
Quebec City	46.8N*	71.3W*	MR-75	same
London	43.0N*	81.3W*	MR-75	same
Ottawa	45.4N*	75.6W*	MR-75	same
Vancouver	49.3N*	123.0W*	Decca 41	same
India				
New Delhi	28.5N*	77.2E*	CPS/9 (?)	Not Mentioned
Calcutta	22.6N*	88.4E*	CPS/9 (?)	Not Mentioned
South Africa				
Pretoria	25.75S	28.23E	Selenia	Not Mentioned
Durban	29.97S	30.95E	Selenia	Not Mentioned
Japan				
Naze	28.2N*	129.4E*	Not Mentioned	Not Mentioned
Tanegashima	30.5N*	131.0E*	"	"
Osaka	34.8N*	135.4E*	"	"
Matsue	35.5N*	133.0E*	"	"

Table 1, Continued:

Nagoya	35.1N*	136.9E*	Not Mentioned	Not Mentioned
Fukui	36.1N*	136.2E*	"	"
Niigata	37.9N*	139.0E*	"	"
Tokyo	35.6N*	139.8E*	"	"
Sendai	38.2N*	141.0E*	"	"
Hakodate	41.9N*	140.8E*	"	"
Sapporo	43.0N*	141.3E*	"	"
Mt. Fuji	35.3N*	138.7E*	"	"
France				
Paris	48.9N*	2.2E*	"	"
Nancy	48.8N*	6.1E*	"	"
Strasbourg	48.7N*	7.8E*	"	"
Marignane	43.2N*	5.5E*	"	"
Bordeaux	44.8N*	0.8W*	"	"
Brest	48.3N*	4.3W*	"	"
Lyon	45.8N*	4.9E*	"	"
Montpellier	43.7N*	3.9E*	"	"
French Overseas				
Saint Denis	21S*	56E*	"	"
Noumea	22.05S*	166.2E*	"	"
Papeete	17.6S*	149.6W*	"	"
Le Raizet	16.3N*	61.5W*	"	"
Le Lementin	14.6N*	61.0W*	"	"

Table 2 lists other radar locations which have sets in operation and which might be able to collect useful information, but for the reasons listed do not do so now. These radars are located in several different areas where there may be penetrations of the tropopause by thunderstorms, particularly in the tropics. Some of the radars in Table 2 are new with very short records. It is hoped that routine scanning techniques and observation times will be developed in the future so that this valuable operational equipment will provide data useful in research as an additional bonus.

Outside the United States, Germany, Japan, and Canada were the only countries to reply that some organizations, both public and private, had research radars. These research radars, however, do not operate continuously, and only one radar in Germany is being used to study the convection-tropopause problem. Data have been received from the German radar for part of one summer in Bavaria. These data show almost no penetrations of the tropopause level by more than 5,000 ft. This matches the results obtained from USAF CPS/9 radars operating in England and Germany (Long,1965). The reply from India suggests that some research work is being done with the radars at New Delhi and Calcutta, and several papers from Indian sources have been received on thunderstorms, but no useful raw data have been received. Only a few countries sent radar data useful for penetration studies and these results are discussed in the next two sections. This leaves large areas of the world with no data, and information on thunderstorm penetrations over these areas will have to be estimated. A method to make such estimates is discussed later.

Table 2: Radar Locations with Potentially Useful Data. Locations in some cases have been estimated (*)

Station Name	Latitude (degrees)	Longitude (degrees)	Reason for current lack of data
Ireland			
Shannon	52.68N	8.92W	Duration of records only three months. May not use RHI often.
East African Met. Dept			
Nairobi	1.3S*	37.4E*	Antenna tilt is usually not done
Entebbe	0.1N*	32.3E*	Same as Nairobi
Dar es Salaam	6.7S*	39.0E*	Same as Nairobi
Nigeria			
Lagos	7.0N*	3.0E*	No regular observations
Kano	12.0N*	8.6E*	New station April 1966
Switzerland			
Zurich	48.2N*	8.6E*	RHI usually not operating
Geneva	46.2N*	6.2E*	same as Zurich
Malagasy Republic			
Arivonimamo	19.0S*	47.5E*	No systematic records kept
Netherlands			
De Bilt	52.2N*	5.2E*	RHI scope seldom used
New Zealand			
Ohakea	43.4S*	172.7E*	No routine height measurements
Invercargill	46.4S*	168.5E*	Same as Ohakea
Nandi	17.9S*	177.5E*	New set, 1966
Auckland	36.9S*	174.7E*	New set, 1966
Philippines			
Guiuan	11.1N	125.75E	New set, end of 1965
Turkey			
Ankara	39.9N*	32.9E*	Tops might be measured, records kept only one day
Belgium			
Uccle	50.7N*	4.4E*	Original data not available
French Overseas			
Cayenne	4.9N*	52.3W*	New set, 1965-66
Saint Pierre et Miquelon	47.6N*	56.2W*	New set, 1965-66
England			
London	51.4N*	0.2W*	RHI not used

III. A Penetration Climatology of North America

A. Canadian data

During this contract, data from several Canadian stations were received and processed. The stations, the data time periods, amount of outage, and several items of penetration data are listed in Table 3. Station locations, radar set types, and frequency of observations are listed in Table 1.

Table 3: Canadian Radar Stations and Penetration Information.

Station	Data time Period *	Average Outage, Apr. to Oct, %	Avg. Penetrations / yr.	Penetration months
Halifax	Nov 64-Dec 65	40	0	
Ottawa	Aug 63-Dec 65	3	15	Jun 5, Jul 2, Aug 8
Quebec	Apr 64-Dec 65	8	0	
Gander	Dec 63-Dec 65	10	0	
Toronto	Feb 65-Dec 65 (less Sep 65)	6	7	Aug 7
Winnipeg	(only data available are hr/mo with tops over 30,000 ft)			

* Tropopause data N/A 15-30 Jun 65, or after Dec 65, for all stations

The indirect information available from Winnipeg will be discussed in the next part of this section, along with the data from Minneapolis, the station closest to Winnipeg.

There is more uncertainty surrounding the data from Canada than there was for the stations in the United States (Long, 1965) for several reasons. Perhaps the most important reason is that the radiosonde stations used for the tropopause information were much farther away from the radar locations than in the United States, where they were in many cases at the same station.

Sable Island (station number 600) was used for Halifax, Maniwaki (722) for Ottawa, Caribou (712) and Maniwaki (722) for Quebec, Stephenville (815) for Gander, and Buffalo (528) was used for Toronto. All of these stations are 50 to 100 miles from the radar locations, and in some cases the soundings may be more than 100 miles from a thunderstorm top measured by the radar set. These facts, when added to the short records shown in Table 3, and the variety of radars used, suggest a lower quality of data for the Canadian stations than for the United States stations.

Table 3 lists penetrations for only two of the stations, Ottawa, and Toronto. Penetrations occurred during June, July, and August only, and Ottawa had more penetrations than did Toronto. The effect of the great lakes on the distribution of penetrations will be discussed in the next section. Table 4 shows the breakdown of the monthly penetrations in Table 3 according to the amount of the penetration.

Table 4: Average Annual Tropopause Penetrations. 0 = one penetration during 1 yr(Toronto), 2 yrs(Ottawa, Jun, Jul), or 3 yrs(Ottawa, Aug). Figures are cumulative numbers above the heights given.

Station	Amount of penetration, 1000's of ft										
	>5	>6	>7	>8	>9	>10	>11	>12	>13	>14	>15
Ottawa											
Jun	5	3	3	2	2	1	0	0	0	0	0
Jul	2	2	1	1	1	1	1	1			
Aug	8	6	4	3	3	2	0				
Total	15	11	8	6	6	4	2	1	0	0	0
Toronto											
Aug(Total)	7	7	7	3	1						

There was only one penetration of more than 13,000 ft, and none of the tops recorded were higher than 60,000 ft. August is the best month for penetrations.

Most of the penetrations occurred in the evening hours, with Ottawa showing several penetrations as late as the hour begining at 2300 local time. The actual hourly distribution of the penetrations is listed below, using all the penetrations over the two or three year period.

Toronto: 0800 (1), 1700 (1), 1800 (1), 1900 (1), 2000 (1), 2200 (1), 2300 (1).

Ottawa: 0100 (1), 0200 (1), 0700 (2), 1000 (1), 1200 (1), 1600 (2), 1800 (1), 1900 (6), 2000 (7), 2100 (1), 2200 (3), 2300 (4).

Times are begining times of one hour periods, followed by the number of penetrations occurring during the hour. With only a few penetrations to work with, it is debatable whether the hourly maximum at Ottawa is at 2000 local time as shown above, or at an earlier hour. It is possible that the late hour is a function of latitude since Missoula, Mont. also shows an hourly maximum around 2100 local time (Long, 1965).

B. United States data

Detailed discussions of penetrations from several radars in the United States have been given by Long (1965, 1966), and this section will present data from United States radars not treated in the earlier reports. After this has been done, the Canadian and American data will be joined to arrive at the pattern of penetrations over the continent.

During this contract data were processed from four stations; Buffalo, N. Y., Minneapolis, Minn., Oklahoma City, Okl., Little Rock, Ark., and Key West, Fla. The data from each station will be presented in the same manner as the other United States data (Long, 1965). The radar set in each case was the WSR-57.

Table 5 shows the months in which penetrations occurred at the stations, along with those months when the radar outage was such that more than 10% of the tops might have been missed due to outage.

Table 5: Months with penetrations and significant radar outage. 0 = penetrations with good radar coverage. nn = month with radar outage high enough to have missed penetrations equal to or greater than 10% of the number of penetrations already recorded for that month.

Station	Call letters	J	F	M	A	M	J	J	A	S	O	N	D
Buffalo, N.Y.	BUF					0	0	0	0				
Minneapolis	MSP				0	0	0	0'62		0	0		
Oklahoma City	OKC		0	0'61		0	0	0	0	0	0		
Little Rock	LIT		0	0	0'61 '63		0'64		0	0			
Key West	EYW		0	0	0	0	0	0	0	0	0		

No attempt was made to adjust the data for radar outage, and Table 5 is presented as a guide to the completeness of the data. Oklahoma City and Key West have penetrations for nine months of the year, and Buffalo only four months. Only Little Rock appears to have sufficient radar outage to cause doubt about the number of penetrations, and only in May.

Table 6 shows the penetrations at each of the stations for each year. The total number for the three or four year period fits

Table 6: Yearly Total Penetrations. N/O = not in operation.

Station	1961	1962	1963	1964	total penetrations
BUF	N/O	6	4	3	13
MSP	N/O	86	34	45	165
OKC	79	76	146	69	370
LIT	85	43	91	62	281
EYW	120	41	37	5	203

well with the results for other stations in the same geographical area (Long, 1965), and the only station that seems to have an unusual year-to-year variation in penetrations is Key West. The high total for 1961 at Key West may include some spurious tops caused by one of the several problems that caused unusual data for that year. A full discussion of the problems of determining tops is given by Long(1965, 1966).

Table 7 gives the yearly average penetrations for the stations as totals above certain penetration amounts. It should be noted

Table 7: Yearly Average Penetrations. (.5 rounded up) Numbers are totals above penetration levels. 0=1/2 tops in 3/4 years.

	Penetration level																		
Station	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
BUF	4	3	2	0															
MSP	55	47	37	27	21	15	11	9	8	4	2	1	1	0	0	0	0	0	0
OKC	93	80	62	54	42	31	27	21	17	12	10	9	7	5	4	3	2	1	
LIT	72	60	40	34	23	18	14	8	6	4	3	2	0	0					
EYW	50	35	25	20	15	11	7	4	3	2	2	1	0	0					

that Minneapolis has more clouds at higher penetration levels than either Key West or Little Rock. This suggests that the convection that takes place at Minneapolis is more vigerous than at the other two stations, although the other two stations have larger total numbers of penetrations over a years time.

Tables 8 through 12 give the total monthly penetrations as totals above certain penetration levels. All of the stations show a gradual increase in penetrations except Minneapolis, which has a sudden onset of penetrations in April, which is also the month with the highest penetrations found. Little Rock also has the highest penetrations in April, and both Little Rock and Minneapolis have the maximum number of penetrations in May. Oklahoma City, in the middle of the severe thunderstorm and tornado area, has the tallest penetrations and the greatest number of penetrations in May, which is also the month of maximum tornado activity for the area. Key West also has the highest penetrations in May, but June is the month with the largest number of penetrations.

The number and height of penetrations decrease after late spring or early summer, with the exception of a small secondary maximum in both the number and height of penetrations at Oklahoma City in September. Oklahoma City shows more high penetrations than any of the stations. Buffalo shows only a few penetrations for the three year period of record there, and its location at the east end of Lake Erie, and just to the south of Lake Ontario probably is the main cause of the low totals.

Table 8: Total Monthly Penetrations, Buffalo 1962 thru 1964
Numbers are totals above penetration levels.

Penetration Level	J	F	M	A	M	J	J	A	S	O	N	D
8							1					
7					4		4					
6					4		6	1				
5					6		6	1				

Table 9: Total Monthly Penetrations, Little Rock 1961 thru 1964
Numbers are totals above penetration levels.

Penetration Level	J	F	M	A	M	J	J	A	S	O	N	D
18				1								
17				1	1							
16	(not			2	5	1						
15	operating			2	7	1						
14	Feb, Mar			2	9	1	1					
13	1961)			3	13	2	1					
12			4	3	13	2	4	1				
11			7	7	22	6	8	3				
10			8	10	26	6	12	6	1			
9			9	15	28	9	17	7	2			
8			9	27	37	11	28	12	5			
7		1	14	28	46	13	33	13	5			
6		1	19	40	72	22	47	20	12			
5		3	19	51	80	27	60	26	15			

Table 10: Total Monthly Penetrations, Key West 1961 thru 1964
Numbers are totals above penetration levels

Penetration Level	J	F	M	A	M	J	J	A	S	O	N	D
19					2							
18					2							
17					5							
16					6							
15					8	1						
14					10	1						
13					15	1		1				
12					15	2	2	1				
11			1		18	6	4	2				
10			2		22	9	7	5	2			
9			3		25	14	7	11	4			
8		1	4		32	20	11	13	4			
7		1	5	1	35	27	15	15	6			
6		1	7	3	41	34	24	24	10			
5		3	8	4	47	50	45	29	16	1		

Table 11: Total Monthly Penetrations, Minneapolis 1962 thru 1964
Numbers are totals above penetration levels.

Penetration Level	J	F	M	A	M	J	J	A	S	O	N	D
22				1								
21				1								
20				1								
19				1								
18				2								
17				2	2	1						
16				2	2	1						
15				3	3	1						
14				5	8	1						
13				10	13	1	1	1				
12				10	15	2	1	2				
11				10	17	4	1	4	1			
10				12	20	6	5	5	1			
9				12	26	8	11	7	1			
8				12	35	10	16	8	1			
7				15	48	20	17	10	1			
6				18	61	27	24	10	2			
5				18	71	31	28	13	2			

Table 12: Total Monthly Penetrations, Okalhoma City 1961 thru 1964
Numbers are totals above penetration levels

Penetration Levels	J	F	M	A	M	J	J	A	S	O	N	D
22					2							
21					5							
20					7							
19					9	1						
18				1	13	2						
17			1	3	18	3						
16			3	4	23	3						
15			3	5	24	3			1			
14			3	6	29	3			1			
13			5	13	39	6			2			
12			6	16	46	8	1		2			
11			6	25	56	11	4		2			
10		2	9	32	60	12	4		2			
9		2	16	45	70	20	6	1	6			
8		2	16	56	87	28	11	2	10	1		
7		2	19	59	104	29	16	3	12	2		
6		2	25	77	128	44	17	7	15	3		
5		2	26	81	147	57	21	14	18	4		

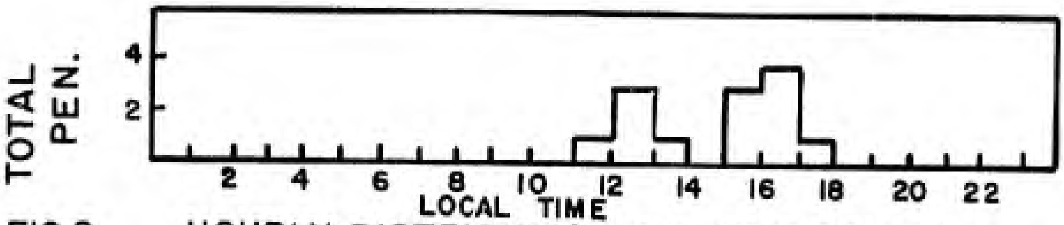


FIG. 2 HOURLY DISTRIBUTION OF TROPOPAUSE PENETRATIONS, BUFFALO, N.Y. (BUF) 1962-1964

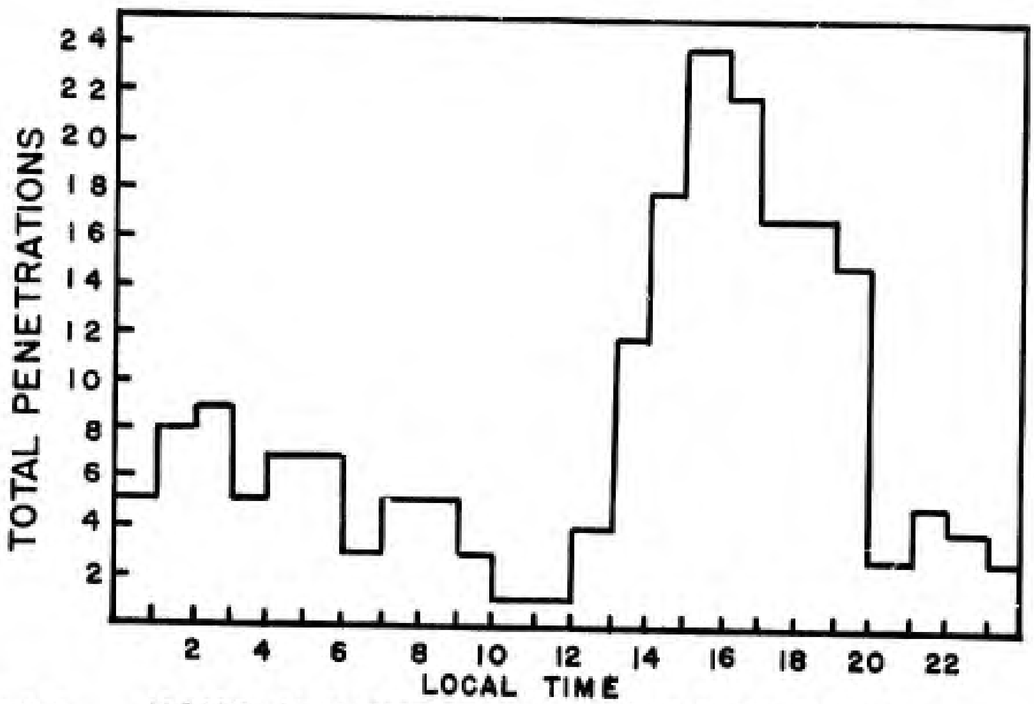


FIG. 3 HOURLY DISTRIBUTION OF TROPOPAUSE PENETRATIONS, KEY WEST, FLA. (EYW) 1961-1964

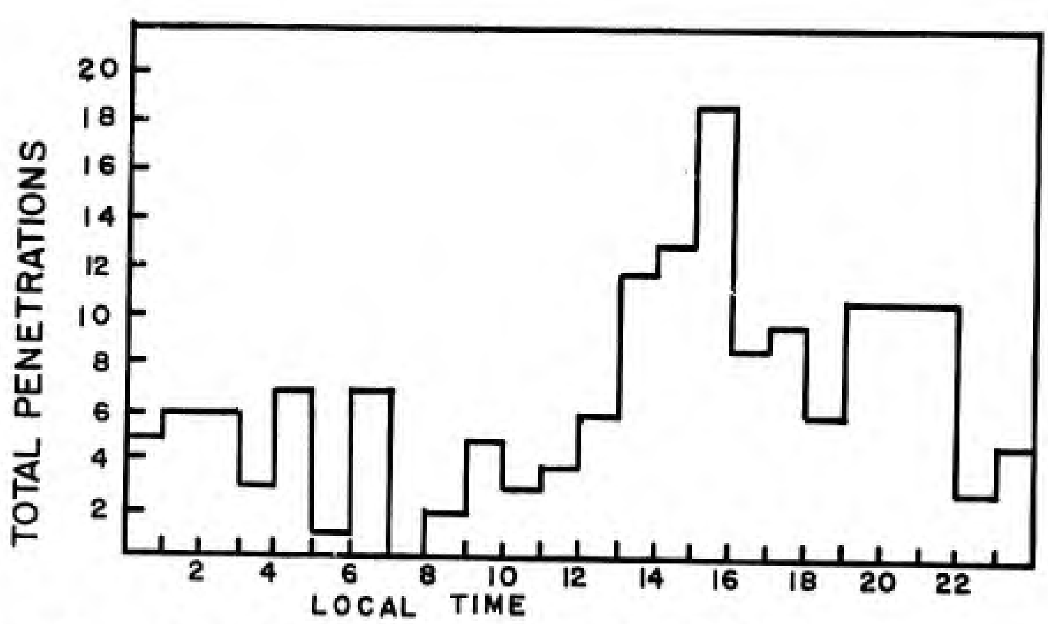


FIG. 4 HOURLY DISTRIBUTION OF TROPOPAUSE PENETRATIONS, MINNEAPOLIS, MINN. (MSP) 1962-1964

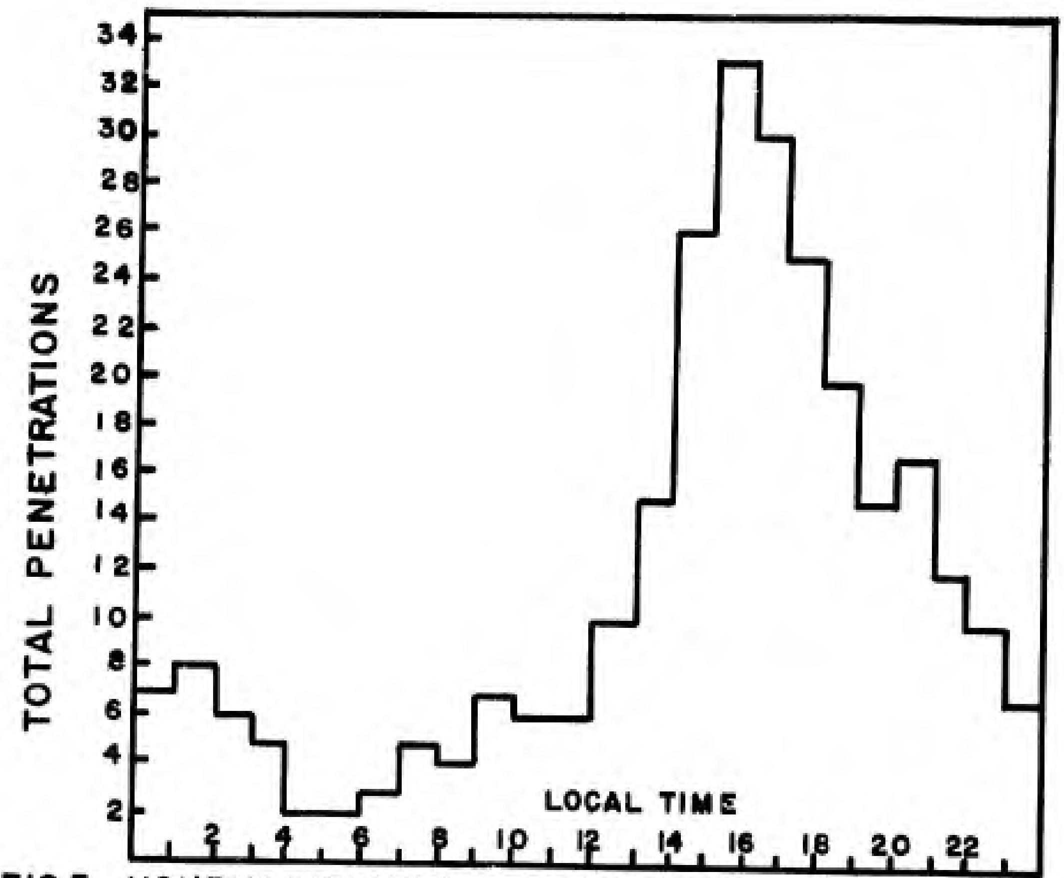


FIG.5 HOURLY DISTRIBUTION OF TROPOPAUSE PENETRATIONS, LITTLE ROCK (LIT) 1961-1964

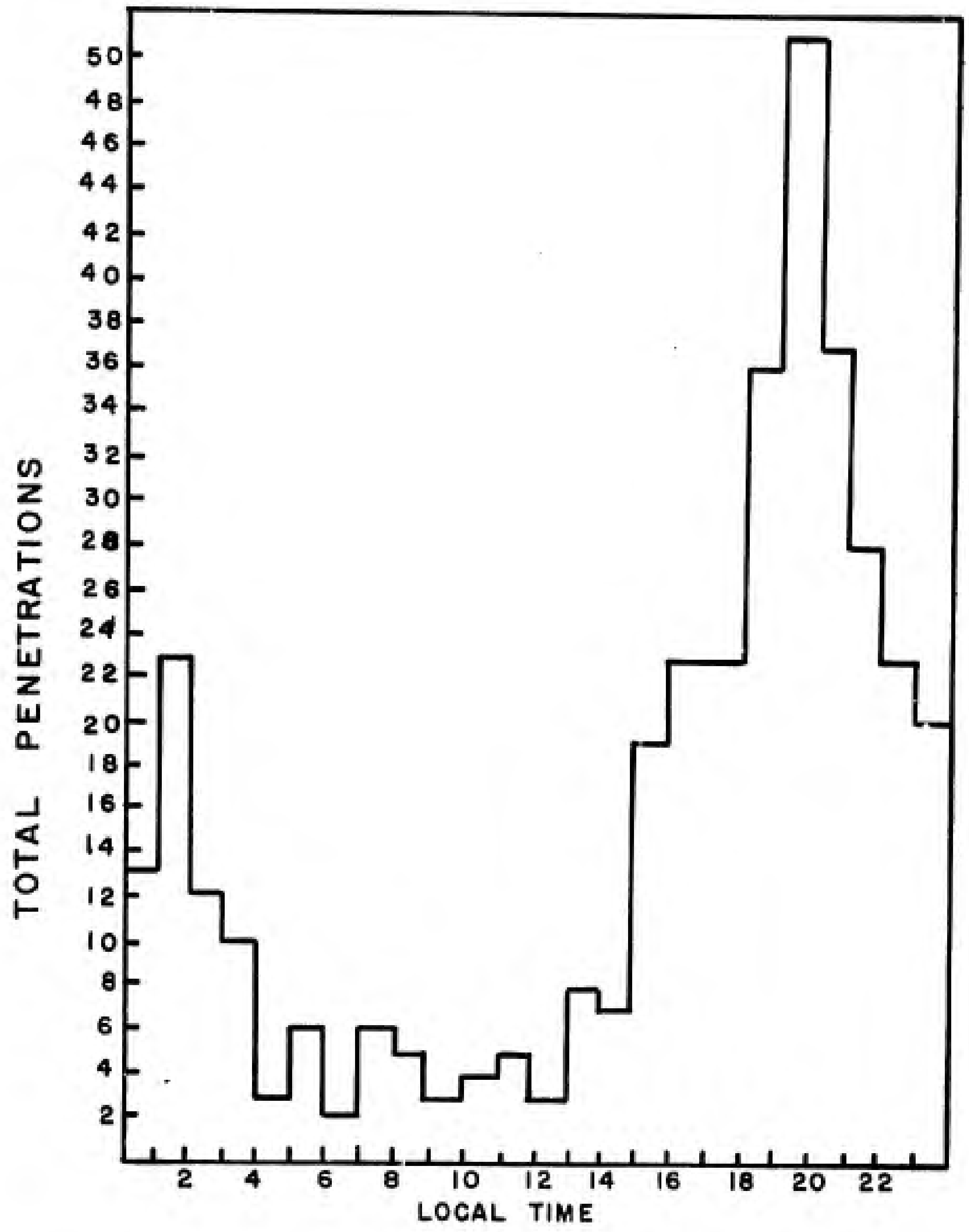


FIG. 6 HOURLY DISTRIBUTION OF TROPOPAUSE PENETRATIONS, OKLAHOMA CITY, OKLA. (OKC) 1961-1964

Figures 2 through 6 show the hourly distribution of penetrations, using the raw data from the three or four year period. All of the stations show afternoon maxima except Oklahoma City, which has an evening maxima, much like the data from Kansas City which is in a similar geographical area, and which also has a large number of occurrences of tornadoes and severe thunderstorms nearby. All of the stations except Buffalo show a tendency to have a secondary maximum of penetrations late at night or just after midnight. In the case of Minneapolis, this occurrs near 2100 local time, but the time for Key West, Little Rock and Oklahoma City is later, either at 0100 or 0200 local time. Again, the secondary maximum is a feature that is found at other stations, notably at Kansas City. Minneapolis and Buffalo are the only two stations that do not show penetrations during every hour of the day.

Table 13 gives the number of penetrations that had tops greater than 60,000 ft. Little Rock had more of these very

Table 13: Penetrations With Tops Greater Than 60,000 ft.

Station	1961	1962	1963	1964	Total
BUF		0	0	0	0
MSP		2	1	0	3
OKC	1	3	8	0	12
LIT	0	0	14	2	16
EYW	10	1	0	0	11

high tops than did Oklahoma City, which had more higher penetrations. These high tops were recorded in 1963, when most of the errors associated with measuring tops were well known, and there is little reason to suspect the number to be incorrect. At Key West, just the opposite is true, since all the very high penetrations were reported in 1961 when there was some doubt that the high tops were being measured correctly.

Table 14 shows the number of consecutive hours with penetrations.

Table 14: Number of Occurrences of Penetrations During Time Periods Longer Than One Hour.

Station	Number of consecutive hours with penetrations 2	3	4	5	6	more than 6
BUF	3					
MSP	30	13	6	1	1	
OKC	50	13	7	4	1	3, 1(7),1(8),1(13)
LIT	26	13	7	3		2, 2(8)
EYW	20	4	1	1	1	2, 2(7)

All three of the stations with the larger number of penetrations had time periods of longer than 6 hours with one or more occurrence in each hour, and Oklahoma City had a 13 hour period of penetrations on one occasion. It should be kept in mind that these data represent consecutive hourly penetrations over an area, not necessarily by the same thunderstorm.

Original radar data sheets were not available from Winnipeg, Canada, but a tabulation of the number of hours that tops were reported to be greater than 30,000 ft was sent for each of the months May through August, 1965. In order to obtain a crude estimate of the penetration information for Winnipeg, the number of hours of tops over 30,000 ft was tabulated for Minneapolis for the same time period . The number at Winnipeg was 55% of the number at Minneapolis. Although the number of hours does not tell us how many tops were over 30,000 ft each hour, much less how far over this level they extended, this percentage figure will be used in the next part of this section to estimate the penetration information for Winnipeg. If Winnipeg does indeed have about half as many penetrations as Minneapolis, this represents more penetrations than any of the Canadian stations listed in Table 3.

C. A penetration climatology

Figure 7 shows the locations of the stations available for a penetration climatology for North America. Of the 23 stations, 15 in the United States were WSR-57 radars, the two in the tropics, Ramey, and Albrook, were USAF CPS/9's, and the six Canadian stations had several different radars, which are listed in Table 1. The radars give fair coverage over the eastern half of the United States, and the southeastern sections of Canada, where penetrations are most likely, and the two USAF stations give an indication of penetrations in the tropics. Exact locations can be found in Table 1, or in Long (1965).

Figure 8 shows the average yearly number of clouds that rise more than 5,000 ft above the tropopause over the continent. There are very few of these clouds in Canada, with the possible exception of the southern part of the prairie provinces, where the estimates at Winnipeg show more than 25 occurrences a year. The northern edge of the "0" line is extended into the Peace River area to the lee of the Canadian Rocky Mountains to allow for one or two penetrations of the tropopause by the thunderstorms that occur with storms moving through that area during summer.

FIG. 7 NORTH AMERICAN RADAR STATIONS

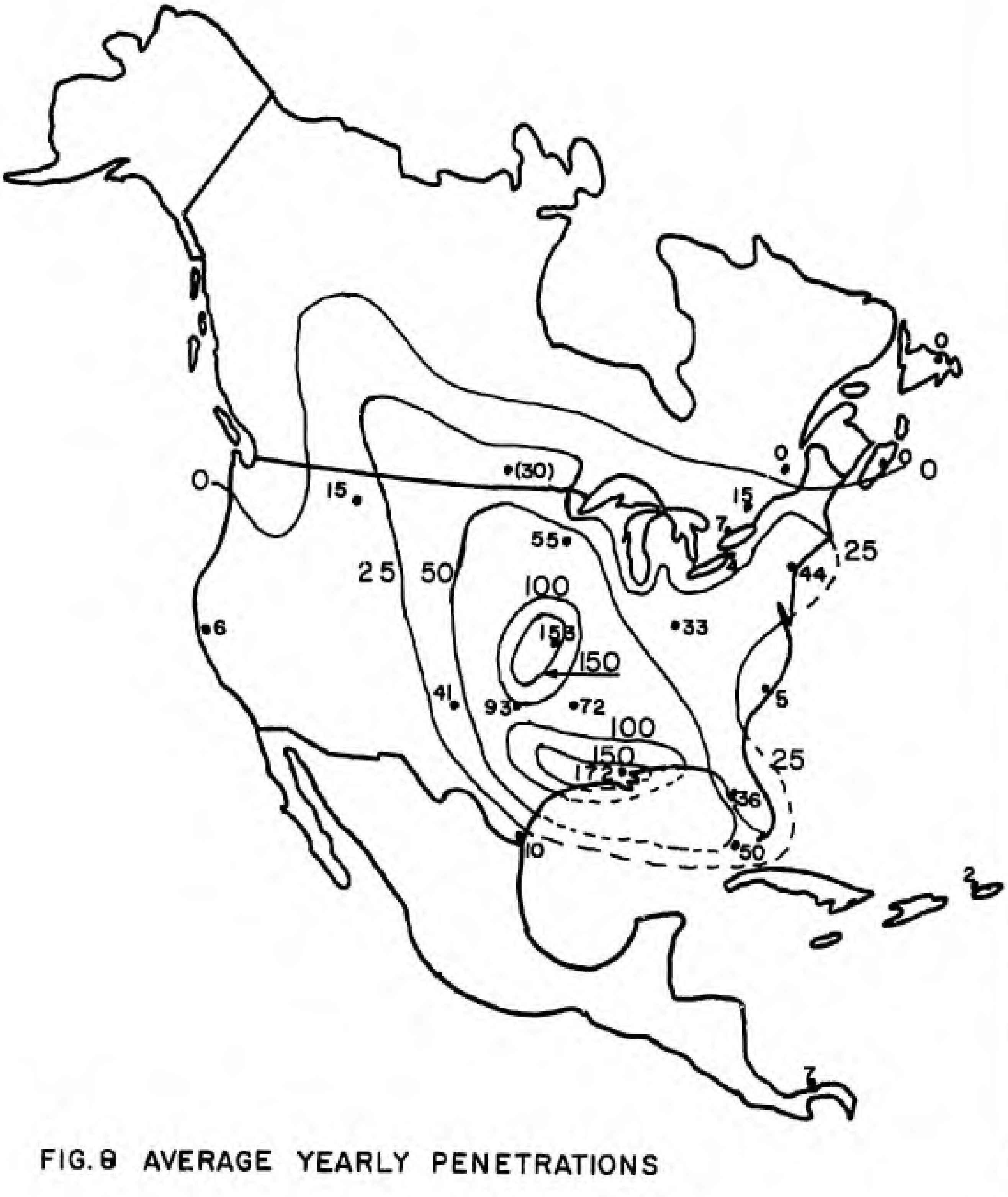


FIG. 8 AVERAGE YEARLY PENETRATIONS

In eastern Canada, there is direct evidence that the line of no penetrations passes through Ontario, then near Montreal, and then eastward out into the Atlantic through the state of Maine. The great lakes present a special problem for North America, since the cold waters have a depressing influence on the number of tops reported well above the tropopause. The small number of penetrations at Buffalo and Toronto was thought to be a result of the lake effect only, and for this reason the iso-line for 25 penetrations was kept south of the lakes, with a narrow extension into central lower Michigan to indicate the possibility of more tops in that area.

Figure 8 shows a double maximum in the United States, one near New Orleans, and the other near Kansas City. The two areas are separated by three stations, Amarillo, Oklahoma City, and Little Rock, all showing considerably fewer penetrations than either New Orleans or Kansas City. All of these stations took observations during 1961 when some tops may have been overestimates of the true tops. No adjustments have been made on Fig. 8 for this problem, but it is likely that if adjustments were made they would not be so large at any one station to change the double maximum idea, mainly because all the stations would probably be adjusted in the same direction, that is towards fewer tops.

There is considerable uncertainty in placing the isolines over the ocean areas near the continent. All that really can be said is that the 25 penetration isoline passes between Key West and the two tropical stations of Ramey and Albrook, and also between Key West and Brownsville.before going on shore in Texas.

The penetrations at Sacramento indicate a few tall clouds in areas where there is an orographic effect to offset normally dry and/or cool conditions in the mid latitudes. Tropical areas will also have a few penetrations where there is an orographic, or tropical storm, or low level meteorological effect to offset the usual lack of sufficient low level convergence to destabilize the atmosphere. Ramey is an example of the orographic effect, and to some extent the tropical storm effect, and the inter-tropical convergence zone is probably an important factor at Albrook, along with some orographic contribution.

Figures 9, 10, and 11 show the average penetrations during three periods which correspond roughly to spring, summer, and fall. It is convenient to use these three time periods, since there were no penetrations at any of the stations during November, December, and January, and the maximum three month period is May, June, and July. Fig. 9 shows the average numbers for the months of February, March and April; there is one maximum on the Gulf of Mexico coast, with an extension of higher numbers northward from there. Other areas, including the tropics, show no penetrations. On Fig. 10 most of the stations show their largest values, with a maximum at Kansas City, a smaller maximum near New York, and a minimum over the great lakes. May is the month of maximum severe thunderstorms and tornadoes for Kansas City, which partly supports the maximum there. On the other hand, Oklahoma City also has a May maximum of severe weather, with many more tornadoes nearby than Kansas City; yet at Oklahoma City the number of penetrations is about half that of Kansas City.

FIG. 9 AVERAGE PENETRATIONS, FEB. THRU APR.

FIG. 10 AVERAGE PENETRATIONS, MAY THRU JUL.

FIG. 11 AVERAGE PENETRATIONS, AUG. THRU OCT.

A zero isoline has been drawn around parts of the great lakes to emphasize the lake effect. Although Buffalo records four penetrations on the average for the May thru July period, it is very likely that large areas over the lakes and nearby have no penetrations during this time period, with zero penetrations at Toronto as an example. Ottawa, somewhat removed from the lakes, had seven penetrations,on the average, and for this reason, the northern boundary of the zero line was carried across Ontario to the north of the lakes, and into the prairie provinces where there is considerable summer thunderstorm activity.

The smaller maximum around New York points out the area just to the east of the Appalachians where summer squall lines and thundershower areas intensify due to the warm lowlands and the influx of Atlantic moisture at very low levels.

Figure 11 shows the decline in the number of penetrations as fall approaches. The northern limit of penetrations is still in Canada, with most of these penetrations occurring during August only. Again, the lake effect has been emphasized with a separate zero isoline. Kansas City once again has a rather large number of penetrations for the period, and New Orleans represents a second maximum along the gulf coast.

All of the stations have more penetrations in the late afternoon and early evening than at any other time, but Kansas City, Oklahoma City, Little Rock, Minneapolis, Key West, and to some extent, Amarillo all have a secondary maximum of penetrations near 0100 or 0200 local time. At all stations having more than just a very few penetrations, there are one or more occasions of penetrations lasting for more than one hour. At the following stations, there are several periods of penetrations that last more than three hours: New Orleans, Kansas City, Oklahoma City, Little Rock, Minneapolis, New York City, and Amarillo.

IV. Penetrations Outside North America

A. Data

Only small portions of the globe have radar coverage to begin with, and of this small number of radars, only a few stations were available for study. In an earlier report (Long,1965), several USAF CPS/9 stations were checked for penetrations with the result that very few were found, either in the high mid-latitudes, or in the tropics. During the course of this contract, a few other stations sent data, with essentially the same result; very few penetrations.

The USAF CPS/9 at Yokota, Japan (35.4N, 140.0E), sent data for the two year period 1964-1965. A comparison of the tops with the tropopause heights for one or more of the Japanese soundings showed no penetrations of more than 5,000 ft, in fact there were only a few penetrations of the tropopause by any amount. The orographic effect apparently is unable to overcome the combination of a narrow island and the cooling effect of the ocean.

Fragmentary data were available from the Manila radar in the Philippines, where reports were taken from once a day on down to once a month. The data indicate one or two penetrations of about 5,000 ft, but it is difficult to determine how far away from the set the cells were, since individual cells were not identified. The data were taken over a three year period and seem to fit in with other data taken in the tropics; that is there may be a few tops more than 5,000 ft above the tropopause each year, but probably less than a dozen. None of the observations at this station were taken when spiral bands associated with tropical storms were close by.

Some information was sent from a Selenia radar at Pretoria, South Africa (25.5 S, 28.2 E), for the months of October, December, and February during the Southern Hemisphere summer of 1964-1965. The data were presented as the number of tops above certain levels. Only one month of tropopause data were available (December 1964), and at the most three clouds had a chance to be more than 5,000 ft above the tropopause during that month. This suggests only a very few tops more than 5,000 ft above the tropopause each year for that area.

B. Other likely areas for tropopause penetrations

A short summary of Section III would seem to say that a continent favored with access to warm tropical or subtropical waters that are equatorward from an area where hot, dry air masses move from west or northwest has the potential necessary for numerous penetrations of the tropopause, provided that the tropopause is low at the time that the warm and moist air is destabilized by the dryer air from the west. Considering the other continents, the most likely area for more than just a few penetrations would seem to be China north of the Yangtze, especially the lowlands from Peking south to Wuhan, and eastward from there to the ocean. A secondary area may be further north in central Manchuria, from Tsitsiar and Harbin southward to Mukden and Port Arthur. These areas have access to the moisture, and are just to the east of very dry regions. These areas are also between latitudes 30 N and 45 N, close enough to the storm track and the lower tropopauses for large penetrations to occur.

Other areas that may have more than a few penetrations each year are: India, north of the tropics, where some high tops have already been reported (Seshadri, 1963); China, south of the area just mentioned to the South China Sea; Russia, just north of the Black Sea, from Odessa to Kiev, and east from there towards Kharkov and Donetsk; Argentina, from the Pampas eastward to the ocean between latitudes 30 S and 40 S. In addition to these areas, there probably are several areas where an orographic effect causes some penetrations, both in the tropics and in the mid-latitudes. It would be difficult to estimate just how many penetrations would occur in these areas, but they seem to be the most likely to meet all the necessary conditions

V. The Behavior of Individual Penetrations

Long (1965, 1966) has shown by analysis of a squall line which contained tropopause-penetrating thunderstorms that not all the thunderstorms in the squall line penetrated the tropopause level, rather that only a few reached the very high altitudes. The nature of tall thunderstorms that do penetrate the tropopause level by large heights has not been studied. This section presents two studies on this special thunderstorm. The first is a study on low level moisture and the height of these storms, and the second examines the efficiency of the storms.

The low level moisture in the air that enters the bottom of a large thunderstorm determines the amount of energy that will be released in that storm over the next hour or two, and the energy release should be a measure of the storm's ability to reach above the tropopause level. To study this problem, it was necessary to determine very accurately the height of the storm cell as well as the value of the moisture entering the bottom of the storm cell just before the cell reached the penetration height. To insure the accuracy necessary, the following criteria were used in order to select cases to be studied;

1. The cloud top must be within 50 n mi of the radar station. This assures a minimum amount of error in the height determination. At this distance or less, the product of the antenna half power beam width and the range is 100 or less, which Donaldson (1963) says will eliminate side lobe errors in the WSR-57 radar.

2. The cloud top must be within 50 n mi of the upper air sounding station. This reduces the effects of fronts and other low level changes in the sounding structure.
3. The cloud top measurement time and the balloon release time must be within three hours of each other. This insures that the sounding is sampling air quite similar to that in which the storm grew, especially in the upper levels.
4. The penetration must take place within a network of surface stations close enough to assure a careful determination of the low level moisture that passed into the bottom of the storm approximately one hour before the top was reported. The surface moisture value is used to modify the moisture profile at low levels if necessary.
5. Only the 00 GMT sounding was used. This eliminates the troubles of early morning inversions.

Date were available from 13 WSR-57 radar stations in the United States over a four year period, but the restrictions mentioned above resulted in a small number of cases that could be used. Since there is some doubt as to the reliability of the data from 1961 (Hanks et al 1964, and Long et al 1965), an effort was made to choose cases from 1962 onward.

Fig.12 shows the variation in top heights for changes in the amount of low level moisture available to the storm for sveral stations. The relatively small number of cases from each station is the result of the selection proeess. Data at each of the stations indicate increasing top heights for increasing amounts of moisture,

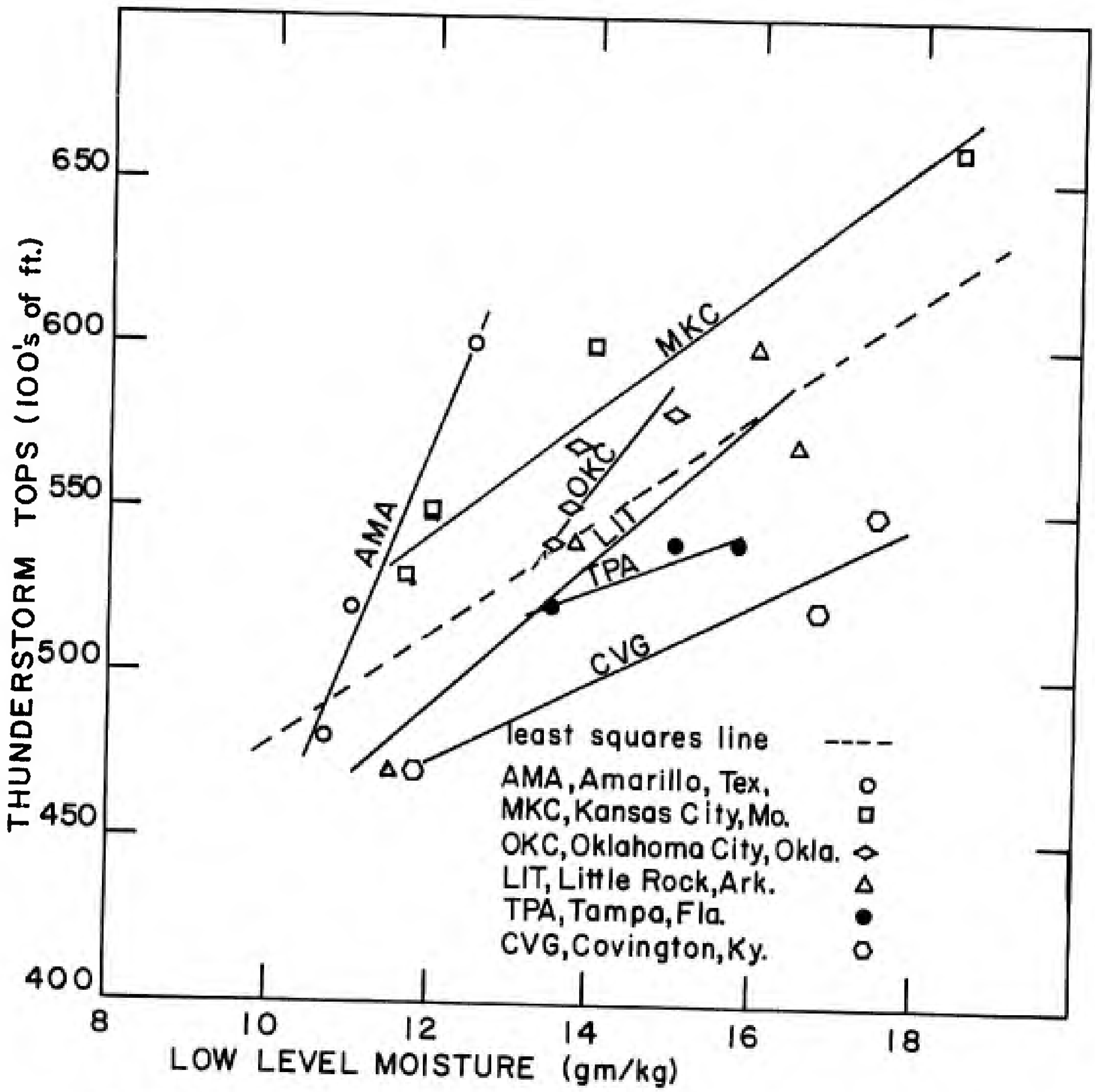


FIGURE 12 THUNDERSTORM HEIGHTS vs. LOW LEVEL MOISTURE

with stations at higher surface elevations showing steeper slopes for their curves. Cloud top sensitivity to moisture ranges from 700 ft/gm/kg at Tampa to 6000 ft/gm/kg at Amarillo. The least squares line for the entire data mass is also shown, and gives a sensitivity of 1700 ft/gm/kg. Since only clouds with tops more than 5000 ft above the tropopause were included in Fig.12, the data for the individual stations should look different below 40,000 ft, since an extension of the lines for the stations in Fig.12 towards the origin would give rather high cloud tops with no moisture at all.

While Fig.12 appears to give a threshold value of about 10gm/kg of low level moisture for tropopause penetrations in the United States, a general rule for estimating the tops of penetrations on the basis of low level moisture seems unlikely. The sensitivity of top heights to changes in moisture may be correlated with station elevation, but the same value of moisture gives top heights that are different for different stations, which suggests different dew point-top height relations for each station. Estimating cloud top heights from low level dew point data would be further complicated by the sharp gradients in low level moisture that have been observed by Rhea (1966) in the central part of the United States where large numbers of penetrations have been reported (Long 1965). In other parts of the world, where surface and upper air stations are few and far between, a surface or low level moisture method of estimating tops can, however, give an approximation of the maximum tops which could occur.

Long et al (1965) have shown success in matching radar thunderstorm tops that had penetrated the tropopause level by more than 5000 ft with cloud top heights computed from a simple energy balance method, using a nearby sounding. The study used only the strongest thunderstorms that were noted among groups of cells, a natural result of selecting tropopause penetrations of more than 5000 ft. Many other cells also grew in the same environment, some of which may have missed being included in the study group by only small margins of height. Thus, only the top fringe of a spectrum of clouds was studied by the simple energy balance method in this study. In an effort to determine if each cloud in this top fraction of tall clouds made the same use of the energy that was available, a measure of the total available energy in each case was plotted against the cloud tops in Fig.13. Many of the cases in Fig.12 were used in Fig.13.

The total energy available to the cloud was estimated by a measure of the total positive area on a thermodynamic diagram traced out by a rising parcel of air, the parcel path determined by the simple method outlined in Long et al (1965). In creating such an area on a thermodynamic diagram, the units of the area will be pressure times temperature, or in this case, centibar-degrees centigrade. Fig.13 shows a wide scatter of the data although the entire data mass for the several stations does show increasing heights as the available energy increases. The least squares line indicates about 1700 ft of top height increase for a 50 centibar-degree change in available energy. The least squares line in Fig.13 is properly part of a curved line since such a line would be expected to pass through the origin, if such effects as precipitation loading are excluded. Although the clouds that

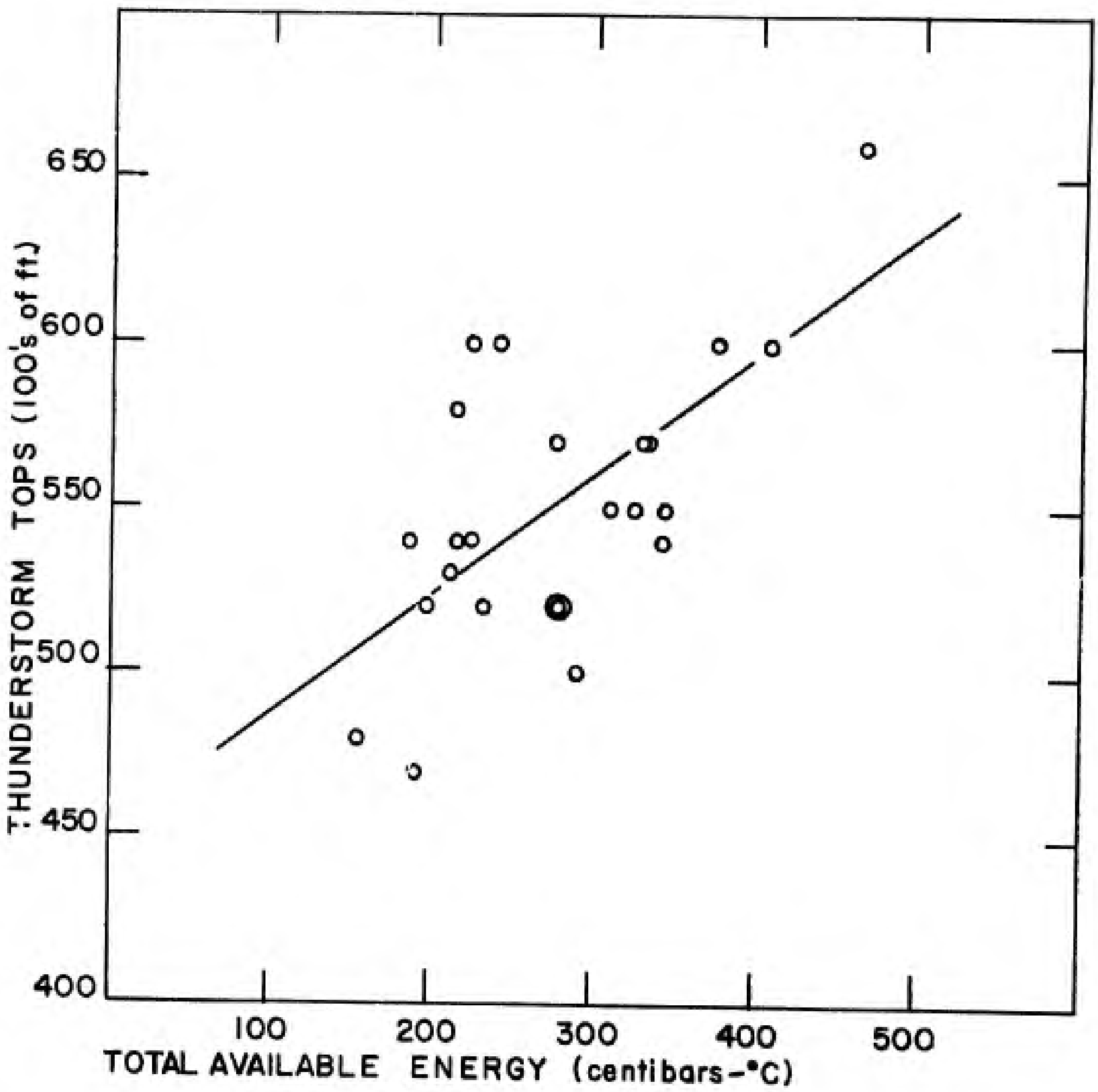


FIGURE 13 THUNDERSTORM HEIGHTS vs. TOTAL AVAILABLE ENERGY

did not penetrate the tropopause by large amounts were excluded. Fig.13 shows wide differences in cloud top heights from storms that had similar amounts of energy available. At the 60,000 ft level, for instance, tops were produced in one case with only about 60% of the energy that it took to get the same top in another case.

Two reasons can be discussed to explain these rather large differences in what was thought to be a group of similar storms. One is that in the growth of thunderstorms above a certain level there may be a limiting factor that is independent of the amount of energy available. Radiation at the top of the cloud, upper wind patterns, effects of precipitation loading over very long vertical distances, cloud drop behavior at very high altitudes and perhaps other problems may account for such an effect, either singly or in combination. The second possibility is that surface patterns of convergence and divergence may have a large effect on the efficiency of the storms, allowing some storms to grow taller than others while the soundings may be quite similar for the two storms.

High level effects have only recently been investigated by Fitzgerald and Valovcin (1964) and others with the use of high altitude aircraft and radiation and photo instruments. Low level effects such as convergence and divergence patterns have been studied for some time, particularly in connection with thunderstorms in the midwest where large numbers of penetrations are found. Studies on the efficiency of the storms as it is related to the high and low level effects mentioned above are beyond the scope of this contract, but such studies are strongly recommended in the light of the availability of the data and the importance of the results to the study of thunderstorms.

The lack of success in estimating thunderstorm tops that can be expected from the use of either dew points of available energy further increases the importance of the simple energy balance method of estimating maximum thunderstorm tops in Long et al (1965). A simple approach such as this gives satisfactory estimates for the top of the highest cloud. More detailed studies are needed, however, to improve thunderstorm top estimations.

VI. The Vertical Distribution of Thunderstorm Penetrations

The vertical distribution of thunderstorm penetrations was briefly noted in Long (1965). Table 3 of that report listed the yearly average cumulative frequency of penetrations above certain levels for the years 1961 through 1964. The equation best fitting the vertical decrease in the number of penetrations was thought to be exponential, and Figs.14 and15 show the variation on semi-logarithmic paper for the ten stations. Constants were calculated for the equation for each station, and to check the goodness of fit, a correlation coefficient (R) was also calculated, where: $R^2=1-\Sigma e^2/\Sigma y^2$; $e=Y-(Q)$; $y=Y-\bar{Y}$; Y= observed value of the dependent variable; (Q) = computed value of the dependent variable; and $\bar{Y}$= the mean of the observed Y's. The level of significance was computed by using the "students" t test. Table 15 gives the information for each station.

Table 15: Constants for the General Equation $Y=Ae^{-bX}$, and Goodness of Fit. Y is the number of penetrations above a certain level and X is the penetration level. R is the correlation coefficient.

Station	A	b	R	Level of significance using "students" t
MSY	811	.265	-.96	.1%
MKC	676	.228	-.93	.1%
NYC	295	.334	-.96	.1%
AMA	118	.217	-.99	.1%
TPA	344	.449	-.99	.1%
CVG	425	.478	-.95	.1%
MSO	243	.532	-.95	1%
BRO	37.9	.233	-.97	.1%
ILM	36.4	.397	-.97	1%
SAC	41.2	.386	-.99	.1%

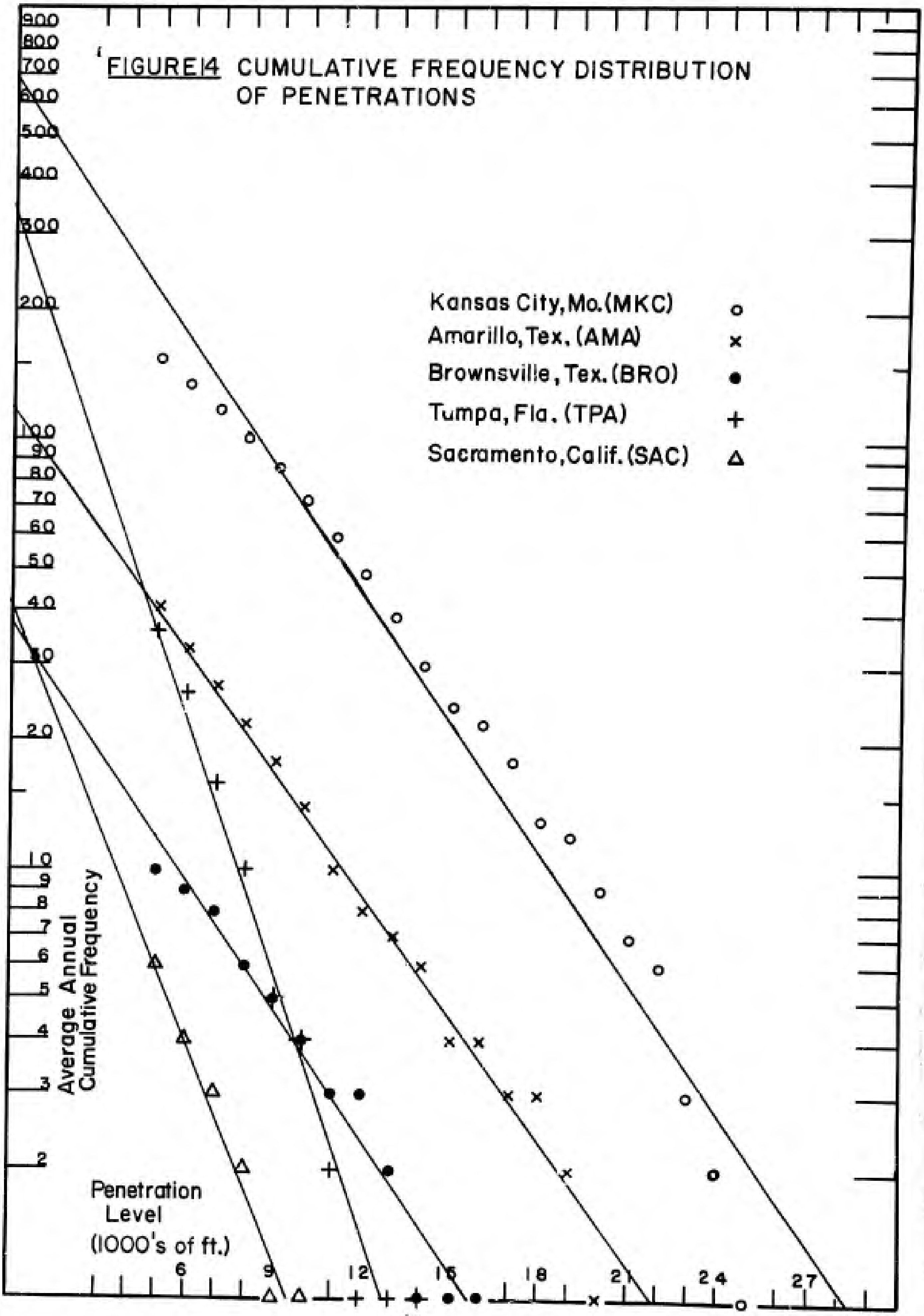
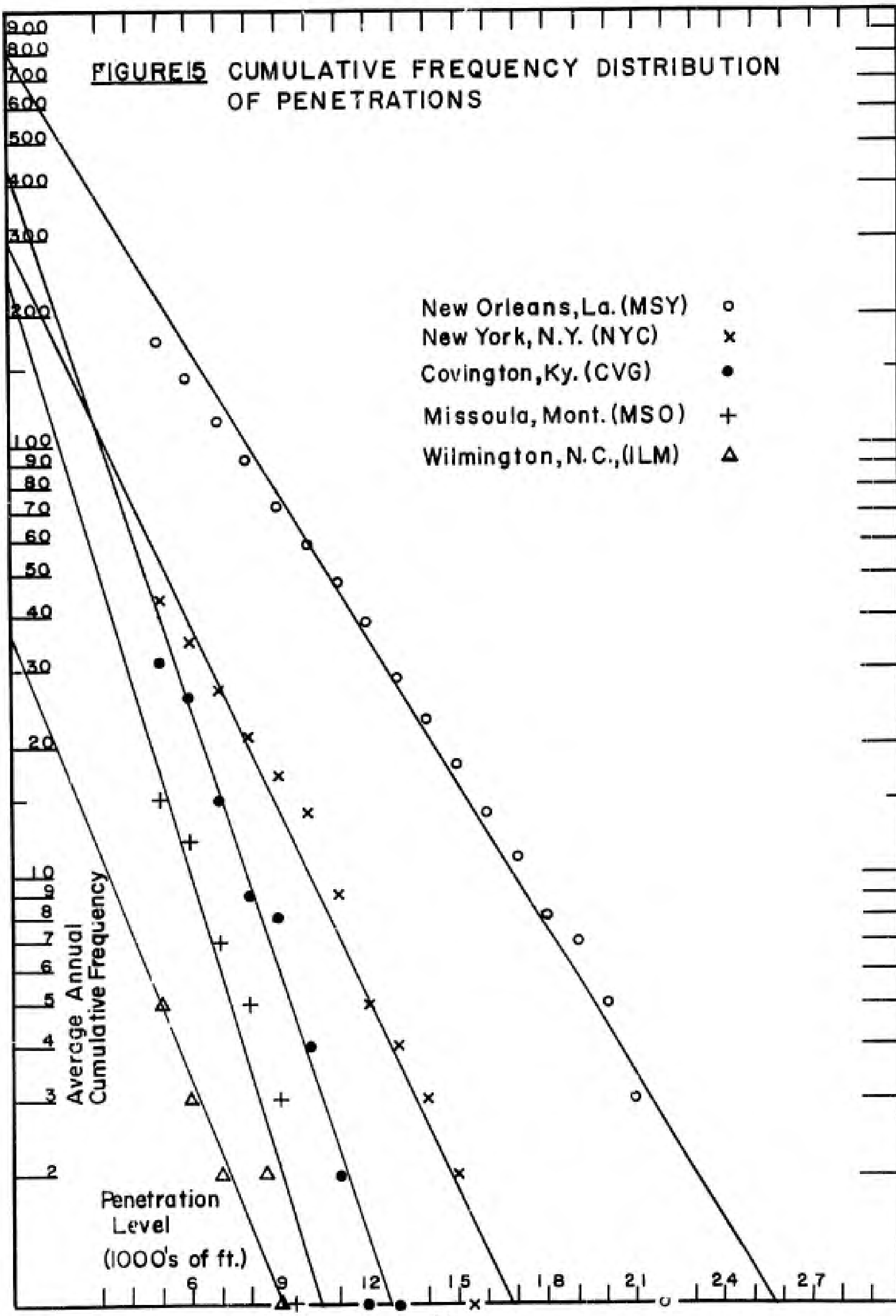


FIGURE 14 CUMULATIVE FREQUENCY DISTRIBUTION OF PENETRATIONS
Kansas City, Mo. (MKC)
Amarillo, Tex. (AMA)
Brownsville, Tex. (BRO)
Tumpa, Fla. (TPA)
Sacramento, Calif. (SAC)
Average Annual Cumulative Frequency
Penetration Level (1000's of ft.)
900
800
700
600
500
400
300
200
100
90
80
70
60
50
40
30
20
10
9
8
7
6
5
4
3
2
6
9
12
15
18
21
24
27

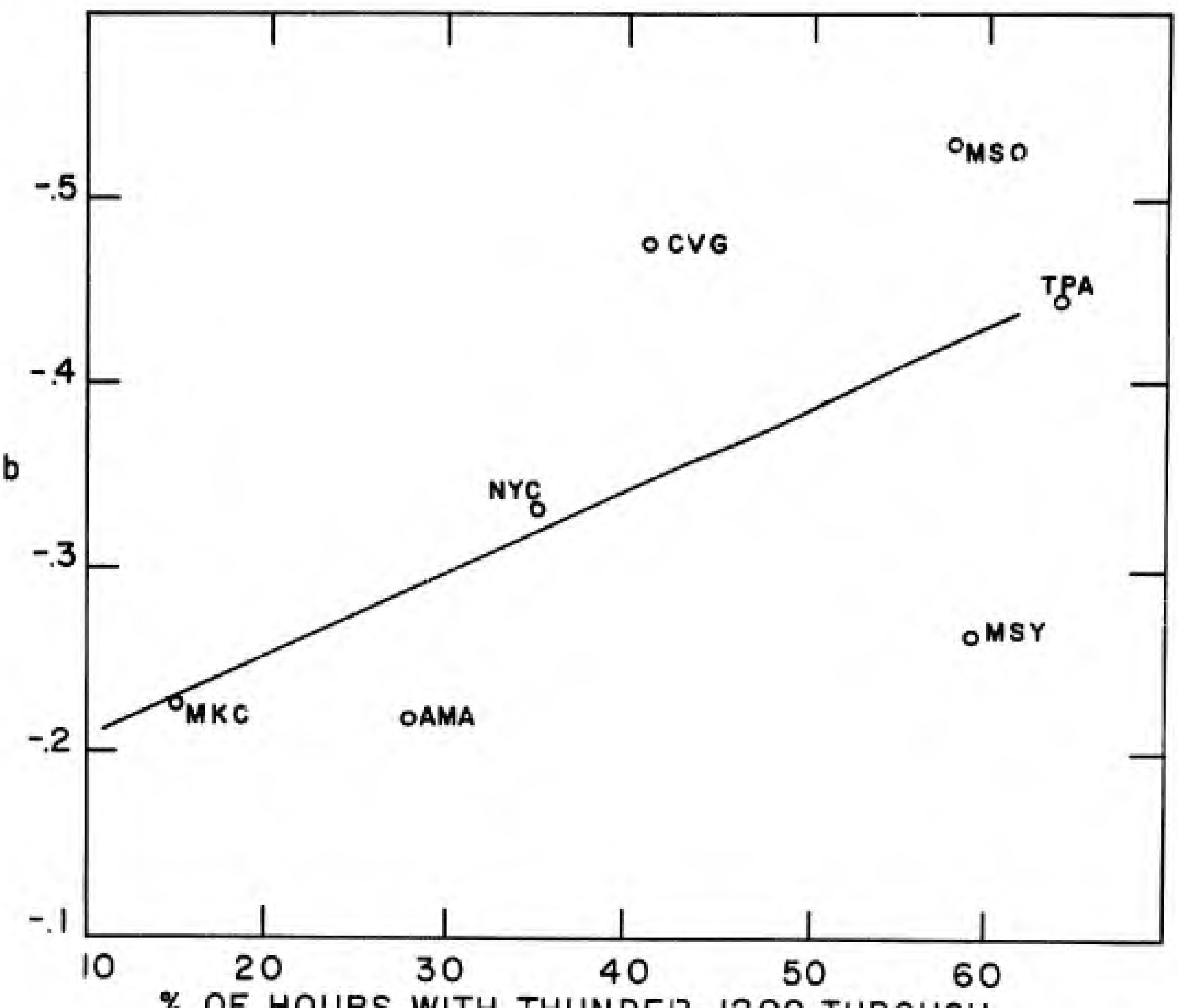
FIGURE 15 CUMULATIVE FREQUENCY DISTRIBUTION OF PENETRATIONS



The outstanding feature of Figures 14 and 15 and Table 15 is the very close fit of an exponential relation, with the significance of the correlation coefficients at levels not often encountered in meteorology. It can be said that penetrations of the tropopause decrease exponentially with the height above the tropopause.

Only penetrations of more than 5,000 ft were tabulated in the study, but an extension of the curves in Fig. 14 and 15 to the tropopause level indicates more than 800 clouds above that level in one year at New Orleans. At the other end of the figures, it is apparent that Kansas City may occasionally have one or two penetrations higher than any recorded in the 1961 through 1964 period. At Kansas City and New Orleans, a few penetrations may occur which will be testing the upper limits of the RHI capability of the WSR-57 (near the 70,000 ft level).

The constant "b" in Table 15 shows considerable variation, from near .21 to more than .53 . Some of this variation may be due to the occurrence of night penetrations of the tropopause. Fig. 16 shows the percent of afternoon thundershowers at the ten stations for the four year period during which penetrations were tabulated in relation to the constant "b" in Table 15. There appear to be slightly higher constants for those stations with higher percentages of afternoon thundershowers. While Fig. 16 hints that thunderstorms may act differently at night than they do in daytime, the data are rather widely scattered, with an average of .352 for all the stations.



% OF HOURS WITH THUNDER 1200 THROUGH 1800 LST, (data from months with penetrations, 1961-64)

FIGURE 16 THE CONSTANT "b" vs. PERCENT AFTERNOON THUNDERSHOWERS

VII. Penetration Estimates

The energy balance method used by Long et al (1965) will determine the highest thunderstorm penetration of the tropopause on a single sounding, if penetrations can occur at all. When this result is combined with the exponential equation, the result will be a distribution of penetrations for the station. The true distribution, however, will only be determined when the sounding tested has sampled the environment in which the tallest thunderstorm can grow. Thus, by choosing a suitable number of soundings from a station during the maximum period of thunderstorm acitvity, and applying the energy balance method for the tallest storm and then using the equation, the distribution of penetrations at the station can be closely estimated. Since Fig. 13 implies that thunderstorms do not use all the energy available to them, the conditions for the growth of the single tallest storm will probably occur a number of times during the maximum thunderstorm season, and not every sounding during the season needs to be tested to get the height of the tallest storm.

There are problems with this procedure, however, since a sounding at a point is being used to represent what might happen over a wide area. Further , the sounding which will give the tallest penetration should be a combination of the maximum heating and moisture values, along with a relatively low tropopause. All of these conditions may occurr quite close to a station, but not at the station, several times each year. Also, since Fig. 13 shows that some storms do not use all the available energy, it is possible that there are some areas where all of the available energy is never used. In spite of these problems, two stations

Little Rock and Buffalo, were chosen as a first test of the procedure outlined above.

These stations were chosen because they represent two different thunderstorm areas, and also because radar data are available to check the accuracy of the procedure. Tenssoundinqs were chosen at random from each of the stations during the summer months of 1963 at 00 GMT, and the energy balance method applied to determine the highest possible storm tops. At Buffalo, where ab about 45% of the total thunderstorms in summer occur between noon and 6 PM local time (Visher, 1954), a constant of .36 was chosen from Fig. 16 . At Little Rock, where 50% of the activity occurs in the afternoon, a constant of .385 was taken from Fig. 16.

Fig. 17 shows the estimated and actual data, along with the equations. The total number to be expected above the tropopause level from the estimation matches very closely the number derived from the actual data, although in the case of Buffalo, this is a matter of compensating errors. The highest penetration was estimated quite closely at Little Rock, but at Buffalo, the error was about 8,000 ft. Patt of the problem at Buffalo is the very small total number of penetrations, and another factor is the shorter data period, only three years compared to four for Little Rock.

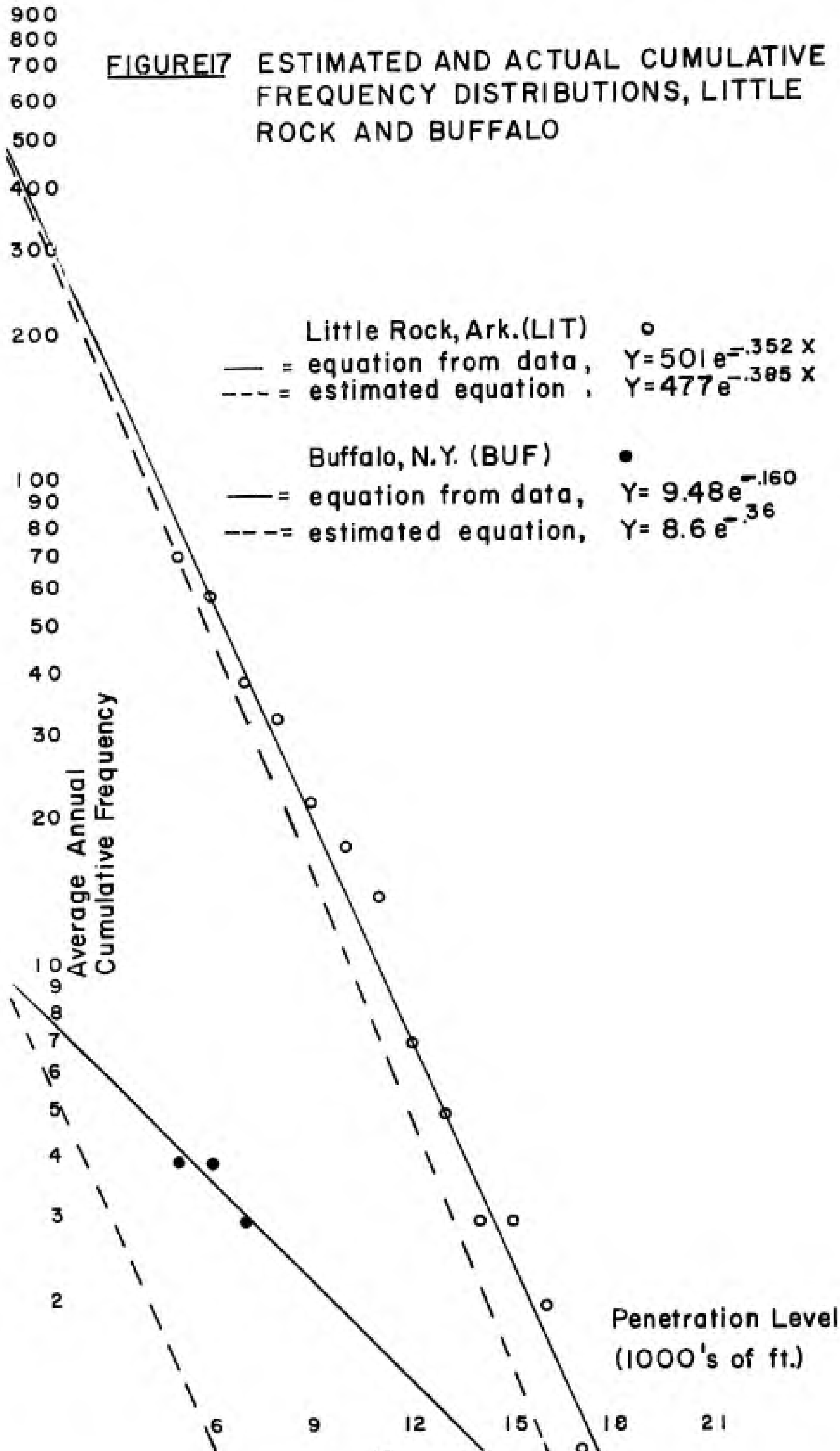


FIGURE 17 ESTIMATED AND ACTUAL CUMULATIVE FREQUENCY DISTRIBUTIONS, LITTLE ROCK AND BUFFALO

VIII. A Computer Program for Sounding Analysis

A. Introduction

Part of this contract specifies that a computer program be written to determine whether a sounding represents conditions that are favorable for the development of thunderstorms which could penetrate the tropopause. Graphical analyses of soundings to determine the height of the tallest thunderstorm are described by Long (1965), but the various graphical aids on meteorological soundingsdiagrams must first be put into mathematical form before machine analysis can take place. Computer operations in meteorology are growing at a rapid pace, and recent papers by Foster and Prosser (1966), and Stackpole (1967), have investigated problems similar to those involved in writing the program this contract calls for. Some of the techniques used below are similar to those used by these authors.

B. Procedure

Aside from transferring the various graphical aids usually present on a thermodynamic diagram into mathematical form, the sounding analysis program divides easily into four main portions: 1. Surface layer calculations, 2. Determination of the lifting condensation level, 3. Determination of the level of free convection, and 4. Accounting for positive and negative energy, and detemining the point where they are equal.

It should be noted again that this program uses the parcel approach as an estimation of the conditions that would produce the tallest thunderstorms, and that only the information on the sounding is used. Thus, no account is taken of effects that might change the sounding, or of effects that might make a parcel differ in its behavior from that of a saturated parcel whose temperature change follows a moist adiabat above the lifting condensation level. In Section V. only certain soundings, taken in the late afternoon were used to determine the maximum thunderstorm heights possible so that they could be compared with radar observations of the tops of storms that developed nearby. The program was written to allow analysis of soundings taken at any time, and it is also different in other ways from the simple graphical analysis discussed in Long (1965). Each of the four sections of the program mentioned above will be discussed, followed finally by a discussion of some of the programming problems.

1. Surface layer calculations. In Long (1965), the surface temperature and the average dew point in the lower 3,000 ft of the atmosphere were used to determine the moist adiabat used in the cloud top calcualtions. In the program a different method is used, involving the lower 160 mb of the sounding. The figure of 160 mb was chosen to include approximately the first 5,000 ft of the atmosphere, roughly up to the 850 mb level. If the surface layer is this deep, there is less chance of missing an overrunning thunderstorm situation where the storms form at the top of a very moist inversion some 3,000 to 5,000 ft off the ground.

Since an average of temperature and/or dew point through part or all of the surface layer sometimes gives a result of no level of free convection, and would not represent the best parcel conditions for thunderstorm growth, each data point in the surface layer is tested to determine which one would become saturated at the warmest moist adiabat. This data point is the one that is lifted, first dry and then moist, adiabatically in the cloud top calculation. The use of one data point instead of an average of either the temperature and/or the dew point through the surface layer allows the use of the conditions most likely to destabilize the sounding and give the height of the tallest possible storm. This is quite important in stratified situations, and the results are not different from the results of the averaging methods when the surface layer is well heated and nearly dry adiabatic to begin with.

2. Determination of the lifting condensation level (LCL). The LCL is actually determined for each point in the surface layer in the search for the "best" moist adiabat, or pseudo-adiabat, as described above. The program merely remembers which LCL pressure goes with the warmest pseudo-adiabat, and calls that pressure PLCLB, for pressure, LCL, best. A complete list of variable names used in the program is given in Section VIII (D), but some of them will be introduced here where the computations are explained.

In the computation of the LCL, saturation vapor pressure, over water, is approximated by:

$$ES = 6.11 \times 10^{(at/(t+b))} \qquad (1)$$

given by Tetens (1930), with a = 7.5, b = 237.3, and t = temperature (C). The saturation mixing ratio, TMS, is defined as:

$$TMS = .622(ES/(P-ES)) \qquad (2)$$

where P = pressure (mb), and ES is computed using the dew point at the chosen data point. Potential temperature, THT, is:

$$THT = (t + 273.16)(1000/P)^{2/7} \qquad (3)$$

The LCL is reached when the line of constant THT meets the line of constant TMS on a thermodynamic diagram, or when the equations for THT and TMS are equal. At this point t = TLCL, and P = PLCL. In solving for PLCL and TLCL, it is helpful to have:

$$D = 7.5t/(237.3 + t) \quad (4)$$

so we can write from (2):

$$TMS = .622(6.11 \times 10^{D}/(P - 6.11 \times 10^{D})) \quad (5)$$

Manipulation of (3) and (5) for PLCL gives:

from (3), $$THT = ((237.3D + 273.26(7.5-D))/(7.5-D))(1000/PLCL)^{2/7}$$

or $$PLCL = 1000((2048.7-35.86D)/THT(7.5-D))^{3.5}, \quad (6)$$

and from (5), $$PLCL = 6.11 \times 10^{D}(.622+TMS)/TMS; \quad (7)$$

Also, (7) can be solved for D as a function of PLCL:

$$D = \log_{10}(PLCL \times TMS/6.11(.622+TMS)) \quad (8)$$

The following method of iteration can be used to find both PLCL and D. TLCL can then be found directly from (4). The iteration calls for guessing a value of D, and then using (6) to find PLCL. This value of PLCL is then used to calculate a new value of D from (8). Using the new D, go back to (6), and so on until the change in PLCL from one calculation to the next is sufficiently small. The last PLCL is taken as the final value; then TLCL is computed. In the program, D is initially set at .5, and the calculation is stopped when the difference is less than 1.0 mb.

3. <u>Determination of the level of free convection(LFC)</u>. In calculating the LFC, the pseudo-adiabats are approximated by Rossby's pseudo-equivalent potential temperature, THTSEB(Rossby,1932):

$$THTSEB = THTD \times \exp(AL \times TMS/cp \times T) \quad (9)$$

where: THTD = partial potential temperature, (A)

$$= T(1000/(P-ES))^{2/7}$$

AL = latent heat of vaporization, cal/gm
   = 596.73-.601 x t
cp = specific heat of air at constant pressure, cal/gm,(C)
   = .24
T = temperature (A)

knowing the LCL information for the "best" data point, one can calculate the "best" THTSE, or THTSEB as it is called in the program, and begin looking for the LFC. The procedure for looking for the LFC is to calculate the temperature of THTSEB at each data point above the LCL, and then compare the two temperatures, to see if THTSEB is warmer than the sounding. Interpolation is then carried out to find the LFC data when the THTSEB does become warmer than the sounding. The scheme to find the temperature of THTSEB at any given pressure is that of Stackpole (1967), where:

$$AA = THTD \times \exp(AL \times TMS/cp \times T) - THTSEB \qquad (10)$$

Using the value of the pressure at the next higher data point, we use (10) to find a "t" such that AA is smaller than a certain number near zero, such as "e". The steps are:

1. Guess at t and TDEL("delta t")
2. Calculate AA, and test for absolute value of AA less than e. If AA passes the test, t is the correct temperature.
3. If AA is bigger than e, make t=t+TDEL, and calculate a new AA, called AA1. Check the absolute value of AA1 against e. If it is smaller , the new t is the correct number. If not go on to 4.
4. If the signs of AA and AA1 are different, the desired t is in between the two calculated values, so divide TDEL by 2.0 and go back to step three.If the signs are the same,go to step 5.
5. If AA1 has a smaller absolute magnitude than AA, we are headed in the right direction, and AA is set equal to AA1, t is set equal to t+TDEL,and we go back to step 3.
6. If AA1 has a larger absolute magnitude than AA, the sign of TDEL is changed and we go back to step 3.
7. It is highly unlikely that AA=AA1, and this possibility is not considered.

4. Accounting for positive and negative energy and determining the point where they are equal. Once the LFC has been reached, the program begins a count of the average difference in temperature between the sounding and THTSEB from one data point to the next. To get a measure of the energy, the average temperature is then multiplied by the pressure difference between the two data points. This is the same method used by Long (1965) to successfully match the tops of clouds with estimates of maximum cloud height from nearby soundings. The measurements and computation of the product of the temperature and pressure differences is a simple matter, so long as the THTSEB temperatures are warmer than the sounding. The program is written in such a way that if middle level inversions are encountered where THTSEB is first cooler, then warmer again than the sounding, all of the energy, both positive and negative, will be accounted for, up to the point where the negative count first exceeds the positive count. The exact pressure where the totals are the same is found by noting when the negative total first exceeds the positive, then going back to the next lowest data point and approaching the "balance" point by taking small increments of pressure and calculating small additions to the negative total until the negative total once again exceeds the positive. The pressure increment is then cut in half, and the procedure repeated until the difference in totals is less than 20.0 mb-(C). The height is then interpolated.

The block diagram (Section VIII,C), the variable names (Section VIII,D), and the program statements (Section VIII,E) were all written in FORTRAN IV language. Since the data are not likely to be arranged in any one way, as few restrictions as possible were put on the input arrangement. The few considered necessary are:

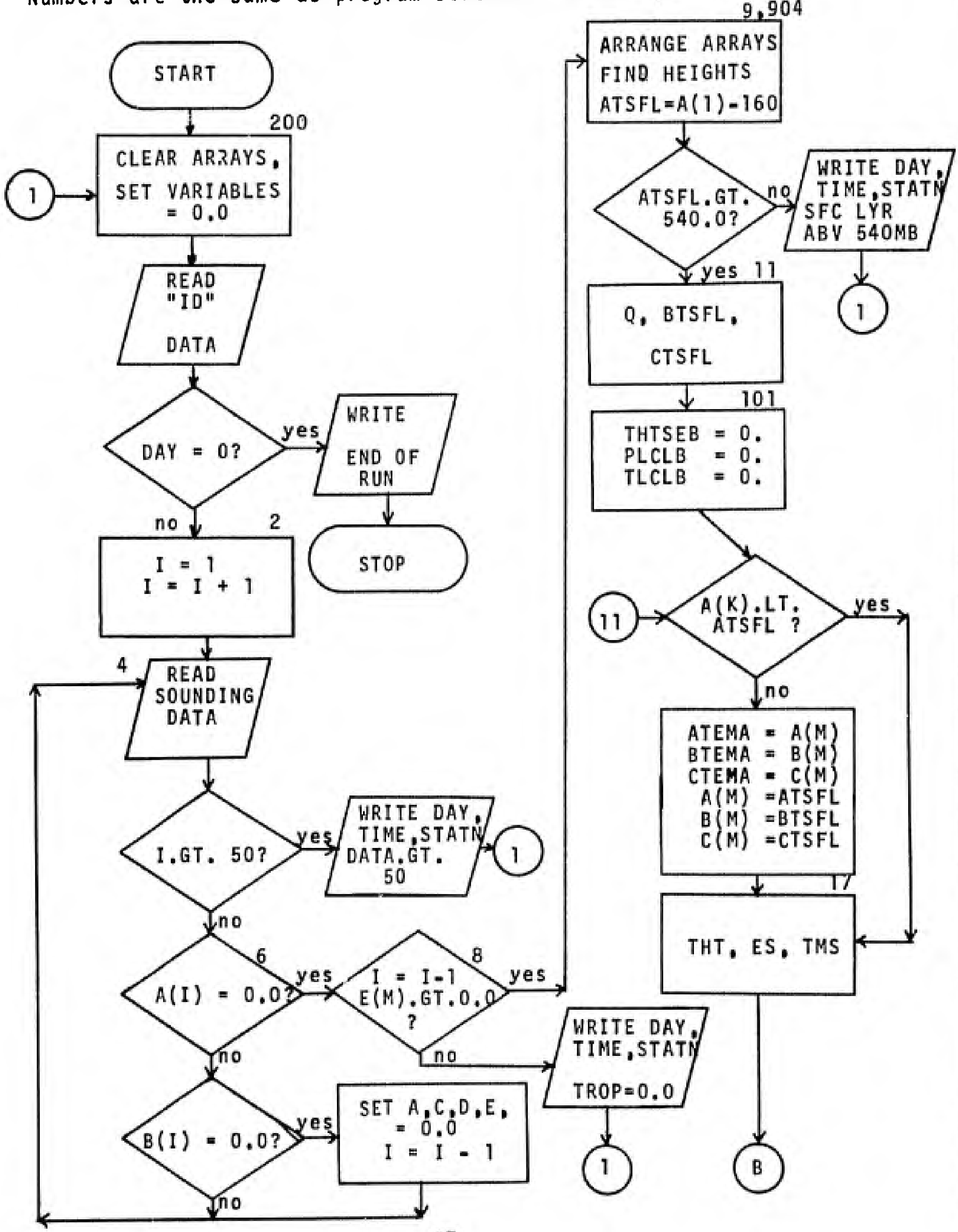
1. Block and station number, and date-time group are first to enter, and are separated from the sounding data.
2. There is a different "card" for each pressure level on the sounding.
3. A card with a pressure of 0000 follows each sounding.
4. The tropopause is identified as one of the pressure levels.
5. A blank card is at the end of the run.
6. The highest data point on the sounding has a height value.

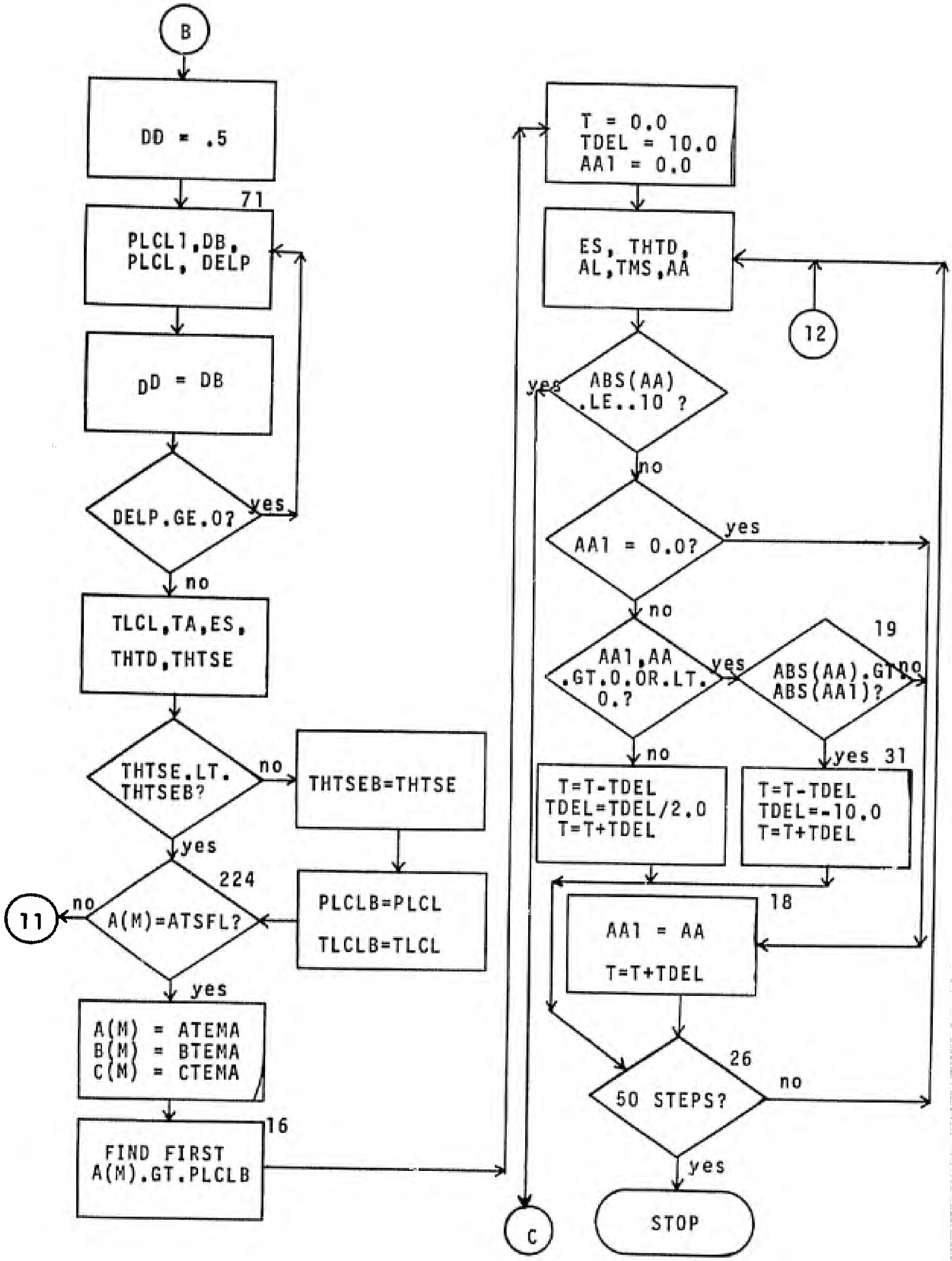
Field specifications for input and output can be found from the program statements in Section VIII,E, and the list of variables in Section VIII,D. The program has one subroutine, whose statements follow those of the main program. The lowest tropopause is used.

During the computations on the surface layer, the program determines whether or not these is a tropopause among the data, and goes to the next sounding (after an appropriate print out) if there is none. Also, a check is made to see if data below ground level are among the data points (that is, data with no temperatures). If so, these points are not included among the data arrays. If any part of the surface layer is above the 540 mb level, the program stops operating on that sounding and goes to the next (after a print out). Pseudo-adiabats are almost parallel to most soundings at or above this level, and strong convection is unlikely to begin at these heights. If the data are out of order pressure wise, the program will arrange them in the proper order.

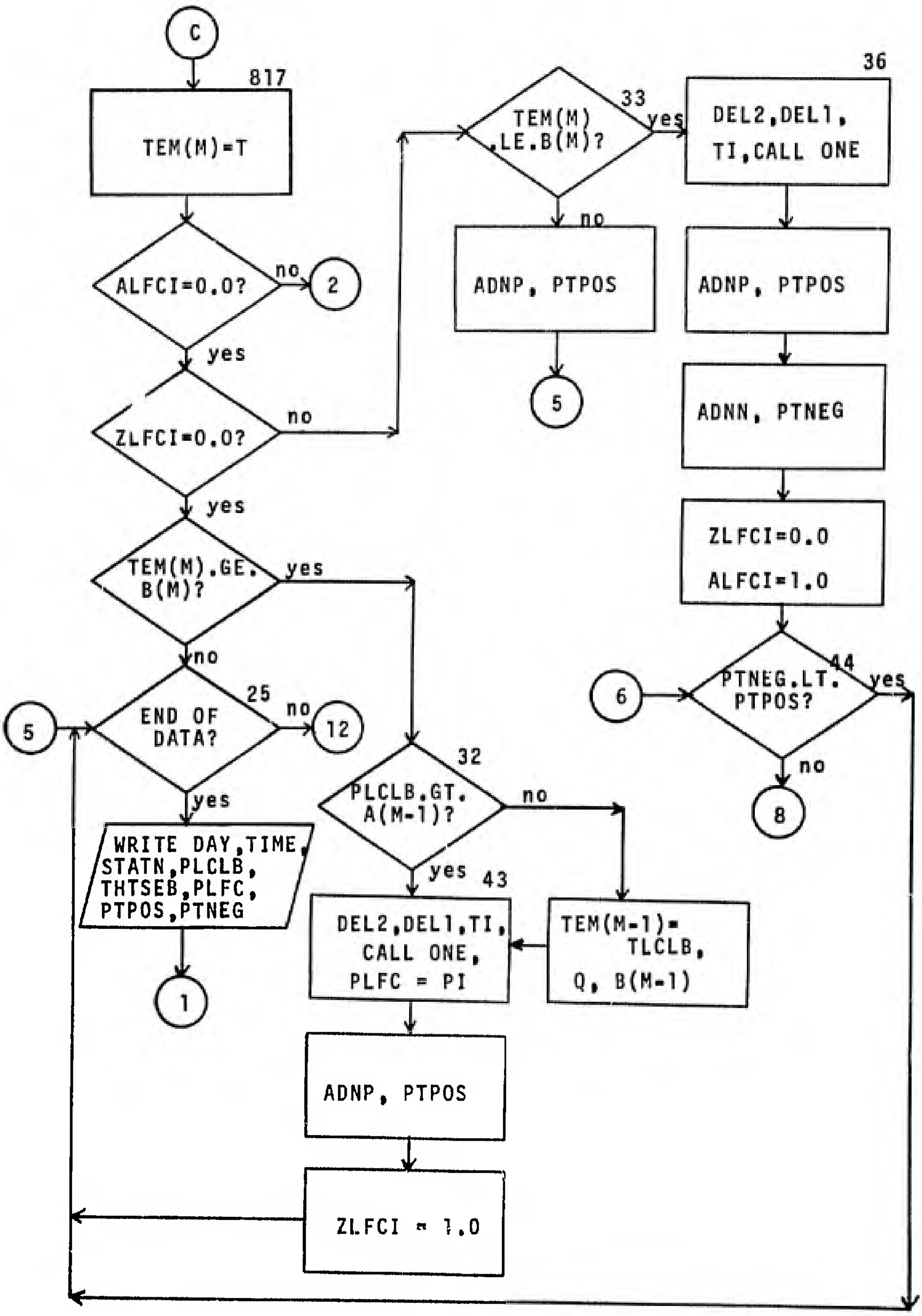
C. Block diagram

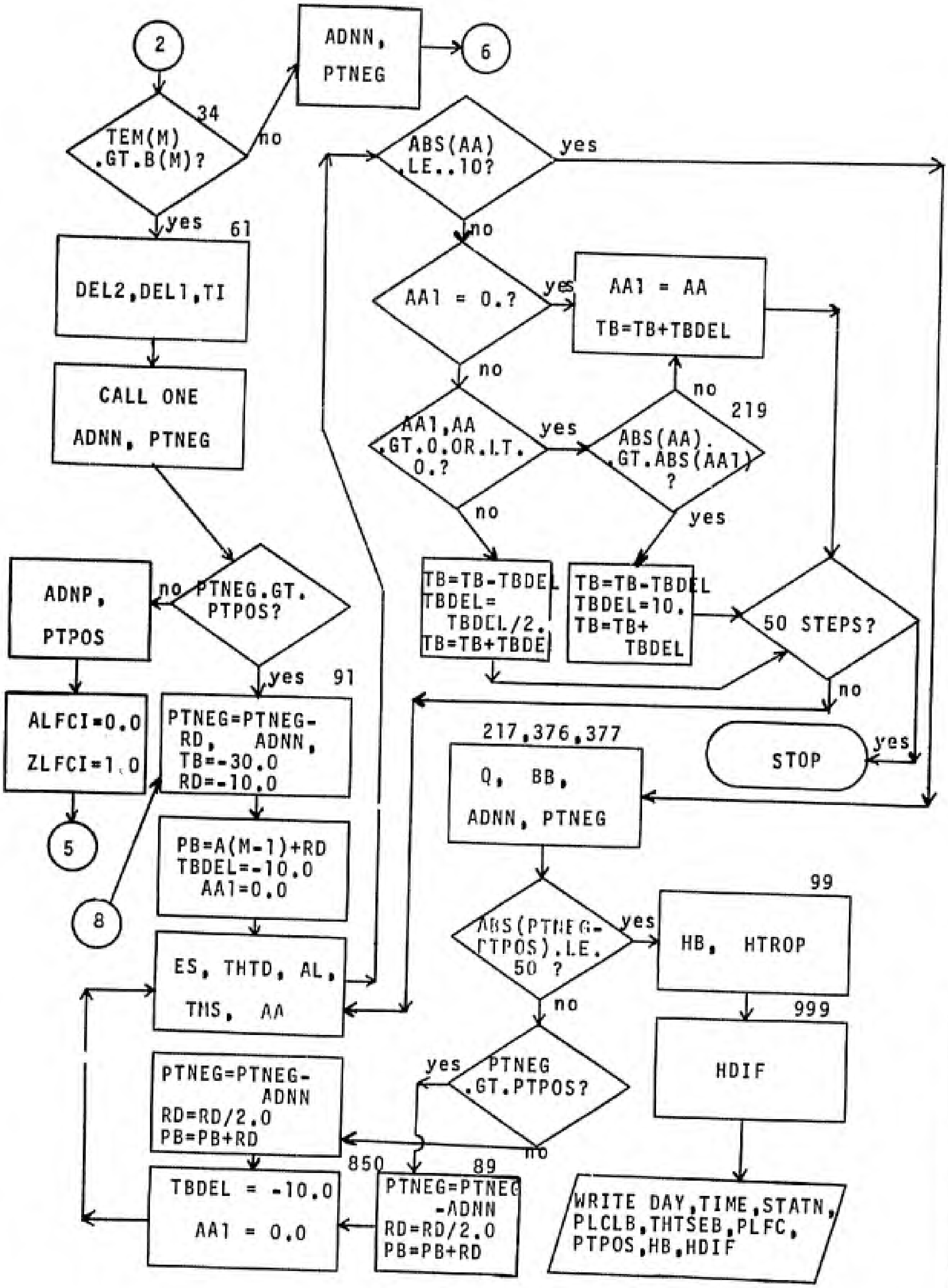
Numbers are the same as program statement numbers.



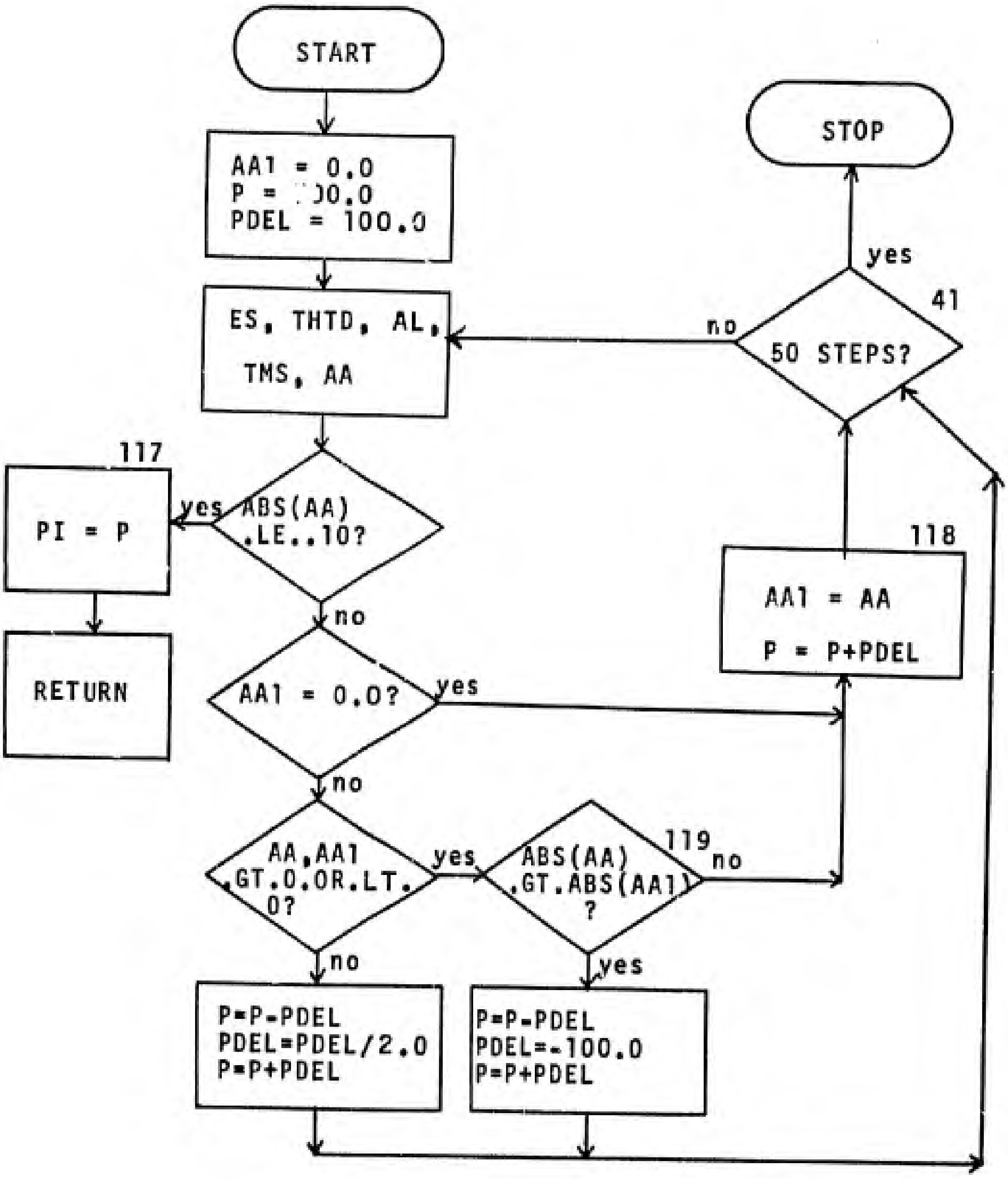


B
DD = .5
71
PLCL1,DB,
PLCL, DELP
DD = DB
DELP.GE.0?
yes
no
TLCL,TA,ES,
THTD,THTSE
THTSE.LT.
THTSEB?
no
THTSEB=THTSE
yes
224
PLCLB=PLCL
TLCLB=TLCL
11
no
A(M)=ATSFL?
yes
A(M) = ATEMA
B(M) = BTEMA
C(M) = CTEMA
16
FIND FIRST
A(M).GT.PLCLB
T = 0.0
TDEL = 10.0
AA1 = 0.0
ES, THTD,
AL,TMS,AA
12
yes
ABS(AA)
.LE..10 ?
no
AA1 = 0.0?
yes
no
19
AA1,AA
.GT.0.OR.LT.
0.?
yes
ABS(AA).GT.
ABS(AA1)?
no
no
yes 31
T=T-TDEL
TDEL=TDEL/2.0
T=T+TDEL
T=T-TDEL
TDEL=-10.0
T=T+TDEL
18
AA1 = AA
T=T+TDEL
26
50 STEPS?
no
yes
C
STOP


C
817
TEM(M)=T
ALFCI=0.0?
no
2
yes
ZLFCI=0.0?
no
yes
TEM(M).GE.B(M)?
yes
no
25
END OF DATA?
no
12
5
yes
WRITE DAY,TIME, STATN,PLCLB, THTSEB,PLFC, PTPOS,PTNEG
1
33
TEM(M) .LE.B(M)?
yes
no
ADNP, PTPOS
5
36
DEL2,DEL1, TI,CALL ONE
ADNP, PTPOS
ADNN, PTNEG
ZLFCI=0.0
ALFCI=1.0
6
44
PTNEG.LT. PTPOS?
yes
no
8
32
PLCLB.GT. A(M-1)?
no
yes
43
DEL2,DEL1,TI, CALL ONE, PLFC = PI
TEM(M-1)= TLCLB, Q, B(M-1)
ADNP, PTPOS
ZLFCI = 1.0


2
ADNN,
PTNEG
6
34
TEM(M)
.GT.B(M)?
no
yes
61
DEL2,DEL1,TI
CALL ONE
ADNN, PTNEG
ABS(AA)
.LE..10?
yes
no
AA1 = 0.?
yes
AA1 = AA
TB=TB+TBDEL
no
no
219
AA1,AA
.GT.0.OR.LT.
0.?
yes
ABS(AA).
GT.ABS(AA1)
?
no
yes
ADNP,
PTPOS
no
PTNEG.GT.
PTPOS?
TB=TB-TBDEL
TBDEL=
TBDEL/2.
TB=TB+TBDEL
TB=TB-TBDEL
TBDEL=10.
TB=TB+
TBDEL
50 STEPS?
yes
91
no
ALFCI=0.0
ZLFCI=1.0
PTNEG=PTNEG-
RD, ADNN,
TB=-30.0
RD=-10.0
217,376,377
STOP
yes
5
Q, BB,
ADNN, PTNEG
PB=A(M-1)+RD
TBDEL=-10.0
AA1=0.0
99
8
ABS(PTNEG-
PTPOS).LE.
50 ?
yes
HB, HTROP
ES, THTD, AL,
TMS, AA
no
999
HDIF
PTNEG=PTNEG-
ADNN
RD=RD/2.0
PB=PB+RD
yes
PTNEG
.GT.PTPOS?
no
850
89
TBDEL = -10.0
AA1 = 0.0
PTNEG=PTNEG
-ADNN
RD=RD/2.0
PB=PB+RD
WRITE DAY,TIME,STATN,
PLCLB,THTSEB,PLFC,
PTPOS,HB,HDIF

SUBROUTINE ONE



D. Variable names

A	=	pressure, mb.
B	=	temperature, C.
C	=	dew point, C.
D	=	height
E	=	tropopause; 1 = first, 2 = second, etc.
TEM	=	temperature on THTSEB
DAY	=	day, as 04, 22, etc.
TIME	=	time, as 00, or 12(GMT)
STATN	=	block and station number,as 72455
I	=	number of data points on sounding, also as index
ATSFL	=	pressure at top of surface layer
Q	=	a ratio
BTSFL	=	temperature at top of surface layer
CTSFL	=	dew point at top of surface layer
THTSEB	=	warmest pseudo-equivalent potential temperature that can be produced from a surface layer
PLCLB	=	best LCL in surface layer
()TEMA	=	a temporary holding place. also used as TEMP(), ATEM().
THT	=	potential temperature
ES	=	saturation vapor pressure
TMS	=	saturation mixing ratio
DD	=	see VIII,B (where it is used as "D")
PLCL1	=	first LCL pressure in iteration for THTSEB
DB	=	second computation of DD
PLCL	=	second LCL
TLCL	=	temperature at LCL, also as TLCLB for best surface lyr. pt.
TA	=	absolute temperature
AL	=	latent heat of vaporization
THTD	=	partial potential temperature
THTSE	=	pseudo-equivalent potential temperature
T	=	an intermediate temperature , C.
TDEL	=	a temperature difference
AA1	=	second calculation of AA
AA	=	see VIII,B
ALFCI	=	an indicator, if =1., negative count underway
ZLFCI	=	an indicator, if =1., positive count underway
PTPOS	=	total of positive energy
PTNEG	=	total of negative energy
ADNP	=	an amount to be added to PTPOS
ADNN	=	an amount to be added to PTNEG
TB	=	a balance temperature where PTPOS=PTNEG
RD	=	an increment of temperature,C
PB	=	pressure where PTPOS=PTNEG
TBDEL	=	an increment for TB
BB	=	sounding temperature where PTPOS=PTNEG
HB	=	height where PTPOS=PTNEG
HTROP	=	tropopause height
PI	=	pressure where THTSEB crosses sounding
TI	=	temperature where THTSEB crosses sounding
DELP	=	a pressure increment, also as DEL()
HDIF	=	HB-HTROP
PLFC	=	pressure of LFC

E. Program statements

```
C- BEGINING OF PROGRAM,CLEAR ARRAYS, SET VARIABLES = 0
      DIMENSION A(50),B(50),C(50),D(50),E(50),TEM(50)
  200 DO 20N=1,50
      A(N) = 0.0
      B(N) = 0.0
      C(N) = 0.0
      D(N) = 0.0
      E(N) = 0.0
   20 TEM(N) = 0.0
      PTPOS = 0.0
      PTNEG = 0.0
      ALFCI = 0.0
      ZLFCI = 0.0
      PLFC  = 0.0
      PLCLB = 0.0
      TLCLB = 0.0
      THTSEB= 0.0
C-READ IN SOUNDING DATA, PRINT IF END OF RUN
      READ (5,1) DAY, TIME, STATN
    1 FORMAT(I6,I2,I5)
      IF(DAY.NE. 0) GO TO 2
      WRITE(6,3)
    3 FORMAT(1H0, 10HEND OF RUN)
      STOP 12
    2 I=0
    4 I=I+1
      READ (5,5) A(I), B(I), C(I), D(I), E(I)
    5 FORMAT (5F6.0)
C-IF MORE THAN 50 DATA POINTS PRINT OUT
      IF(I.LE. 50) GO TO 6
```

```
      WRITE (6,7) DAY
    7 FORMAT( 1HO,4HDAY ,I6,2X,5HTIME ,I2,2X,
     16HSTATN ,I5,2X,10HDATA.GT.50)
      GO TO 200
C-TEST FOR LAST DATA CARD
    6 IF(A(I).NE. 0.0) GO TO 8
C-OMIT DATA POINTS WITH NO TEMPERATURES, CHECK FOR TROPOPAUSE
      IF(B(I).NE. 0.0) GO TO 4
      A(I) = 0.0
      C(I) = 0.0
      D(I) = 0.0
      E(I) = 0.0
      I=I-1
      GO TO 4
    8 I=I-1
      DO 21M = 1,I
      IF(E(M).GT. 0.0) GO TO 9
   21 CONTINUE
      WRITE(6,10) DAY, TIME, STATN
   10 FORMAT(1HO,4HDAY ,I6,2X,5HTIME ,I2,2X,
     16HSTATN ,2X,8HTROP = 0)
      GO TO 200
C-REARRANGE DATA POINTS TO PUT HIGHEST PRESSURE FIRST
    9 DO 22J=1,I
      K=J+1
      DO 22L =K,I
      IF(A(J).GE.A(L)) GO TO 22
      TEMPA =A(J)
      TEMPB =B(J)
      TEMPC =C(J)
```

```
      TEMPD = D(J)
      TEMPE = E(J)
      A(J) = A(L)
      B(J) = B(L)
      C(J) = C(L)
      D(J) = D(L)
      E(J) = E(L)
      A(L) = TEMPA
      B(L) = TEMPB
      C(L) = TEMPC
      D(L) = TEMPD
      E(L) = TEMPE
   22 CONTINUE
C- GIVE HEIGHTS TO DATA POINTS THAT DONT HAVE THEM
      K = 0
      DO 229K = 1,I
      IF(K.EQ.1) GO TO 229
      IF(K.EQ.I) GO TO 904
      IF(D(K).NE. 0.0) GO TO 229
      IF(D(K+1).NE. 0.0) GO TO 238
      DO 240M=1,50
      IF(D(M).EQ.0.0) GO TO 240
      ATEM6 = A(K+1)
      ATEM7 = A(K-1)
      A(K+1) = A(M)
      D(K+1) = D(M)
      D(K) = D(K-1)+((A(K-1)-A(K))/(AK-1)-A(K+1)))*(D(K+1)-D(K-1))
      A(K+1) = ATEM6
      A(K-1) = ATEM7
      GO TO 229
```

```
  240 CONTINUE
      STOP 16
  238 D(K) =D(K-1)+((A(K-1)-A(K))/(A(K-1)-A(K+1)))*(D(K+1)-D(K-1))
  229 CONTINUE
C-FIND PRESSURE AT TOP OF SURFACE LAYER
  904 ATSFL = A(1)-160.0
C-IF ATSFL IS ABOVE 540MB, PRINT OUT
      IF(ATSFL.GT.540.0) GO TO 11
      WRITE (6,12) DAY,TIME,STATN
   12 FORMAT( 1H0, 4HDAY ,I6,2X,5HTIME ,2X,
     16HSTATN ,I5,2X,17HSFC LYR ABV 540MB)
      GO TO 200
C- FIND TEMPERATURE AND DEW POINT AT TOP OF SURFACE LAYER
   11 DO 23K=1,I
      IF(A(K).GT.ATSFL) GO TO 23
      Q= (A(K-1)-ATSFL)/(AK-1)-A(K))
      IF(B(K-1).LE.B(K)) GO TO 76
      BTSFL = B(K-1)-(B(K-1)-B(K))*Q
      GO TO 78
   76 BTSFL = B(K-1)+(B(K)-B(K-1))*Q
   78 IF(C(K-1).LE.C(K))  GO TO 77
      CTSFL = C(K-1)-(C(K-1)-C(K))*Q
      GO TO 101
   77 CTSFL = C(K-1)+(C(K)-C(K-1))*Q
      GO TO 101
   23 CONTINUE
C- COMPUTE THTSEB FOR SURFACE LAYER
  101 THTSEB = 0.0
      PLCLB = 0.0
      TLCLB = 0.0
      DO 24M = 1,I
```

```
      IF(A(M).GT.ATSFL) GO TO 17
      ATEMA = A(M)
      BTEMA = B(M)
      CTEMA = C(M)
      A(M) = ATSFL
      B(M) = BTSFL
      C(M) = CTSFL
   17 THT = (B(M)+273.16)*(1000.0/A(M))**.2857
      ES = 6.11*10.0**(7.5*C(M)/(237.3+C(M)))
      TMS = .622*(ES/(A(M)-ES))
C- COMPUTE LCL TO WITHIN 2 MB
      DD = .5
   71 PLCL1 = 1000.0*((2048.7-35.86*DD)/(THT*(7.5-DD)))**3.5
      DB = ALOG10(PLCL1*TMS/(6.11*(.622+TMS)))
      PLCL= 1000.0*((2048.7-35.86*DB)/(THT*(7.5-DB)))**3.5
      DELP = ABS(PLCL1-PLCL)
      DD=DB
      IF( DELP.GE.2.0) GO TO 71
      TLCL = 237.3*DD/(7.5-DD)
C-COMPUTE THTSEB
      TA = 273.16+TLCL
      AL = 596.73-.601*TLCL
      ES = 6.11*10.0**(7.5*TLCL/(237.3+TLCL))
      THTD = TA*(1000.0/(PLCL-ES))**.2857
      THTSE = THTD*EXP(AL*TMS/(.24*TA))
      IF(THTSE.LT.THTSEB) GO TO 224
      THTSEB = THTSE
      PLCLB = PLCL
      TLCLB = TLCL
  224 IF(A(M).NE.ATSFL) GO TO 24
```

```
      A(M) = ATEMA
      B(M) = BTEMA
      C(M) = CTEMA
      GO TO 16
   24 CONTINUE
C-FIND NEXT DATA POINT ABOVE LCL AND FIND T ON THTSEB
   16 DO 25M=1,I
      IF(A(M).GT.PLCLB) GO TO 25
      T = 0.0
      TDEL = 10.0
      AA1 = 0.0
      DO 26K = 1,50
      ES = 6.11*10.0**(7.5*T/(T+237.3))
      THTD=(273.16+T)*(1000.0/(A(M)-ES))**.2857
      AL=596.73-.601*T
      TMS = .622*(ES/(A(M)-ES))
      AA=THTD*EXP(AL*TMS/(.24*(273.16+T)))-THTSEB
      IF( ABS(AA).LE..10) GO TO 817
      IF( AA1.EQ.0.0) GO TO 18
      IF( AA1.GT.0.0.AND.AA.GT.0.0.ORAA1.LT.0.0.ANDAA.LT.0.0)GO TO
      T=T-TDEL
      TDEL=TDEL/2.0
      T=T+TDEL
      GO TO 26
   19 IF(ABS(AA).GT.ABS(AA1)) GO TO 31
      GO TO 18
   31 T=T-TDEL
      TDEL = -10.0
      T=T+TDEL
      GO TO 26
```

```
   18 AA1 = AA
      T=T+TDEL
   26 CONTINUE
      STOP 13
  817 TEM(M)=T
C-ARE WE COUNTING POSITIVE OR NEGATIVE NUMBERS, OR ARE WE BELOW LFC
      IF(ZLFCI.NE. 0.0) GO TO 33
      IF(ALFCI.NE. 0.0) GO TO 34
      IF(TEM(M).GE.B(M)) GO TO 32
      GO TO 25
C- IS THERE A DATA POINT BETWEEN PLCL AND PLFC ,START LFC COMPUTATION
   32 IF(PLCLB.GT.A(M-1)) GO TO 43
      TEM(M-1) = TLCLB
      Q= (A(M-1)-PLCLB)/(A(M-1)-A(M))
      B(M-1)=B(M-1)-Q*(B(M-1)-B(M))
   43 DEL2=B(M)-TEM(M)
      DEL1=B(M-1)-TEM(M -1)
      TI=(B(M-1)*DEL*-B(M)*DEL1)/(DEL2-DEL1)
      CALL ONE (TI, THTSEB, PI)
C-ADD POSITIVE NUMBERS ABOVE LFC
      ADNP=((TEM(M)-B(M))/2.0)*(PI-A(M))
      PTPOS=PTPOS +ADNP
      ZLFCI = 1.0
      GO TO 25
C- HAS THTSEB CROSSED OVER SOUNDING
   33 IF( TEM(M).LE.B(M)) GO TO 36
C- ADD POSITIVE NUMBERS
      ADNP=((TEM(M)-B(M)+TEM(M-1)-B(M-1))/2.0)*(A(M-1)-A(M))
      PTPOS = PTPOS + ADNP
      GO TO 25
C- FIND TI AND PI
```

```
   36 DEL2=B(M)-TEM(M)
      DEL1= B(M-1)-TEM(M-1)
      TI=(B(M-1)*DEL2-B(M)*DEL1)/(DEL2-DEL1)
      CALL ONE (TI, THTSEB, PI)
C-ADD POSITIVE AND NEGATIVE NUMBERS
      ADNP=((TEM(M-1)-B(M-1))/2.0)*(A(M-1)-PI)
      PTPOS = PTPOS + ADNP
      ADNN=((B(M)-TEM(M))/2.0)*(PI-A(M))
      PTNEG = PTNEG + ADNN
      ZLFCI = 0.0
      ALFCI = 1.0
   44 IF(PTNEG.LT.PTPOS) GO TO 25
C-FIND BALANCE LEVEL, FIRST TAKE 1/2 STEPS, THEN 1/4, ETC.
   91 PTNEG = PTNEG - ADNN
      TB=-30.0
      RD = -(A(M-1)-A(M))/2.0
      PB=A(M-1)+RD
      TBDEL = -10.0
      AA1 = 0.0
      DO51K=1,250
      ES=6.11*10.0**(7.5*TB/(TB+237.3))
      THTD = (273.16+TB)*(1000.0/(PB-ES))**.2857
      AL=596.73-.601*TB
      TMS= .622*(ES/(PB-ES))
      AA=THTD*EXP(AL*TMS/(.24*(273.16+TB)))-THTSEB
      IF(ABS(AA).LE..10) GO TO 217
      IF(AA1.EQ.0.0) GO TO 218
      IF(AA1.GT.0.0.AND.AA.GT.0.0.OR.AA1.LT.0.0.AA.LT.0.0)GO TO 219
      TB =TB-TBDEL
      TBDEL = TBDEL/2.0
```

```
      TB=TB + TBDEL
      GO TO 51
  218 AA1 = AA
      TB=TB+TBDEL
      GO TO 51
C- FIND BALANCE TEMPERATURE
  217 Q=(A(M-1)-PB)/(A(M-1)-A(M))
      IF(B(M-1).LE.B(M)) GO TO 376
      BB=B(M-1)-B(M-1)-B(M))*Q
      GO TO 377
  376 BB=B(M-1)+(B(M)-B(M-1))*Q
  377 ADNN=((B(M-1)-TEM(M-1)+BB-TB)/2.0)*(A(M-1)-PB)
      PTNEG = PTNEG + ADNN
      IF(ABS(PTNEG-PTPOS).LE.50.0) GO TO 99
      IF(PTNEG.GT.PTPOS) GO TO 89
      PTNEG = PTNEG - ADNN
      RD* RD/2.0
      PB=PB+RD
      GO TO 850
   89 PB=PB-RD
      PTNEG=PTNEG-ADNN
      RD=RD/2.0
      PB=PB+RD
  850 TBDEL=-10.0
      AA1=0.0
   51 CONTINUE
      STOP  99
C-FIND HEIGHT OF BALANCE LEVEL
   99 HB=D(M-1)+(AM-1)-PB)/(A(M-1)-A(M))*(D(M)-D(M-1))
      DO66K=1,I
```

```
C-FIND TROPOPAUSE HEIGHT
      IF(E(K).EQ.0.0) GO TO 66
      HTROP= D(K)
      GO TO 999
   66 CONTINUE
C-COUNT NEGATIVE NUMBERS
   34 IF TEM(M).GT.B(M)) GO TO 61
      ADNN= ((B(M)-TEM(M)+B(M-1)-TEM(M-1))/2.0)*(A(M-1)-A(M))
      PTNEG = PTNEG+ADNN
      GO TO 44
C-FIND CROSSOVER POINT, CHECK TOTALS, AND ADD POSITIVE NUMBERS
   61 DEL2= B(M)-TEM(M)
      DEL1=  B(M-1)-TEM(M-1)
      TI=(B(M-1)*DEL2-B(M)*DEL1)/(DEL2-DEL1)
      CALL ONE (TI, THTSEB, PI)
      ADNN=((B(M-1)-TEM(M-1))/2.0)*(A(M-1)-PI)
      PTNEG=PTNEG+ADNN
      IF (PTNEG.GT.PTPOS) GO TO 91
      ADNP=((TEM(M)-B(M))/2.0)*(PI-A(M))
      PTPOS =PTPOS+ADNP
      ALFCI=0.0
      ZLFCI=1.0
   25 CONTINUE
      WRITE(6,63) DAY, TIME,STATN,PLCLB,THTSEB,PLFC,PTPOS,PTNEG
   63 FORMAT(1H0,4HDAY ,I6,2X,5HTIME ,I2,2X,
     16HSTATN ,I5,/1H0,8HPLCLB + ,F9.3,2X,9HTHTSEB = ,
     2F9.3,2X,7HPLFC = ,F9.3,/1H0,8HPTPOS = ,F9.1,
     32X,8HPTNEG = ,F9.1,2X,13HNO BALANCE PT)
      GO TO 200
  999 HDIF=HB-HTROP
```

```
      WRITE(6,65) DAY,TIME,STATN,PLCLB,
   65 FORMAT(1H0,4HDAY ,I6,2X,5HTIME ,I2,2X,
     16HSTATN ,I5,/1H0,8HPLCLB = ,F9.3,2X,9HTHTSEB = ,
     2F9.3,2X,7HPLFC = ,F9.3,/1H0,8HPTPOS = ,F9.1,
     32X,5HHB = ,F9.1,2X,7HHDIF = ,F9.1)
      GO TO 200
      END
```

SUBROUTINE ONE

```
C-PROGRAM BEGINS(SUBROUTINE ONE)
      SUBROUTINE ONE(TI,THTSEB,PI)
      AA1=0.0
      P=700.0
      PDEL=100.0
      DO41M=1,50
      ES=6.11*10.0**(7.5*TI/(TI+237.3))
      THTD=(273.16+TI)*(1000.0/(P-ES))**.2857
      AL=596.73-.601*TI
      TMS=.622*(ES/(P-ES))
      AA=THTD*EXP(AL*TMS/(.24*(273.16+TI)))-THTSEB
      IF(ABS(AA).LE..10) GO TO 117
      IF(AA1.EQ.0.0)GO TO 118
      IF(AA1.GT.0.0.AND.AA.GT.0.0.OR.AA1.LT.0.0.AND.AA.LT.0.0)GO TO 119
      P=P-PDEL
      PDEL=PDEL/2.0
      P=P+PDEL
      GO TO 41
  119 IF(ABS(AA).GT.ABS(AA1)) GO TO 131
      GO TO 118
  131 P=P-PDEL
```

```
      PDEL = -100.0
      P=P+PDEL
      GO TO 41
  118 AA1=AA
      P=P+PDEL
   41 CONTINUE
      STOP
  117 PI= P
      RETURN
      END
```

IX. Summary

Some data are available on thunderstorm penetrations of the tropopause from radars with RHI capability in other parts of the world. These stations are listed, along with a second list of radars with RHI capability which, for several reasons, are not producing useful data.

Several stations in Canada, and three from other regions did send data in addition to the stations reported on in a previous report. The Canadian stations were concentrated in the southern and eastern parts of the country, and showed patterns similar to stations in the United States which were located nearby. Data are also presented for several other United States stations other than those reported on previously. These stations are, in general, located in between the stations studied earlier, and support the patterns found earlier. One important result from the new United States data is the northward extension of the region of numerous penetrations up to near the Canadian border. A second finding is a lower number of penetrations at Oklahoma City than at Kansas City and New Orleans, although Oklahoma City has more severe weather than the other two sites. Aside from the total number of penetrations and distributions derived from this number, Oklahoma City was quite similar to the other sites in its area, showing, for instance, a nighttime secondary maximum of penetrations, like Kansas City.

The Canadian and American data were combined to give a climatology for the North American Continent, with emphasis on three

items. The first item is the location of the area of maximum penetrations. The area appears to be on the coast of the Gulf of Mexico in Louisiana and eastern Texas. A secondary area appears to be in the region of maximum occurrence of tornadoes and severe thunderstorms, roughly from Kansas City southward towards Oklahoma City. A breakdown into three month periods suggests a small maximum along the east coast, near New York, in summer. The second item is the effect of the great lakes. There were two stations located on the lakes in the combined group, and both showed fewer penetrations than a station further to the north, and removed from the lakes. This lake effect is thought to extend to all of the lakes, since the stations were on one of the shallow eastern lakes(Ontario), and the larger lakes are deeper and colder, therefore decreasing chances for very warm temperatures needed for penetrations.
The third item is the northern limit of penetrations. Stations in eastern Canada, and northeastern United States give a good picture of the northern limit, which passes through New England and parts of southern Quebec and Ontario. No data were available across the prairie provinces, but penetration totals were estimated for Winnipeg. Since the estimates at Winnipeg suggested larger numbers of penetrations than the other Canadian stations, the northern limit of penetrations was placed over the northern parts of the prairie provinces and south along the eastern edge of the Canadian Rocky Mountains.

The fragmentary information outside North America suggests only a few favored areas where more than just a few penetrations are likely to occur each year. These favored areas seem to be northeastern China, and parts of India, Russia, and Argentina. Strong orographic effects may cause penetrations in isolated areas elsewhere.

Even if more radar data had been received, large areas of the world still must have their penetrations estimated. Two studies suggest that the sole use of low level moisture or the amount of available energy will not be successful in estimating thunderstorm tops. The same low level moisture values give different cloud tops for different stations, and the sharp gradients of moisture at the surface can radically alter the height computations over short distances and times. Different storms seem to use different amounts of the same total energy available to them, producing several different top heights above the tropopause using the same initial conditions.

An exponential equation of the form $Y = Ae^{-bX}$ was found to fit the cumulative frequencydistribution of penetrations very closely at all of the ten United States stations studied in the first part of the contract period. The constant "b" was found to have some variation with the amount of night thunderstorm activity, suggesting that day and night thunderstorms may act differently.

A method of estimating annual cumulative frequency distributions of penetrations using a simple energy balance method to find the top of the highest cloud that could occur, and the exponential equation for the rest of the distribution was tested on two stations with good results.

A computer program to estimate the height of the highest cloud that could form from any sounding is included in this report. The program also determines how much above or below the tropopause this cloud top will be. There are very few restrictions on the arrangement of the data, so as to make the program available to a variety of data input. The program is written to handle problems dealing with data below ground level, a lack of a tropopause, low level inversions, soundings starting at very high levels, and very stable soundings. Program statements and variable names are included along with a block diagram.

X. References

Donaldson, R. J., Jr., (1963), Radar as a severe thunderstorm sensor. Paper presented at the XIII General Assembly IUGG-Berkeley, California.

Fitzgerald, D.R., and Valovcin, F.R., (1964), High altitude observations of the development of a tornado producing thunderstorm. Paper presented at the Conference on Physics and Dynamics of clouds, Chicago, Illinois.

Hanks, H.H., Jr., Long, M.J., and Beebe, R.G., (1964), Tropopause Penetrations by Cumulonimbus Clouds, AFCRL-64-111, Scientific Report No. 1, Contract AF19(628)-2454, Atmospheric Research & Development Corp.,Kansas City, Mo.

Long, M.J., (1965), Tropopause Penetrations by Cumulonimbus Clouds-II,AFCRL-65-331, Scientific Report No. 2, Contract AF19(628)-2454, Atmospheric Research & Development Corp., Kansas City.

Long, M.J., Hanks, H.H., Jr., and Beebe, R.G., (1965), Tropopause Penetrations by Cumulonimbus Clouds, AFCRL-65-561, Final Report, Contract AF19(628)-2454, Atmospheric Research & Development Corp., Kansas City.

Long, M.J., (1966), A case of rapid cooling near the tropopause, near a line of tall thunderstorms, J. Appl. Meteor. Vol. 5, 851-856.

Prosser, N.E., and Foster, D.S., (1966), Upper air sounding analysis by use of an electronic computer, J. Appl. Meteor., Vol. 5, 296-300.

Rhea, J. O., (1966), A study of thunderstorm formation along dry lines, J. Appl. Meteor., Vol. 5, 58-63.

Rossby, C.G., (1932), Thermodyanmics applied to air mass analysis. MIT and Woods Hole Oceanographic Institution Papers in Physical Oceanography and Meteorology (Massachusetts Institute of Technology Meteorology Papers), Vol. 1, No. 3, 41 pp.

Seshadri, N., (1963), A radar study of heights of tops of cumulonimbus clouds around New Delhi, Ind. J. Meteor. and Geoph., Vol. 14, 46-49.

Stackpole, J.D., (1967), Numerical analysis of atmospheric soundings, J. Appl. Meteor., Vol 6, 464-467.

Tetens,O., (1930), Uber einige meteorologische Begriffe, Z. Geophys., Vol. 6, 297-309.

Visher, S.S., (1954), Climatic Atlas of the United States, Harvard University Press, Cambridge, p 169.

UNCLASSIFIED
Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Atmospheric Research & Development Corp. 1600 Genesee St. Rm. 856 Kansas City, Mo. 64102	2a. REPORT SECURITY CLASSIFICATION unclassified 2b. GROUP

3. REPORT TITLE
THUNDERSTORM PENETRATIONS OF THE TROPOPAUSE, A CLIMATOLOGY AND A METHOD OF ESTIMATION

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Scientific. Final period covered Aug 1965 thru Jul 1967 approved 5 Sept 1967

5. AUTHOR(S) (Last name, first name, initial)
Michael J. Long

6. REPORT DATE August 1967	7a. TOTAL NO. OF PAGES 79	7b. NO. OF REFS 13

8a. CONTRACT OR GRANT NO. AF19(628)-5189	9a. ORIGINATOR'S REPORT NUMBER(S)
b. PROJECT NO. Task, Work Unit No.'s 8624- 01 01	
c. DoD Element 62405394	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) AFCRL-67-0471
d. DoD Subelement 681000	

10. AVAILABILITY/LIMITATION NOTICES
Distribution of this document is unlimited. It may be released to the Clearinghouse, Department of Commerce, for sale to the general public.

11. SUPPLEMENTARY NOTES Tech., Other	12. SPONSORING MILITARY ACTIVITY Air Force Cambridge Research Laboratories (CRE) L.G. Hanscom Field Bedford, Massachusetts 01730

13. ABSTRACT

Data sources for radar measurement of thunderstorm penetrations of the tropopause level outside the United States are listed, and a climatology for North America is presented. Important features are a double maximum over central and southern United States, a decrease in penetrations around the great lakes, and a few penetrations north of 50 N. Although few penetrations were found outside North America, northeastern China is listed as the next most likely area for large numbers of penetrations.

Two studies suggest that the sole use of low level moisture or the maximum amount of energy available to a storm will not be successful in estimating penetration amounts. An equation of the form $Y=Ae^{-bX}$ was found to fit the cumulative distribution of penetrations at ten United States stations. A method of estimating the cumulative frequency distribution of penetrations based on a determination of the highest penetration and the above equation gave good results. A computer program is included which will determine the highest penetration likely from a sounding.

DD FORM 1 JAN 64 1473 0101-807-6800

UNCLASSIFIED
Security Classification

14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
Radar locations						
Tropopause penetration climatology						
Thunderstorm moisture						
Thunderstorm energy						
Tropopause penetrations						
Penetration estimates						
Sounding computer program						

INSTRUCTIONS

1. **ORIGINATING ACTIVITY:** Enter the name and address of the contractor, subcontractor, grantee, Department of Defense activity or other organization *(corporate author)* issuing the report.

2a. **REPORT SECURITY CLASSIFICATION:** Enter the overall security classification of the report. Indicate whether "Restricted Data" is included. Marking is to be in accordance with appropriate security regulations.

2b. **GROUP:** Automatic downgrading is specified in DoD Directive 5200.10 and Armed Forces Industrial Manual. Enter the group number. Also, when applicable, show that optional markings have been used for Group 3 and Group 4 as authorized.

3. **REPORT TITLE:** Enter the complete report title in all capital letters. Titles in all cases should be unclassified. If a meaningful title cannot be selected without classification, show title classification in all capitals in parenthesis immediately following the title.

4. **DESCRIPTIVE NOTES:** If appropriate, enter the type of report, e.g., interim, progress, summary, annual, or final. Give the inclusive dates when a specific reporting period is covered.

5. **AUTHOR(S):** Enter the name(s) of author(s) as shown on or in the report. Enter last name, first name, middle initial. If military, show rank and branch of service. The name of the principal author is an absolute minimum requirement.

6. **REPORT DATE:** Enter the date of the report as day, month, year; or month, year. If more than one date appears on the report, use date of publication.

7a. **TOTAL NUMBER OF PAGES:** The total page count should follow normal pagination procedures, i.e., enter the number of pages containing information.

7b. **NUMBER OF REFERENCES:** Enter the total number of references cited in the report.

8a. **CONTRACT OR GRANT NUMBER:** If appropriate, enter the applicable number of the contract or grant under which the report was written.

8b, 8c, & 8d. **PROJECT NUMBER:** Enter the appropriate military department identification, such as project number, subproject number, system numbers, task number, etc.

9a. **ORIGINATOR'S REPORT NUMBER(S):** Enter the official report number by which the document will be identified and controlled by the originating activity. This number must be unique to this report.

9b. **OTHER REPORT NUMBER(S):** If the report has been assigned any other report numbers *(either by the originator or by the sponsor)*, also enter this number(s).

10. **AVAILABILITY/LIMITATION NOTICES:** Enter any limitations on further dissemination of the report, other than those imposed by security classification, using standard statements such as:

(1) "Qualified requesters may obtain copies of this report from DDC."

(2) "Foreign announcement and dissemination of this report by DDC is not authorized."

(3) "U. S. Government agencies may obtain copies of this report directly from DDC. Other qualified DDC users shall request through ________."

(4) "U. S. military agencies may obtain copies of this report directly from DDC. Other qualified users shall request through ________."

(5) "All distribution of this report is controlled. Qualified DDC users shall request through ________."

If the report has been furnished to the Office of Technical Services, Department of Commerce, for sale to the public, indicate this fact and enter the price, if known.

11. **SUPPLEMENTARY NOTES:** Use for additional explanatory notes.

12. **SPONSORING MILITARY ACTIVITY:** Enter the name of the departmental project office or laboratory sponsoring *(paying for)* the research and development. Include address.

13. **ABSTRACT:** Enter an abstract giving a brief and factual summary of the document indicative of the report, even though it may also appear elsewhere in the body of the technical report. If additional space is required, a continuation sheet shall be attached.

It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as *(TS)*, *(S)*, *(C)*, or *(U)*.

There is no limitation on the length of the abstract. However, the suggested length is from 150 to 225 words.

14. **KEY WORDS:** Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, roles, and weights is optional.