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U.S. DEPARTMENT OF COMMERCE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
Environmental Research Laboratories

Florida Cumulus Seeding Experiment for Drought Mitigation, April-May 1971

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Office
of the Director
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COLORADO
November 1971

ENVIRONMENTAL RESEARCH LABORATORIES

OFFICE OF THE DIRECTOR

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NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

BOULDER, COLORADO

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Boulder, Colorado
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ABSTRACT

A record drought in south Florida in the spring of 1971 led Governor Reubin Askew to request Dr. R. M. White, Administrator of NOAA, for aid. Consequently EML, with the cooperation and partial support of the Central and Southern Florida Flood Control District, undertook a dynamic cumulus seeding program in two target areas, one to the north (4400 n mi^2) and the other to the south (2800 n mi^2) of Lake Okeechobee.

In the 61-day operational period from 1 April - 31 May, flights were conducted on 16 days, with actual seeding on 14 days. Real time runs of the EML one-dimensional cumulus model on the 1200 GMT Miami radiosonde eliminated 38 days as unseedable; seven additional seed days might have been obtained had a back-up seeder aircraft been available. Altogether, 2066 50-gm AgI flares were dropped into 196 clouds or cloud complexes. Severe drought and cloud scarcity forced abandonment of planned randomization.

Evaluation was by rain gages and 10-cm radars, the WSR-57 of the National Weather Service and the calibrated radar of the University of Miami (beginning 10 May). Altogether, seeded clouds produced about 180,000 acre-feet of rain. Conservative estimates ascribe about 100,000 acre-feet to seeding, leading to a benefit-to-cost ratio for the program exceeding thirty-to-one. As expected, however, the seeding could not break the drought and contributed only about three percent of the water or five to ten percent of the actual two-monthly rainfall in south Florida. Nevertheless, the seeded precipitation was highly beneficial locally and quenched numerous drought-produced fires.

About 70 percent of the seeded precipitation fell on four seeded days, while about 25 percent fell on one day (April 26) in which the seeded clouds were associated with an old front and strong vertical wind shear. Cumulonimbus merger played the key role in all heavily raining cases.

Possible adverse side effects of dynamic seeding, such as severe weather and ecological damage due to the silver content of rainfall, are being studied carefully by EML.

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1. INTRODUCTION

Despite a rather high mean annual rainfall of 50 to 60 inches (fig. 1), Florida is occasionally subjected to severe drought. The drought over south Florida from spring 1970 through spring 1971 reached record proportions. Following very heavy rains over south Florida during March 1970 (over 18 inches in some locations), a severe and prolonged drought set in over the area. During the 12-month period from April 1970 through March 1971 rainfall at Miami International Airport was 65 percent of normal (annual mean of 59.76 inches), and during the 6-month period from October 1970 through March 1971 rainfall was only 26 percent of normal (6-month mean of 18.88 inches). During the normal dry season (November through April) only 2.04 inches fell at the airport, not even a third of the previous record dry season rainfall of 6.47 inches that was recorded from November through April 1944/45. In addition, the rainfalls during November 1970 (0.09 inches) and April (0.07) resulted in the driest November and April since records began in 1911.

Another factor that contributed greatly to the drought was the lack of significant daily rains that would permit the rainfall to reach sub-surface water tables. From May 1970 through April 1971 24-hour rainfall amounts of more than one inch occurred only eight times compared

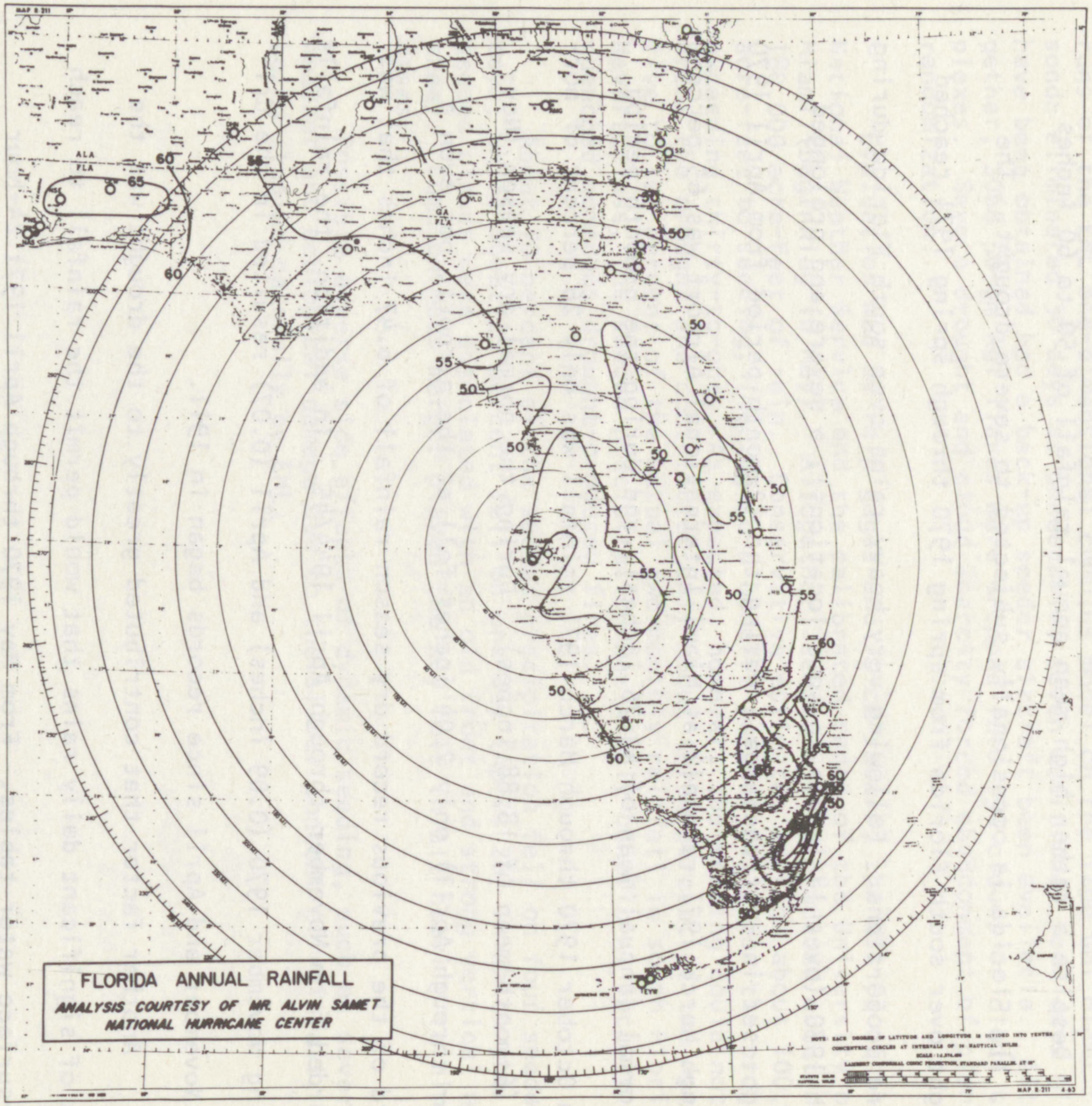


Figure 1. Annual rainfall for the state of Florida. Twenty years of record and 200 stations went into the analysis. Analysis courtesy of Mr. Alvin Samet of the National Hurricane Center.

to a normal of 23 times. From September 16, 1970 through April 30, 1971 daily rain amounts did not exceed one inch. This 226 day period exceeds by a large amount the previous record of 118 days in 1956-57.

The record drought combined with high daytime temperatures during April 1971 to damage plant and wild life over south Florida. Numerous grass and muck fires were reported over much of the Florida Everglades (fig. 2) and water tables dropped to record lows. By the end of April 1971 the threat of salt water intrusion to drinking supplies along the immediate coast was severe. The water levels of several wells in the Miami Springs and Homestead areas were below sea level and many home wells were dry. The level of Lake Okeechobee, the large fresh water reservoir for south Florida, dropped from 16.8 ft on 3 April 1970 to 14.2 ft on 25 August 1970 to a minimum of 10.31 ft on 7 June 1971 (lows of 10.14 ft in 1956 and 10.25 ft in 1962). A plot of the lake level from January through mid-June 1971 is found in fig. 3. For the central and southern Florida conservation areas as a whole, the water deficit on April 1, 1971 exceeded three million acre-feet.

South Florida was not the only region experiencing a severe drought during 1970 and 1971. Much of southern United States was suffering from a lack of rainfall as shown in fig. 4. Besides parts of Florida, much of Texas was especially dry. It is not known whether the same or separate causes were responsible for the droughts in Texas and Florida.

Although the precipitation in May 1971 was still below normal (4.13 versus a normal of 6.44 inches), locally heavy rains helped considerably. Above normal rains in June 1971 (11.55 versus a normal of 7.37)

Figure 2. A grass and muck fire in south Florida during the severe drought of 1971.

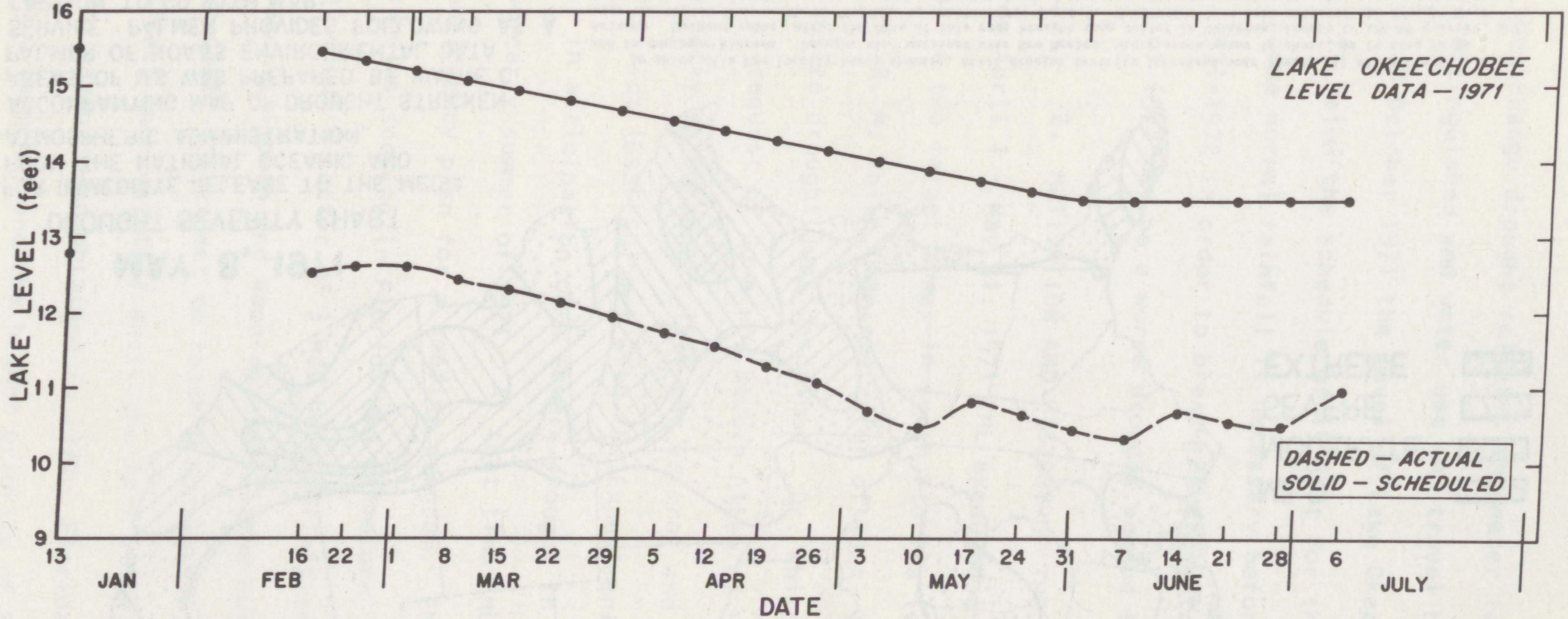
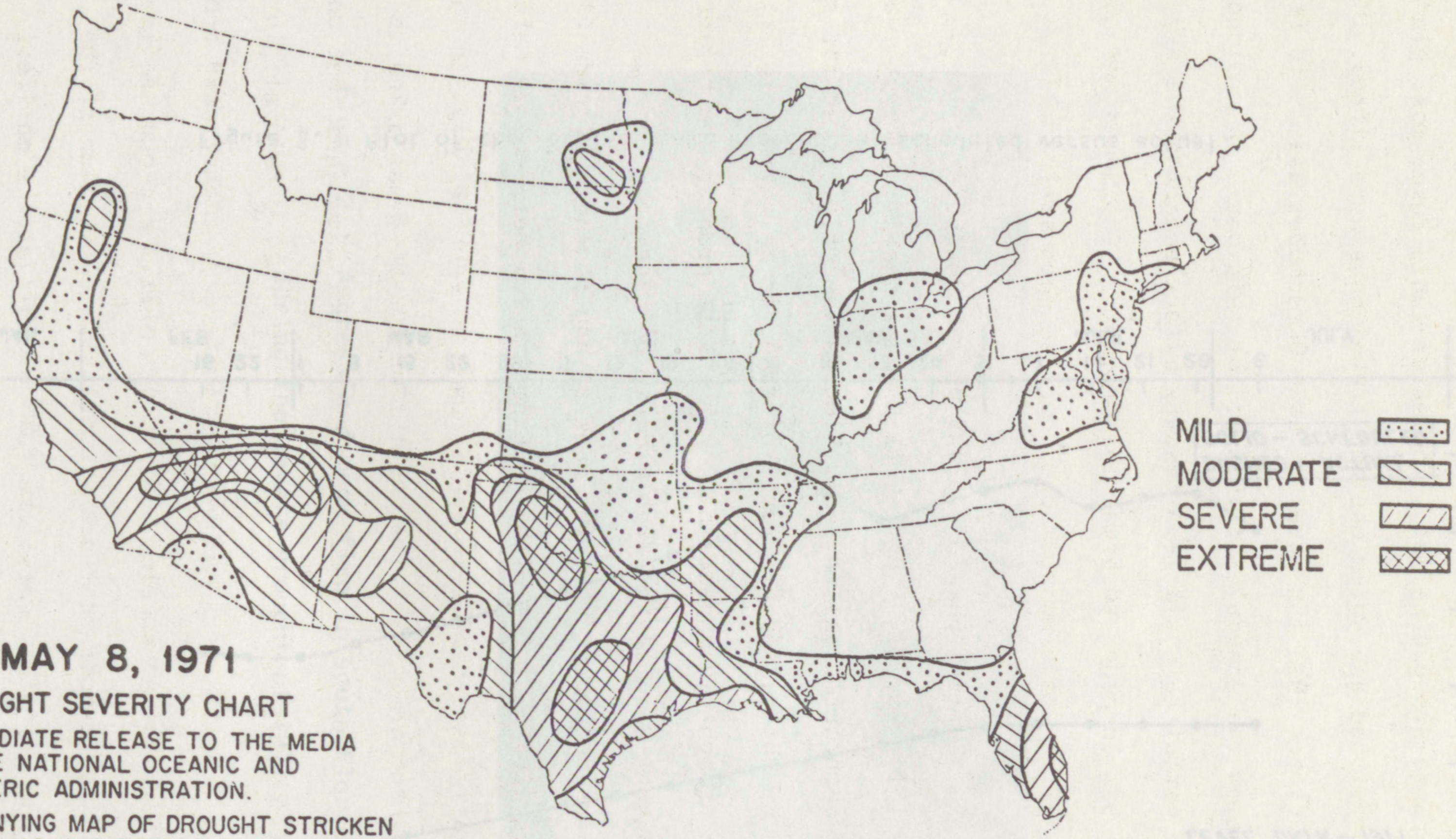


Figure 3. Plot of the level of Lake Okeechobee; scheduled versus actual.



MAY 8, 1971

DROUGHT SEVERITY CHART

FOR IMMEDIATE RELEASE TO THE MEDIA FROM THE NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION.

ACCOMPANYING MAP OF DROUGHT STRICKEN AREAS OF U.S. WAS PREPARED BY WAYNE C. PALMER OF NOAA'S ENVIRONMENTAL DATA SERVICE. PALMER PROVIDES FOLLOWING AS A CAPTION TO GO WITH MAP:

In spite of a few locally heavy showers, areal drought severity increased over Texas, all along the Gulf coast and in southern Florida. Drought also worsened over New Mexico, where stock water is short, as it also is in Arizona. Weekend rains, after the date of this map, brought some relief in Oklahoma, except in the NW quarter, and over the region from northern Virginia to southern New England. Good rains last week relieved the drought over Indiana and Ohio; in fact, they may have marked the end of the abnormally dry weather that has been going on there since March.

Figure 4. Drought severity chart for the United States as of 8 May, 1971.

provided short-range drought relief. The water table rose, most glades fires were extinguished and water use and travel bans were lifted. However, as of 18 October 1971 the level of Lake Okeechobee was 14.10 ft, nearly 1.5 ft below the schedule of 15.5 ft for this date. A prolonged period of above normal rainfall is necessary before entering the dry season of 1971-1972 in order to break the drought. If it does not occur, the spring of 1972 may be a worse drought period than spring 1971.

2. MOTIVATION AND HISTORY OF THE PROJECT

From April 1 - May 31, 1971 EML executed a special cumulus seeding experiment in two target areas in south Florida (see fig. 5) at the request of Dr. R. M. White, Administrator of NOAA, in an attempt to mitigate the severe drought just described. Dr. White ordered the Project at the official request of Governor Reubin Askew of Florida.

As early as December, 1970 the Central and Southern Florida Flood Control District (C&SFFCD) met with the Experimental Meteorology Laboratory (EML) in anticipation of a severe drought in south Florida in the spring and early summer of 1971. At that time EML-NOAA was asked to prepare a contingency plan for a seeding program. EML explained that operational cumulus seeding in Florida was premature. While rainfall increases of about a factor of 3 had been definitively demonstrated from single clouds (Simpson and Woodley, 1971), the multiple cloud seeding experiment could not expect to reach a conclusive evaluation of the seeding effect upon rainfall until the fall of 1971 at the earliest, only seven cases having been obtained in 1970. Florida agriculturists (primarily tomato farmers) and the higher priority of Project Stormfury within

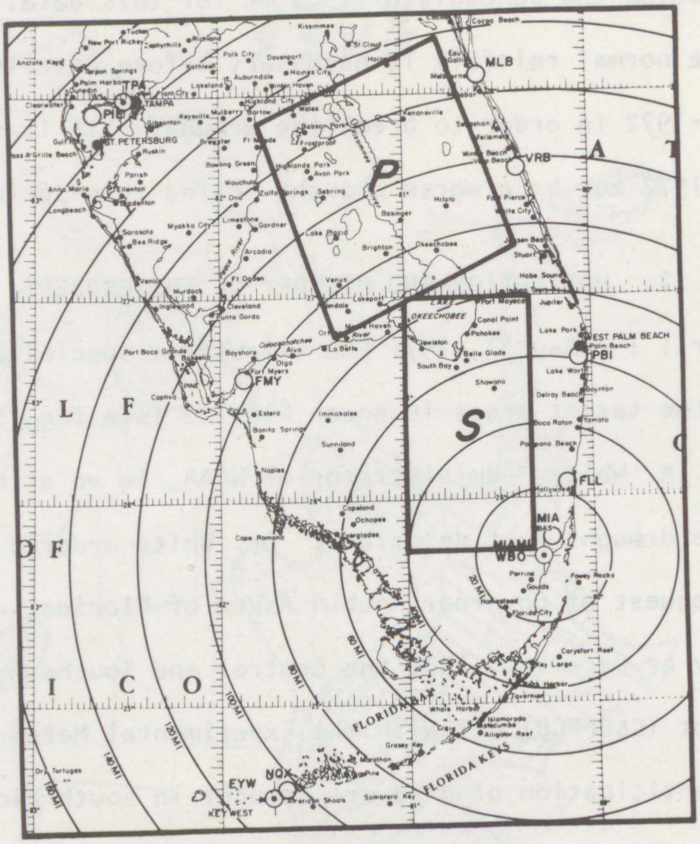


Figure 5. Primary (P) and secondary (S) seeding areas for the April-May 1971 drought mitigation seeding program.

NOAA restrict the Florida cumulus seeding in the research target (evaluatable by the University of Miami calibrated radar) to a four to six week period in June and the first half of July.

It was therefore agreed between EML and the Flood Control District to design and jointly support a randomized semi-operational program for April 1 - May 31 in the important watershed areas in such a way as to permit quantitative evaluation. Our previous successes with single clouds (more than 250 acre-feet increase per cloud) gave us some confidence that if as many as ten seedable days presented themselves, with approximately five to ten seedable clouds on each GO day, the expected water increase would justify the moderate expense to the State and to NOAA and the enormous effort involved for EML and the Research Flight Facility (RFF). As the drought and accompanying severe fires worsened to emergency proportions in early spring, it became clear that we were morally obliged to make our best efforts available to the community and that the scientific prematurity of the effort had to be both explained honestly and converted as much as possible into a learning opportunity. Similarly, other areas of even greater prematurity (sociological, legal and public relations) had to be faced and turned as much as possible into a pilot program to help NOAA and other organizations evolve ways of coping with such problems in this and other locations in the future.

3. EXPERIMENT DESIGN AND SCIENTIFIC QUESTIONS ADDRESSED

The Flood Control District agreed to lease, establish and tend 81 recording raingages of the tipping bucket variety. EML purchased 40 more. Thus, a network of gages, one every 36 sq miles, was provided in the primary target area P (fig. 5) where it was planned to randomize by days two to one in favor of the "seed" instruction. Near the end of April it became clear that virtually no cumuli were presenting themselves in the primary target and a secondary target was established south of Lake Okeechobee in the main cloud breeding areas. Unfortunately, this area could not coincide with the EML research target (see fig. 6) because of the on-going tomato harvest in the western part of the latter area. The University of Miami calibrated radar was put into operation to cover the southern target beginning May 10. By this time it was too late for randomization in this target to provide a sample anywhere nearly large enough for decision or statistical analysis and further, the drought was too severe to justify any control cases.

The seeding was done primarily by the NOAA-RFF DC-6 (39C), accompanied on a few of the missions by the NOAA-RFF B-57 which seeded simultaneously. The DC-6 flew at 19,000 ft and the B-57 at 20,000 ft (pressure altitude) during all missions (temperature about -10°C or a bit lower). The seeding was done with the purpose of promoting cloud mergers. Active towers in the height range 19-26,000 ft were chosen in which the cloud water content exceeded 0.5 gm m^{-3} (as measured by the Johnson-Williams hot wire). Each eligible tower was seeded with 1-21 50-gm flares, fired about one per 100-200 m. The optimum procedure appeared to be to promote growth to cumulonimbus of several nearby clouds and then to try to get them to merge by seeding intervening fresh towers. Once a single vigorous cumulonimbus was thriving, it was often apparently possible to promote a huge merged system by continuously seeding the fresh upshear tow-

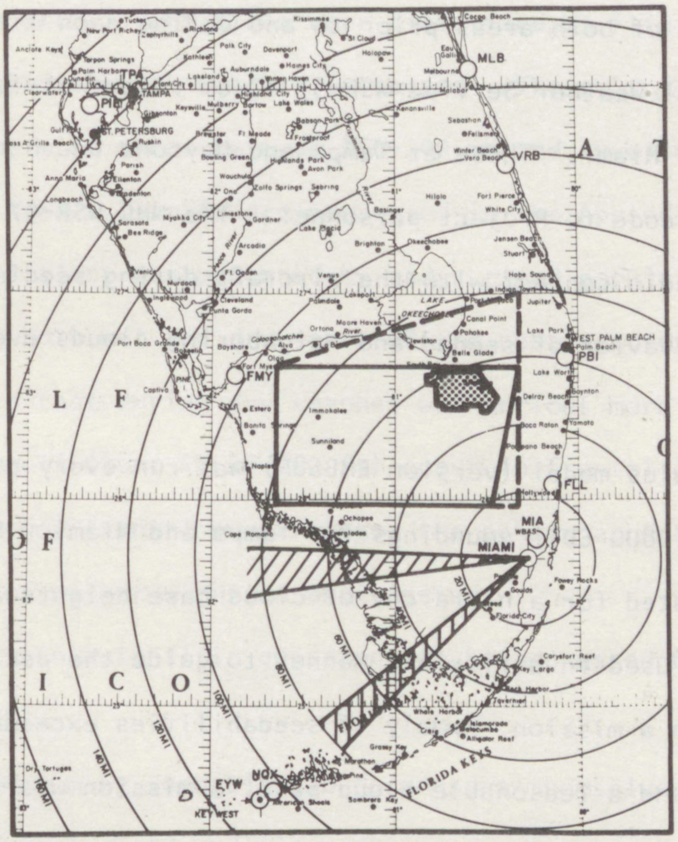


Figure 6. Map showing EML research area. Solid outline 1970, dashed 1971. Dotted area shows location of dense raingage and surface measurement network. Cones are obstructed (blind) areas of University of Miami radar.

ers (generally to the west).

Radar suveys of both areas prior to and during each mission were made by the National Weather Service WSR-57 10-cm radars at Tampa, Daytona Beach and NHC, Miami. Those at Tampa and Daytona Beach reported by a special teletype code to Project personnel. The NHC WSR-57 operators in Miami were in radio contact with the aircraft during seeding missions and reported the behavior of seeded and neighboring clouds every few minutes.

The EML cumulus model (version EMB68P) was run every day in real time on the 1200Z (0800 EDT) soundings for Tampa and Miami. Seedability (in km) was calculated for a hierarchy of cloud base heights and radii. These results were used in a flexible manner to guide the decision whether or not to launch a mission: namely if seedabilities exceeded 1 km for one or more radii and a reasonable cloud base, a mission was virtually always launched. However, missions were also sometimes launched on days of predicted poor seedabilities if an appreciable possibility of a favorable change was forecast.

The drought situation made sounding changes more common and the model predictions less valuable than in our usual spring and summer programs. Part of the reason was frequent weak frontal passage, part was enhanced sea breeze due to the dry peninsula and part that the cumuli altered their environment more markedly than in a normal moist tropical air mass.

Safeguards against severe weather occurrences had to be incorporated into experiment design, following a small hail and high wind occurence in the Miami area in connection with two seeded clouds on April 26 (described later.) Conditions were classified as A through D, as the risk of anticipated severe weather increased. The criteria were based directly on the wind shear between 850-200 mb and inversely on the Showalter stability index. Details are presented in the Appendix.

The Project was preceded by radar cloud population studies for all months, for both wet and dry years of the past records. Results (Holle, 1971) showed that during dry seasons and periods more than half of the seedable cumuli (tops 15-25,000 ft) occur in frontal or trough situations. In the rare non-frontal occurrences, the echoes appeared so isolated that difficulty of merger might be anticipated.

The main scientific questions to be addressed by this type of program are:

1) How many seedable clouds present themselves where, when and under what conditions during a severe drought in south Florida? What happens when dynamic seeding is applied to these clouds?
2) What are the optimum seeding techniques, in terms of aircraft patterns, cloud selection and number of flares to promote mergers?
3) Can dynamic seeding be applied to promote precipitating mergers under frontal conditions in Florida? These situations are usually accompanied by high wind shear and often by middle and upper cloudiness. Such conditions were found unfavorable for explosive growth in our single-cloud experiments.

4) Can the rainfall in a severe drought in south Florida be augmented sufficiently by dynamic seeding to justify the cost and effort of a program like this? (About $125,000 to NOAA and $40,000 to the State of Florida.)

It should be noted that the question does not arise here whether dynamic seeding could "break" a drought, since this is meteorologically impossible. A large part of the media and education program (discussed later) jointly undertaken by EML and the NOAA Public Information Office (PIO) has been directed toward explaining the limitations of seeding to the public, while retaining cautious optimism regarding the cost-benefit ratio of this project.

4. OPERATIONAL SUMMARY

A summary of the results of flight operations during the experiment is provided in Table 1. Also included in the table are those days in the operating period on which seeding flights were not attempted and why. Sixteen seeding missions were flown, of which 14 actually resulted in seeding. This demonstrates the large "pay off" of the numerical cumulus model, which eliminated 38 days as unsuitable or marginal for the experiment (discussed later). The apparent results of the seeding were categorized at the end of the experiment into four classes, namely

0 No apparent effect

1 Apparent single cloud growths induced, but no mergers

2 Impressive growth with precipitating mergers, but some natural clouds behaving similarly

3 Impressive growth with precipitating mergers. Seeded clouds

behaved anomalously--behavior not duplicated or anticipated naturally

Altogether the experiment consumed 2066 50-gm silver iodide flares (Simpson et al., 1970). Seventy-two flight hours were used by the RFF DC-6 (39C) and 33 by the RFF B-57. There were a total of 196 seeding passes flown, with 12-25 runs characterizing a "successful" day with good mergers (see Table 1). Typically on such a day seven to ten clouds or cloud complexes would be seeded, and up to as many as 12-15 towers, some of them repetitively. Two seeding aircraft were coordinated in tandem on four days. Better growth could have been obtained on at least three other days in Category 3 had a second aircraft been available.

Seven more seeding missions could have been obtained had a back-up seeder aircraft and crew been available to operate on the days that the DC-6 had to undergo routine repair and maintenance.

Of the 38 days that were unsuitable for the experiment weatherwise, 32 were too dry and six were too disturbed. Out of these 38 unsuitable days, three were marginally unsuitable and missions would have been flown had the aircraft been available.

The primary seeding target (see fig. 5) proved much less satisfactory both meteorologically and operationally than we originally believed it would be. This was due in part to unfavorable weather conditions and to about 4000 acres of tomatoes of which we were unaware in planning the experiment. While these comprised a negligible percentage of the area, to eliminate them from the target would have reduced the working area by about one-third, which was impossible.

TABLE I. Summary of Operations April-May 1971 Seeding Program

Date Year 1971	Showalter Stability Index 8am	8pm	Shear 850-200mb Miami 12Z (°)	(kts)	Area Cov.* (n mi^2) 1800Z	Cell Azi (°)	Movemt Speed (kts)	Max Seedability 750< R<1500 8am	8pm	Cloud Base (ft)	No Acft Involved	DC-6 Take-Off Time (Z)	Temp at Seed Level °C (min)	(max)
4/1-3											0			
4/4	+ 3.0	+ 6.0	282	79	385	130	10-15	2.65	0	~3500	1	1710	-14.7	-13.9
4/5-15											0			
4/16	+ 5.8	+ 5.0	288	92	0	190	10-12	0	0	~7500	1	1747	-14.2	-11.3
4/17-20											0			
4/21	+ 7.5	+ 5.5	317	82	0	300	20	4.00	4.25	3000	1	1800	- 6.2 (16 k ft)	
4/22-23											0			
4/24	+ 5.5	+ 2.0	293	65	M	270	35	0	1.35	~3500	1	1723	-12.3	-10.4
4/25	+ 1.3	+ 6.0	307	71	152	270	20	0	3.2	~3500	1	1635	-11.4	- 9.1
4/26	- 3.0	+ 3.0	328	72	M	270	15	0	3.95	~3000	2	1720	-11.7	- 8.4
4/27-30											0			
5/1	- 1.5	- 6.0	308	48	436	280	35	0	2.4	3500	1	1835	-13.3	- 8.0
5/2-6											0			
5/7	+10.5	+11.0	298	33	0	090	10	0	2.1	5000	1	1800	-12.2	-10.4
5/8	+ 4.6	+ 0.5	282	28	54		NIL	0.95	2.1	5000	1	1730	-13.5	-10.9
5/9	+ 3.1	+ 5.0	305	38	54		NIL	0	3.6	5000	1	1810	-13.4	-10.1
5/10	+ 4.6	+ 4.3	275	17	291	270	40	4.1	1.9	<3500	2	1710	-11.7	- 8.2
5/11											0			
5/12	+ 7.5	+ 2.5	273	62	213	160	15	4.65	2.5	4500	1	1745	-19	-19
5/13-20											0			
5/21	+ 2.0	0.0	282	69	30	300	16	0	3.7	2000	1	1715	-14.3	-10.2
5/22	+ 5.3	+ 6.0	328	36	203	330	8	4.7	3.3	3500	2	1815	-13.0	-10.8
5/23-24											0			
5/25	+ 6.5	+ 5.0	353	59	1004	085	8	0.3	2.1	~2500	2	1729	-13.0	- 9.2
5/26	+ 5.0	+ 5.0	311	65	152	020	10	0	0.0	~2500	1	1800	-11.7	- 9.0
5/27-31											0			

* Within 100 n mi of Miami

General Seeding Area	Seeding Times GMT (1st)	(last)	No. Seeding Passes	Amt of AgI (kgms)	Apparent Effect of Seeding	Remarks
						Too dry.
SW of Okeechobee	1855	1917	3	1.2	0	No growth, frontal and dud day.
						Too disturbed(4/5); too dry(4/6-14); suitable but both acft down (4/15).
No. target area	1913	2128	5	1.8	0	Envelope opened, decision seed, clouds bad.
						Too dry.
			0	0		Clouds suppressed.
						Too dry.
No. target area	1826	2120	17	4.8	2	Old front, hi shear, clds grew but so did natural clds.
No. of Okeechobee	1749	2046	25	10.3	3	Old front, hi shear. Explosive growth with mergers. No other Florida CB's.
W. of Miami	1825	2058	18	10.3	3	High shear, explosive mergers. Rain extended more than 90 mi N-S. Some small hail and high winds.
						Suitable but both acft down (4/27); marginally suitable (dry) but DC-6 down (4/28); too dry (4/29-30).
So.(secondary) target	1957	2253	20	10.4	2	Frontal zone. Nat rain & 2 explosive seeded growths 1-2" from one seeded cloud.
						Suitable but DC-6 down (5/2); too dry (5/3-6)
Due west of U/M	2004	2207	12	6.1	3	Clds visible fm NHC. 1 merger of 2 seeded CB's, 1 nat CB.
SW portion of So. target	1850	2032	3	2.9	2	One CB fol seeding. Flt aborted. Many natural CB's.
Center of So. target	1859	2124	15	5.6	2	Seeded clds organized slowly but made good merger, as did non-seeded clouds.
So. target area	1813	2135	21	11.8	1	Three small CB's but no merger. Nearby natural CB suppressed seeding area.
						Suitable but DC-6 down.
No seeding	NA	NA	NA	NA	NA	Clouds all suppressed out.
						Marginally suitable (disturbed) but DC-6 down (5/13); too disturbed (5/14-16); marginally suitable, dry (5/17); too dry (5/18-19); too dry (5/20).
So. target area	1855	2131	15	10.3	2	S of diffuse front. Clds grew slowly but impressively.
So. target area	1906	2204	19	13.9	3	Mergers of mergers. Explosive growth. 4-5" in South Miami area.
						Too disturbed, cld debris fm 22nd (5/23); too dry (5/24).
So. target area	1828	2025	6	8.2	0	Slow growth. Unimpressive. Clds marginally suitable. Returned early.
So. target area	1900	2127	16	10.3	3	Impressive. Merger to 50,000' 3"/hr. Seeded cld biggest CB over South Florida.
						Suitable but acft down (5/27); suitable but acft taken for other NOAA use (5/28); suitable but acft down, crew rest (5/29); too dry (5/30-31).

More serious, however, was the fact that about one-third of the area was occupied by aircraft performing acrobatics and was thus unavailable to project aircraft for several hours each day. If this restriction is not remedied, this target will be unsuitable for future experiments.

An indispensable addition to the evaluation was the fact that the University of Miami radar was able to swing into (minimal) operation on two days notice, and was operative beginning May 10.

5. METHODS OF ESTIMATING RAIN VOLUME AND THE EFFECT OF SEEDING

In the discussion of each day of experimentation that follows, an attempt is made to estimate the volume of rain that fell from the subject clouds and the effect that silver iodide seeding may have had on its production or augmentation. Whenever possible rain volume is estimated using UM/10-cm radar observations and the calculation scheme described by Woodley (1970). This method is preferable in most cases to the use of raingage records, primarily because the gage density in the interior of Florida is totally inadequate to define rain volume accurately and only marginally suitable along the heavily populated coastlines. The UM/10-cm radar began operation on 10 May 1971 so the most suitable method of rain estimation was not possible until this date. The radar reflectivities and appropriate rainfall rates for this period appear in Table 2.

The second method of calculating rain volume was space integration of an isohyetal pattern that was known to be associated with a seeded cloud. This method is accurate when the rain occurs in a dense gage network and when there are no other (non-seeded) showers that complicate the analysis. The gage density in target P (fig. 5) was barely adequate to

Table 2. Iso-echo Contour Values for 1971 Radarscope Film*

Level	NO ATTEN (in/hr)	3 dB ATTEN (in/hr)
MDS	.01	.02
#1	.10	.18
#2	.54	.90
#3	3.30	5.40

* inferred from relation $Z = 300\ R^{1.4}$; Z ($mm^6\ m^{-3}$), R ($mm\ hr^{-1}$).

depict shower rainfall with reasonable accuracy, but it was inadequate elsewhere. To overcome this deficiency an appeal was made to the general public to make their rain records available to our laboratory for April and May 1971. The much appreciated response of approximately 125 individuals helped fill in some of the gaps along the coastline, but the interior regions remained devoid of gage records. For this reason rain analyses were made for the Florida east coast (Palm Beach to Homestead) for all days in April and May, but no such analyses were attempted elsewhere. With the exception of target P, the rain volume calculations for clouds over the interior of Florida were made using radar observations or not at all.

The third method of estimating the volume of rainfall from seeded clouds is the least satisfactory. It involves the use of WSR-57 radar observations and the rain nomogram in fig. 7 that was constructed from

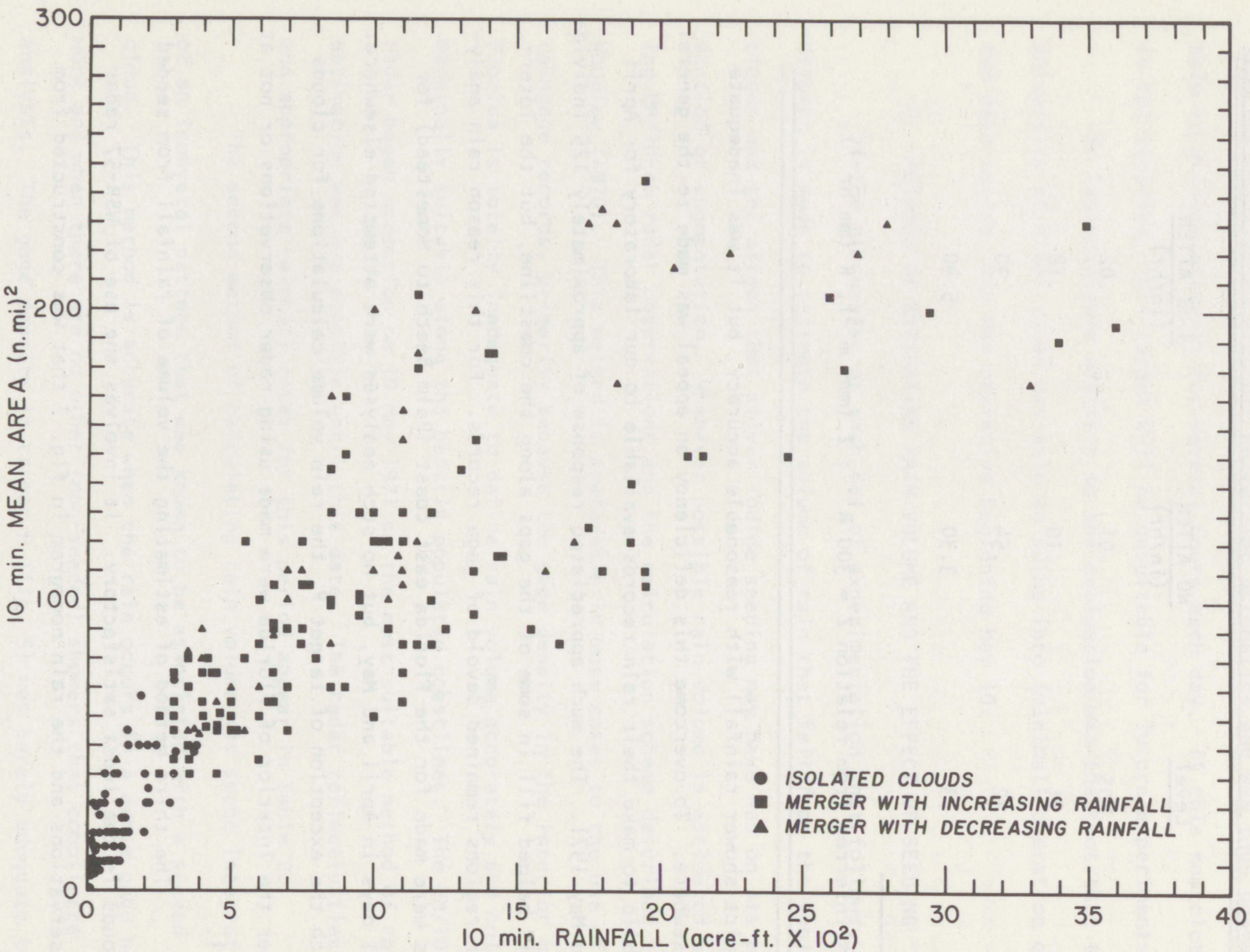


Figure 7. Ten-minute mean echo area versus the 10-minute rainfall production for the echo as calculated from UM/10-cm radar observations. All calculations were made from 1970 radar observations.

UM/10-cm radar observations (Woodley, Norwood and Sancho, 1971). In this figure, the 10-min mean echo area at the minimum discernable signal (MDS) is plotted versus the calculated rainfall production for that echo for the same 10-min period. Knowing the mean area of an echo in any 10-min period, one can then make an estimate of the volume of precipitation represented by that echo for the same time period.

The main assumption that one makes in applying the rain nomogram to WSR-57 radar observations is that the MDS for the WSR-57 and the UM/10-cm radar is the same. This assumption results in a rain overestimate, because the Miami WSR-57 radar is more sensitive than the UM/10-cm. (The increased sensitivity and consequent larger echo size does not correspond to rain reaching the ground). A comparison of a rain estimate using the nomogram in conjunction with WSR-57 radar observations with that made using a dense raingage network was made on 26 April 1971. The nomogram technique resulted in an estimate that was a factor of 1.38 greater than that provided by the gage network. Consequently, as a first approximation all rain volume estimates that were made using the nomogram were decreased by this factor.

In any seeding experiment one wishes to know what effect seeding had on the precipitation from the subject clouds. Over the long term such a determination is possible provided cloud selection has been randomized. However, determining the effect for any one seeding or for a series of non-randomized seedings, such as the April - May 1971 seeding experiments, is an especially difficult task. In the analysis of this experiment several estimates of seeding effect are made for each day of operation ranging from the minimum to the maximum likely effect of seeding. In this way a seeding effect scale is generated that can be used to determine the likelihood that the results of the seeding justified the effort and money that were expended.

The estimates of the effect of seeding were the following:

1) a simple statement of no effect when the seeding was done under highly disturbed weather conditions or when the clouds failed to grow at all.

2) inference based on the single cloud results which indicated that mean seeded rainfall was a factor of 3.3 greater than mean non-seeded rainfall. Thus, total rain volume from the seeded clouds in April and May 1971 was multiplied by 3.3/4.3 to estimate the rainfall due to the seeding.

3) inference based on the numerical model results that were obtained in real time. Total rain volume was multiplied by the model-generated ratio:

$$\frac{\overline{PP}(S) - \overline{PP}(NS)}{\overline{PP}(NS)}$$

where $\overline{PP}(S)$ and $\overline{PP}(NS)$ are the mean precipitation production for seeded and non-seeded clouds respectively for cloud radii in the interval $750m \leq R \leq 1500m$ for the 915m cloud base. The calculation is made only for cloud radii in the specified intervals that are predicted to reach the -4C temperature level.

4) inference based on comparison. The rainfall produced by a seeded system on a given day is differenced with the rainfall from the most intense, overland, non-seeded system within

100 n mi of the Miami radars

5) a simple statement that all the rainfall from the seeded clouds was due to seeding.

For a given seeding instance it is unlikely that all methods would provide a reasonable estimate of the effect of seeding. Thus, on a day with heavy, extensive natural precipitation it borders on the ridiculous to assert that all rainfall was caused by the seeding, so estimate 5 would not be considered reasonable for this day. Estimates 1 and 5 are the easiest to apply, but perhaps the least valid. Method 2 has the single cloud results as a solid foundation, but it is not at all clear that the single cloud results can be applied without alteration to multiple cloud seeding. Method 4 is of value in some instances, because it provides a measure of how anomalous a particular seeding event was.

Method 3 requires more elaboration. Simpson and Wiggert (1971) have found high positive correlation between model predictions of the difference in precipitation fallout between seeded and control clouds and the measured rainfall differences, although the rain volume differences that are inferred from the model predictions are much smaller in magnitude than that which is observed. This failing is due to model inability to consider coalescence within the cloud body below the rising tower and to its inability to model repeated tower generation and cloud organization. Nevertheless, estimate 3 is useful because it provides a minimum estimate of the effect of seeding. It was used with soundings close in space and time to the actual seedings. A realistic hierarchy of radii rather than a single radius was used because many cloud towers of varying horizontal sizes were seeded during the course of a day's seeding operation.

In the section that follows, the days of seeding operations are documented on a day-by-day basis. The rainfall from the seeded clouds is calculated and a range of seeding effects is calculated using the methods just described. The calculations are summarized in Table 6 at the end of the section.

6. DAY-BY-DAY DOCUMENTATION

In the discussion of the days that follows there are several common denominators that can be summarized here so that they need not be repeated in each discussion. For most days a photographic cloud summary is presented. Unless specified otherwise in the discussion: All photographs were taken from the DC-6 aircraft while it was flying at 20,000 ft MSL; all times are Greenwich Mean Time, the "T" time is the time of initial seeding of the cloud that is shown, and letters in the upper left of the photographs are camera direction. The clouds themselves are often identified to facilitate the discussion. When appropriate, rainfall analyses are presented for the southeast Florida coastal region, from Palm Beach southward. These analyses are fairly accurate in the immediate coastal region where the private sector made their rain observations available to EML. However, the analyses deteriorate badly inland from the coast where there are few gages. The "0" or no rain line on the western margins of these analyses is based on very little data and is, therefore, quite inaccurate. No rain analyses were possible over the western portion of the south Florida peninsula because of almost no raingages.

All rainfall has been measured in inches.

April 4, 1971 - This was the first day of actual seeding operations. An old cold front in south-central Florida moved slowly northward as a warm front during the day. Extensive middle and upper cloudiness precluded any operations in target P and area S had not been established at this time. Three clouds were seeded near the southwest shore of Lake Okeechobee in a region where there was little upper cloud. The clouds showed no visual response to the seeding, although they precipitated lightly as did their unseeded counterparts in the vicinity. The temperature at a flight altitude of 20,000 ft was -16C; the -10C level was at 13,500 pressure altitude. In most cases the seeding was done in clear air about 1000 ft above cloud top. The seeded cloud motion was to the northeast toward Lake Okeechobee, away from the tomato growing areas to the south and southwest.

Most significant finding on 4 April 1971: No effect of seeding was noted on this day.

April 16, 1971 - Florida was embedded in northwesterly flow at middle and upper levels on this day. Apparently suitable clouds were found in target P. A randomized seeding instruction was opened and the action carried out on two clouds. Seeding conditions deteriorated during the day and the day was declared non-experimental later in the flight. Upon this declaration, it was learned that the two clouds had been seeded with a total of 16 flares (flight altitude 18,500 MLS; temperature -13C). Because the seeded clouds had shown no response nor visual change following the seeding, we became concerned that the flares were not burning completely following ejection from the aircraft into the cloud. Consequently, an experimental seeding was attempted to determine whether the flares were working as intended. A cloud with a top of approximately 17,000 ft was seeded with 20 flares at an altitude of 16,000 ft. Subsequently, the DC-6 aircraft descended to 15,000 ft and ice nuclei counts were made with a Bigg-Warner chamber (activation temperature of -20C) to see whether flare-produced ice nuclei were present in the cloud. Over 80 nuclei per liter were detected in the sample made during cloud penetration, representing almost two orders of magnitude more than the natural background on this day. This led to the conclusion that the flares were working as designed and the clouds failed to respond to seeding for meteorological reasons.

Most significant finding on 16 April 1971: While no effect of seeding was detected in cloud behavior on this day, tests confirmed that the silver iodide flares were ejecting and burning as programmed.

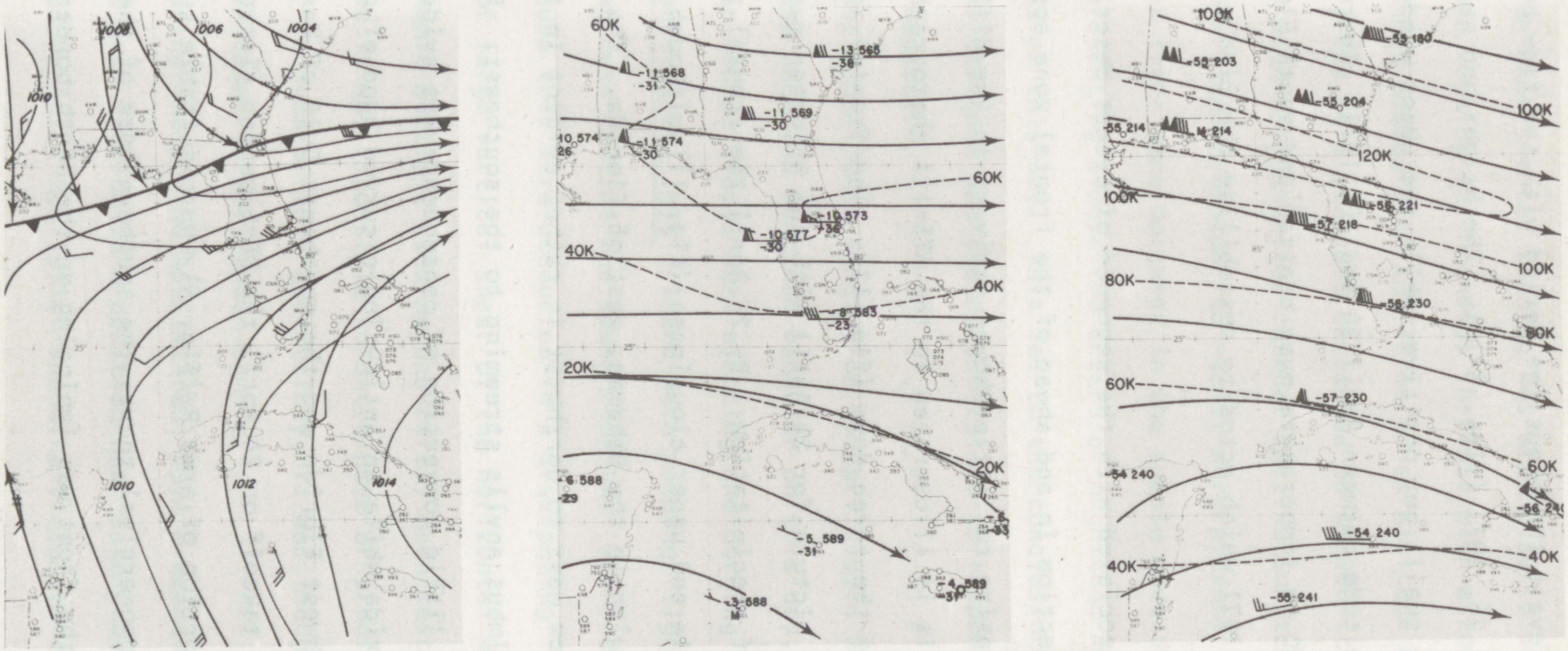
<u>April 24-26, 1971</u> - There were seeding flights on April 24, 25 and 26 ranging over central and south Florida. The seedings were not randomized because they were conducted in a dissipating front region under conditions of large vertical shear of the horizontal wind. Prior to these dates dynamic multiple seeding had rarely been tested under such conditions, and it was impossible to anticipate or predict the results of the seeding. Because of this uncertainty, it was thought inadvisable to include such cases in the random sample.

During the period April 24-26, 1971 a weakening cold front drifted southward over Florida to a position near Lake Okeechobee where it had dissipated by April 26, 1971. The wind field veered at the surface, 500 and 200 mb pressure levels thoughout the period with the flow becoming anticyclonic by April 26, 1971 (figs. 8-10). The height and surface pressure changes were small, but positive, while the upper winds showed small changes in magnitude between April 24 and 26, 1971. There was a slight drop in the 500 mb temperature over central and south Florida by 1200 GMT on 26 April 1971 which acted to destabilize the middle troposphere.

The weather associated with the sequence of events described above was active convection in and ahead of the frontal zone across Florida on 24 April decreasing to little shower activity in the diffuse zone by 26 April 1971. This is illustrated in the ATS-III photograph near solar noon for each of the three days (fig. 11). The frontal zone is rather obvious on the picture for 24 April with the brighter masses corresponding to areas of precipitation. By 25 April the frontal zone consisted of mainly middle and upper cloudiness (fig. 11) although active convection was continuing in the Bahamas, east of Florida. The veering of the upper winds from west to northwest is rather evident in this picture with the cumulonimbus anvils streaming to the southeast. By early afternoon on 26 April little convection of consequence was evident over central and south Florida while an anticyclonic curved band of cloudiness could be seen in northwest Florida and the northeast Gulf of Mexico.

After 1723 GMT takeoff on 24 April the DC-6 seeder aircraft proceeded to the north portion of area P (fig. 5) where suitable supercooled clouds were found. Upon arrival there, the southern edge of the cloudiness associated with the front was impinging on the north border of the

1200 GMT APRIL 24, 1971



SURFACE 500 mb 200 mb

Figure 8. Surface streamline and pressure analyses.

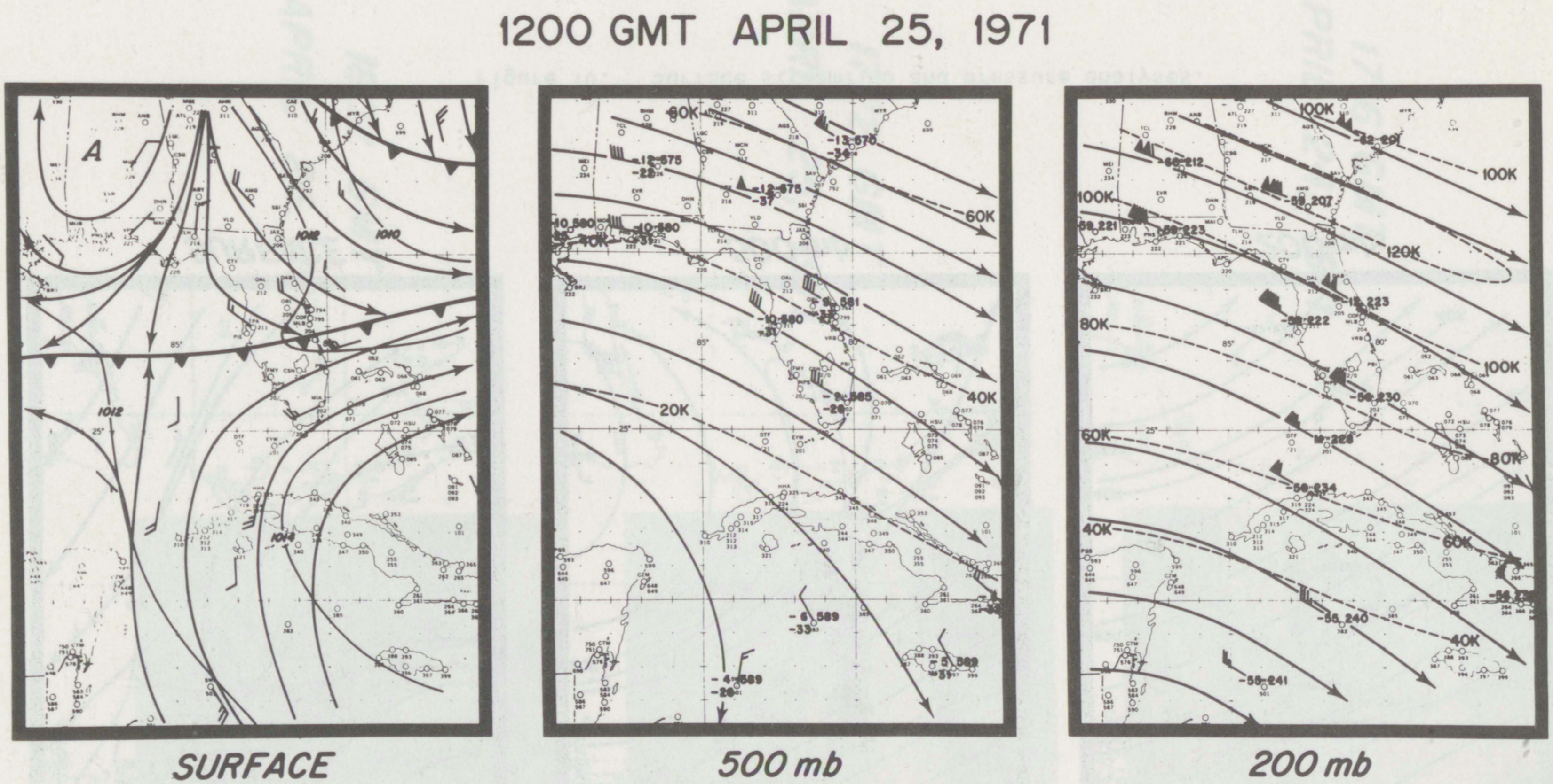


Figure 9. Surface streamline and pressure analyses.

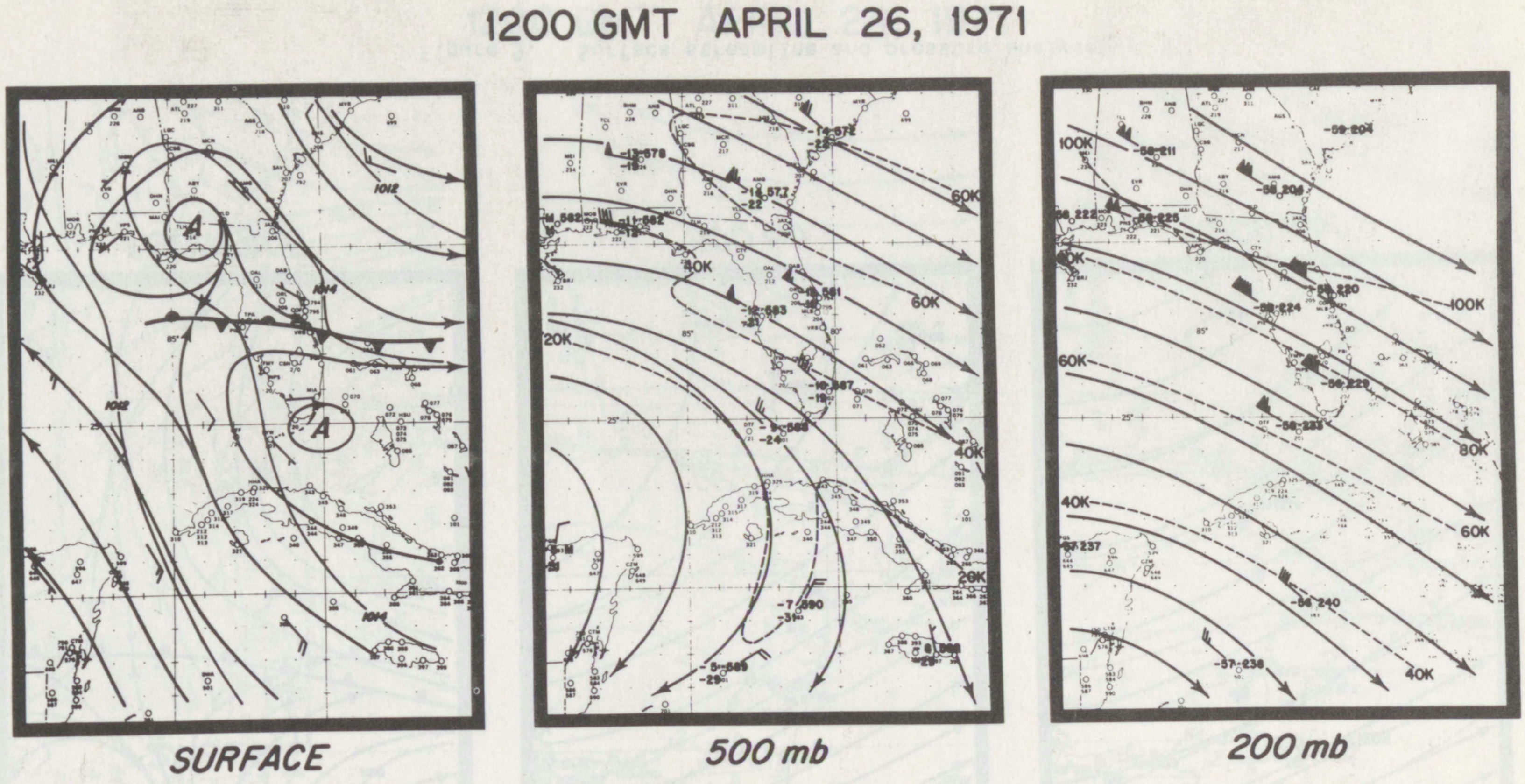


Figure 10. Surface streamline and pressure analyses.

1716 GMT
APRIL 24, 1971

1722 GMT
APRIL 25, 1971

1802 GMT
APRIL 26, 1971

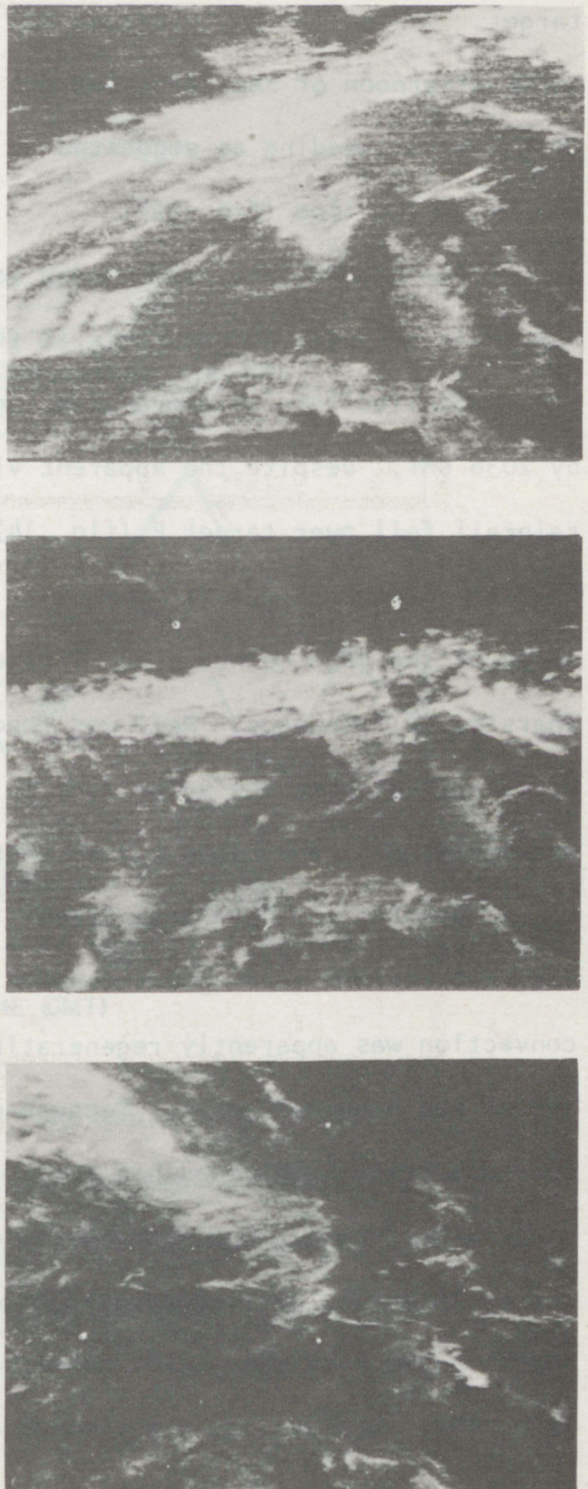


Figure 11. Blown up ATS-III satellite photograph for the Florida region. Times and dates as shown.

target. Convection in this zone had waned during the late morning and early afternoon of the 24th, but was apparently regenerating at the time of the first seeding as suggested by a plot of the maximum cloud top height in the line (fig. 12).

The clouds that were seeded south of the weak frontal zone grew, but their unseeded counterparts to the north and west grew as well. The area organized into an impressive, and rather photogenic (fig. 13), system by 2036 GMT. Despite the apparent vigor of the system, rather little rainfall fell over target P (fig. 14), perhaps due to the rapid movement (35 kts) of the showers to the east. Heavier rain probably occurred north of the gage network, but little can be said about it because of the sparsity of raingages. Hail was reported in the Cocoa Beach-Melbourne areas, a fact none too surprising in view of the 60,000 ft top height that was achieved by the cloud system that traversed the area.

Seeding may have been responsible for some of the rainfall on this day, but because seeding was done in a frontal region at a time when the convection was apparently regenerating, it is likely that most of the events had natural causes. Because of this likelihood, none of the rain that occurred on this day has been attributed to the seeding (Table 6).

The frontal zone returned to a rather inactive state by late evening on 24 April, but regenerated once again during the early morning hours on the 25th when 1.50 inches fell in the south portion of area P (fig. 15). However, at the time of the first seeding near the east shore of Lake Okeechobee on 25 April there was no precipitation over the Florida peninsula.

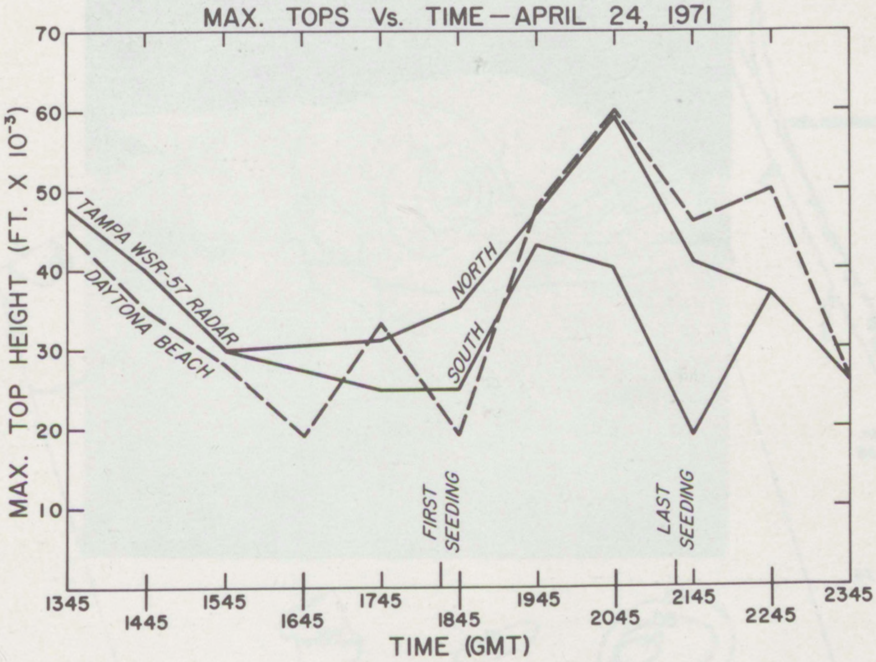


Figure 12. Time-height plot of the maximum cloud top height measured by the National Weather Service WSR-57 radars at Tampa and Daytona Beach. North and South refers to two distinct lines of echoes.

Figure 13. A photograph of a portion of the cumulonimbus line along the north edge of area P at 2036 GMT 24 April 1971. Flight altitude was 20,000 ft, camera direction to the northeast, and maximum cloud top exceeded 50,000 ft.

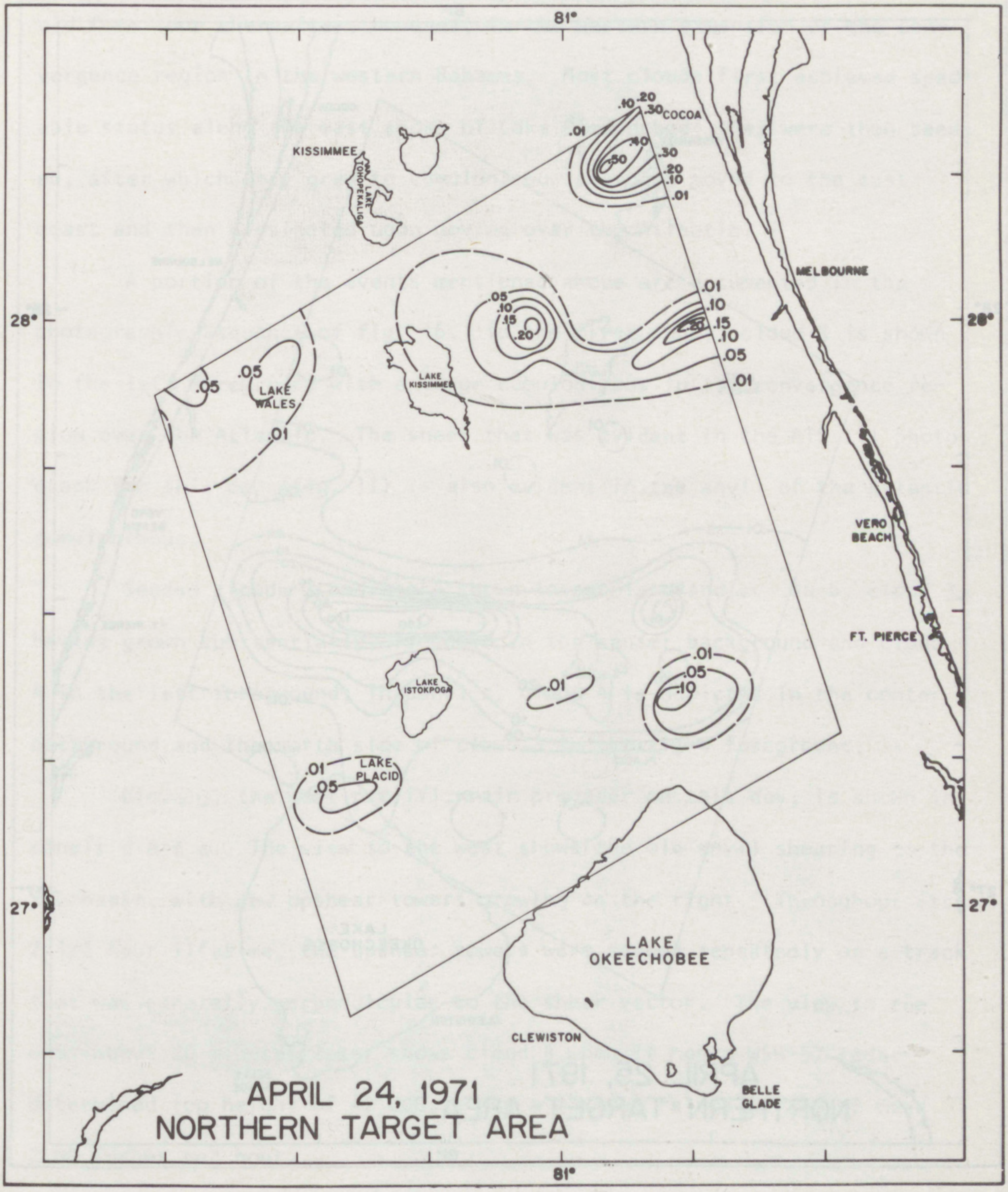


Figure 14. Rainfall over area P on 24 April 1971.

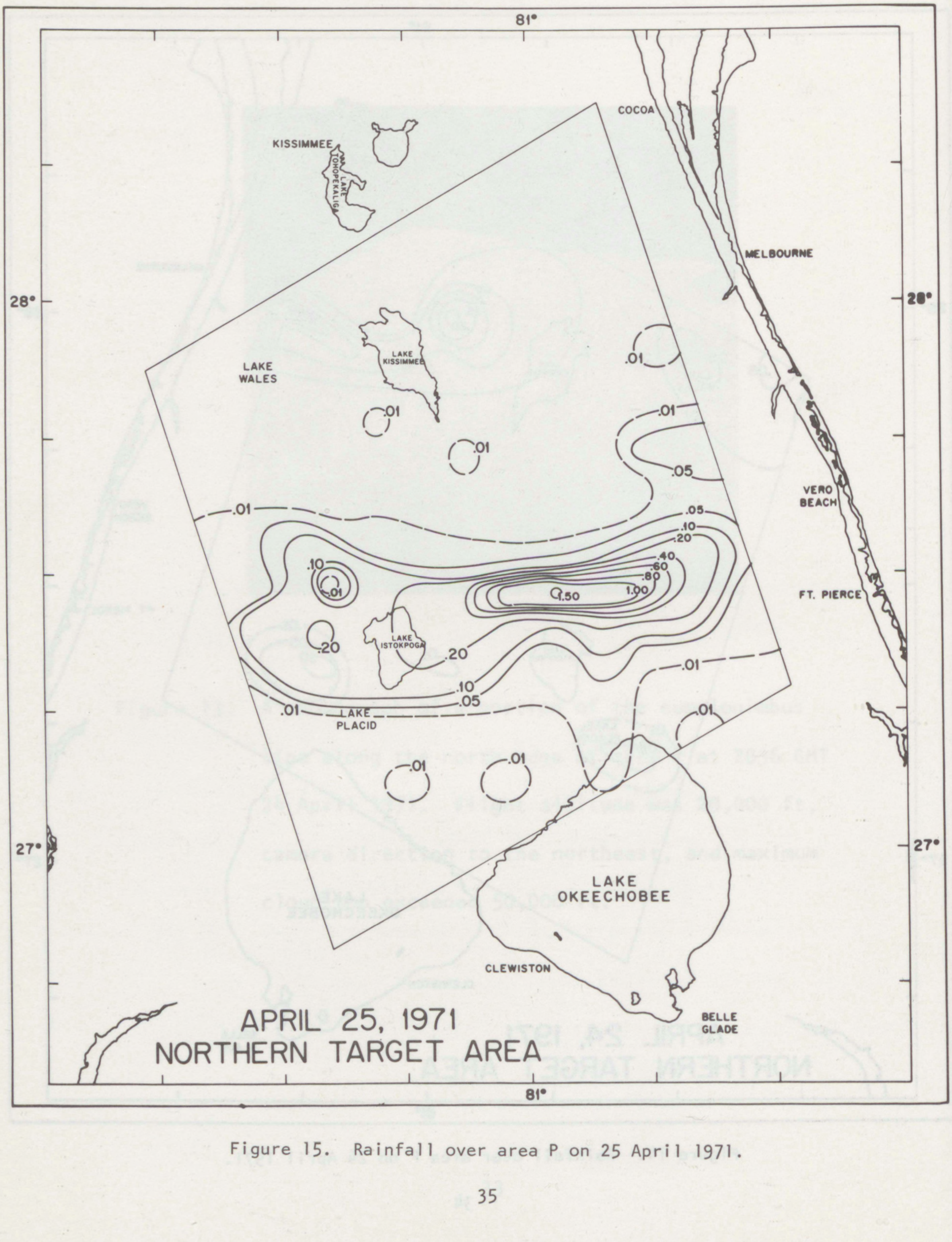


Figure 15. Rainfall over area P on 25 April 1971.

When the DC-6 seeder aircraft first reached flight altitude no suitable clouds were found over the Florida peninsula. Suitable clouds did form soon thereafter, however, in the western extension of the convergence region in the western Bahamas. Most clouds first achieved seedable status along the east shore of Lake Okeechobee; they were then seeded, after which they grew to cumulonimbus stature, moved to the east coast and then dissipated upon moving over the Atlantic.

A portion of the events mentioned above are documented in the photographic sequence of fig. 16. In the first panel, cloud 3 is shown in the left foreground with a large cumulonimbus in the convergence region over the Atlantic. The shear that was evident in the ATS-III photograph for this day (fig. 11) is also evident in the anvil of the Atlantic cumulonimbus.

Seeded clouds 3 and 4 are shown in panels b and c. In b, cloud 3, having grown substantially, is shown in the center background and cloud 4 in the left foreground; in panel c, cloud 4 is depicted in the center background and the north side of cloud 3 in the right foreground.

Cloud 3, the most prolific rain producer on this day, is shown in panels d and e. The view to the west shows the old anvil shearing to the southeast, with new upshear towers growing on the right. Throughout its 2 1/2 hour lifetime, the upshear towers were seeded repeatedly on a track that was generally perpendicular to the shear vector. The view to the east about 20 minutes later shows cloud 3 when it had a WSR-57 radar-determined top height of 42,000 ft and a maximum rainfall rate of over 2.00 inches per hour.

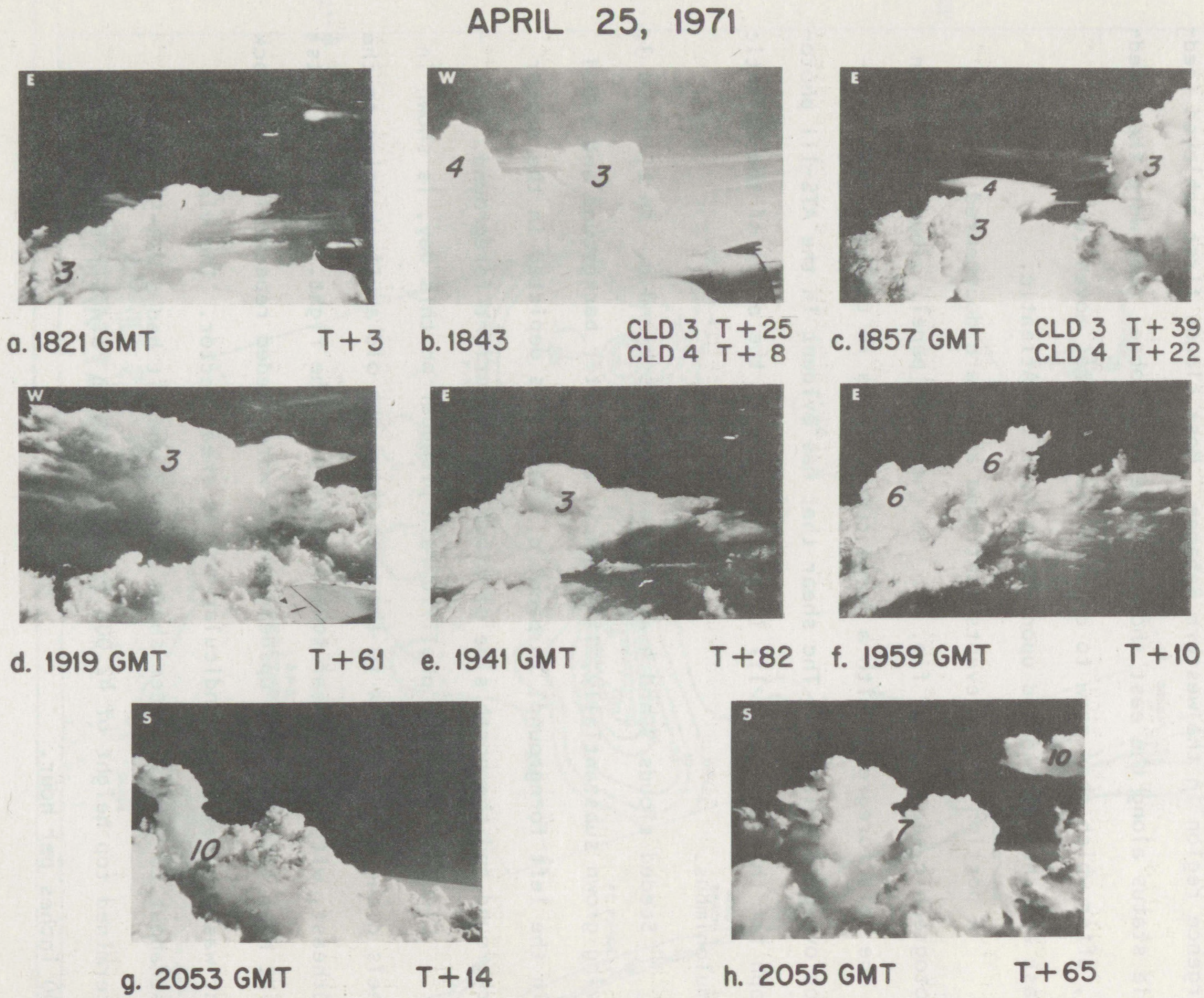


Figure 16. Airborne photographic sequence for 25 April 1971. All photographs from 20,000 ft MSL. T refers to time of seeding and times in each panel relative to T are for the clouds shown. Letter at upper left is camera direction.

Selected views of other clouds on this day are provided in panels f, g and h. All clouds shown attained cumulonimbus stature at some time during their lifetimes.

Rainfall estimation from the seeded clouds of 25 April 1971 was accomplished using WSR-57 radar observations and the rain nomogram (fig. 7) rather than with raingages, because there were almost no raingages in the region traversed by these clouds. Although 0.75 to 0.90 inches of rain fell from seeded clouds along the Atlantic east coast, these values were of little use in the overall volumetric water calculations.

The rain estimates for 25 April 1971 are presented in Table 6 at the end of this section, pp 131-32. The total rain from the cloud systems on this day was 29,480 acre-feet uncorrected and 21,362 when altered by the correction ratio mentioned in an earlier section. The minimum and maximum rainfall per cloud or cloud complex that precipitated was near 565 and 7518 acre-feet respectively.

The estimates of the seeding effect on this day range from approximately 2900 acre-feet for the model-derived estimate to 21,362 acre-feet if all of the rainfall is attributed to seeding. A zero seeding effect is not considered reasonable for this day because no shower activity other than that from the seeded clouds was observed after the time of initial seeding on this day. The fact that the subject clouds were precipitating lightly at seeding and the presence of cumulonimbus clouds in the Atlantic precludes the assertion that all the precipitation was due to seeding. The choice for the most reasonable designation goes to the estimate based on the single cloud results (16,394 acre-feet).

After dissipation of the seeded clouds on 25 April 1971 no other shower activity formed on the south Florida peninsula until about 1530 GMT on 26 April 1971 when small showers with top heights near 20,000 ft formed about 20 n mi southwest of Miami. These showers moved eastward into the Atlantic at a speed of 10-15 kts. By the time of the takeoff of the DC-6 seeder aircraft at 1720 GMT, there was once again no precipitation over the south Florida peninsula. When the aircraft reached its flight altitude of 20,000 ft MSL, light showers had commenced once again just west of Miami, although most clouds were not much above flight level (panel a of fig. 17). Cloud conditions were unsuitable for seeding in target area P so attention was focused on the cloud group west of Miami and Ft. Lauderdale.

The first group of seeded clouds (clouds 1 through 6) received a total of 93 50-gm silver iodide pyrotechnics that were dispensed from the DC-6 aircraft over a period of 50 minutes into the upshear (northwest) sides of the clouds. Growth was slow at first as the clouds struggled in the shearing environment (panel c of fig. 17). Upon continued seeding, however, the clouds grew and merged (panel d of fig. 17) until they grew into a cumulonimbus mass more reminiscent of a Midwestern storm than the typical Florida thunderstorm (panel e, fig. 17). The merged system grew to 53,000 ft, produced small hail, strong winds and up to 3.00 inches of precipitation in the Miami area (fig. 18). Most of the rainfall from this cloud complex fell into Biscayne Bay, although 3800 acre-feet fell on land (Table 6, pp. 131-32).

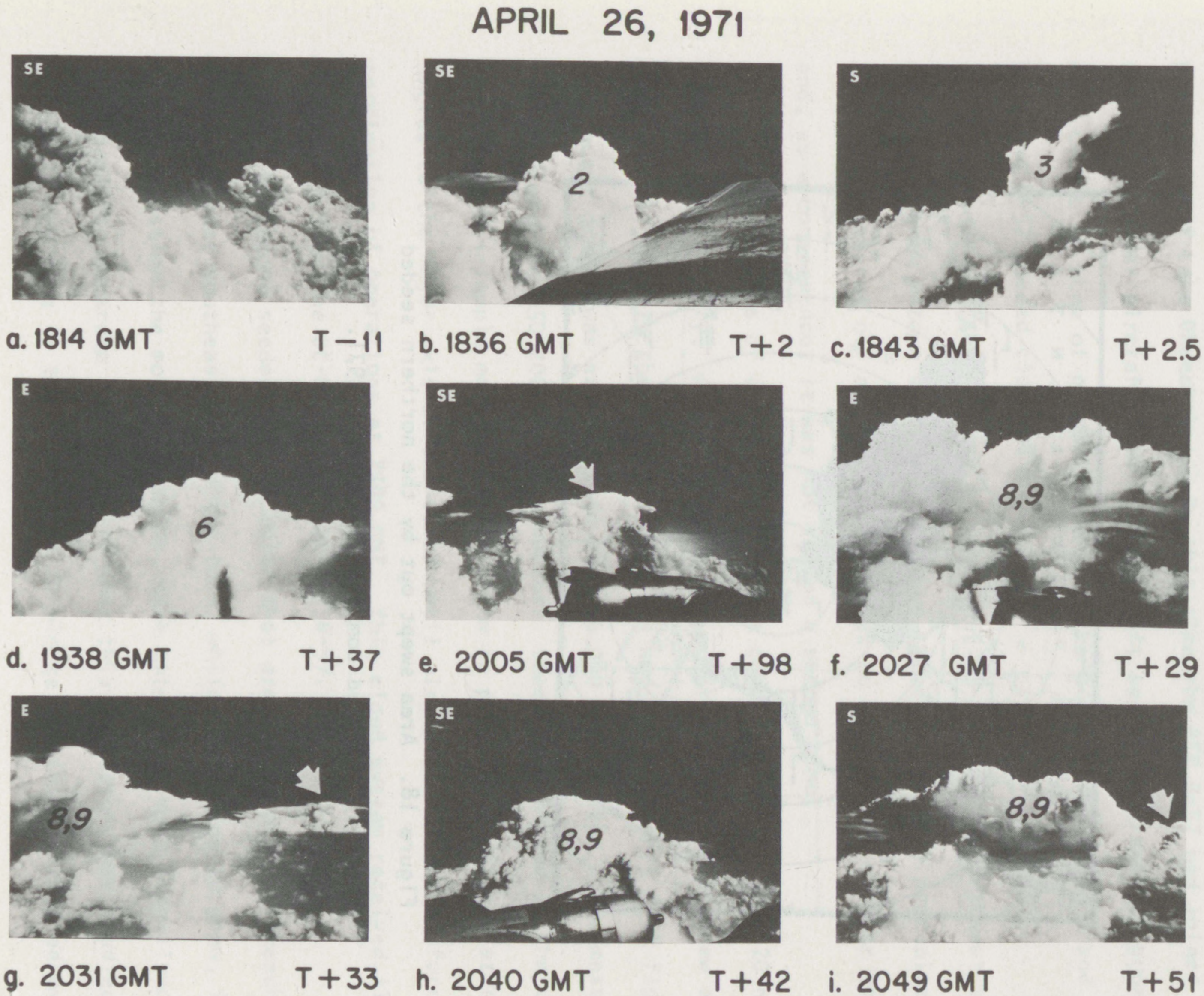


Figure 17. Airborne photographic sequence for 26 April 1971. Rest of caption same as that for figure 16.

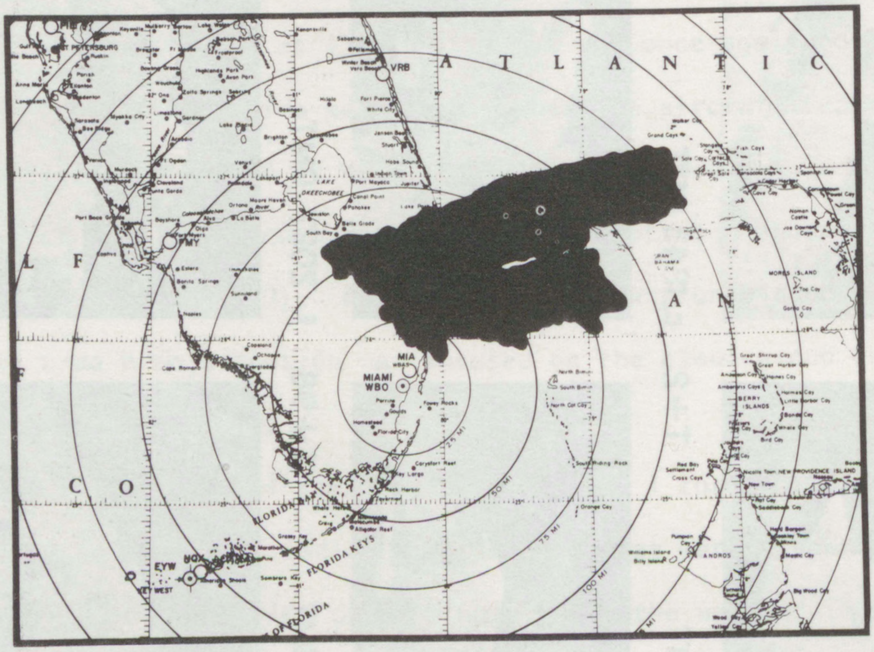


Figure 18. Area swept out by the northern seeded cloud complex on 26 April 1971.

The second seeded cloud complex was similar to the first. Seeding was discontinued on the first complex (marked with an arrow in panels e and g) after it had achieved cumulonimbus stature and had moved into the Miami area and attention was focused on a second group of clouds 10-20 n mi south of Lake Okeechobee. By this time the RFF B-57 had joined the DC-6 as a seeder aircraft, and both aircraft seeded separate but proximate clouds in hope of promoting merger; the B-57 seeded cloud 7 and the DC-6 and B-57 seeded clouds 8 and 9.

Cloud 7 was seeded when it was about 38 n mi north-northwest of Miami. It grew into a small cumulonimbus, produced a small precipitation echo, then sheared off and died. It failed to produce new upshear towers and, as a consequence, it was not seeded a second time.

The seedings of clouds 8 and 9 were conducted about 15 to 20 n mi northwest of cloud 7. After seeding, the towers of each cloud grew and merged until finally the clouds themselves had merged (panel f of fig. 17). Subsequent growth was explosive to over 56,000 ft with the cloud mass oriented along the 850-200 mb shear vector. Seeding continued in the upshear towers (example marked with an arrow in panel i) on tracks at right angles to the major axis of the cloud until aircraft malfunction forced termination of operations at 2100 GMT. This cloud system received 114 flares; 30 from the DC-6 and 84 from the B-57.

The second seeded cloud complex that grew south of Lake Okeechobee and moved east-southeastward to the coast while continuing to grow, is without question the most impressive, most extensive, most long-lived and most prolific separate seeded entity that this laboratory has studied to date. At one time in its 6 hour and 20 minute lifetime it covered over

1000 n mi^2; it swept out an area (fig. 18) of 5300 n mi^2 and produced an estimated total of 97,504 acre-feet of water, 42,054 on land and 55,450 over the Atlantic. The overland figures were computed using the isohyetal analysis for this cloud (fig. 19), while the overwater volume was computed using the nomogram and then corrected. This cloud produced hail and probably produced point rainfalls exceeding 3.00 inches, although no such value was measured by the rather porous gage network. The next day officials of the Central and Southern Florida Flood Control District (C&SFFCD) asserted that this cloud had extinguished many grass and muck fires that were rampant over the conservation areas southeast of Lake Okeechobee.

It is vital to know what role seeding played, if any, in the events of 26 April 1971, especially when one considers that:

1) the more prolific cloud produced approximately two-thousandths of the mean annual precipitation for the Florida peninsula south of 27°N latitude (assuming a uniform annual mean of 55 inches).

2) the storms approached severe limits with small hail, strong winds (60 mph in gusts) and heavy rain.

The detailed analysis that follows will not prove or disprove seeding causality for the events of 26 April 1971, but it will aid in better understanding them.

The events of 26 April 1971 were documented through concurrent use of WSR-57 radar observations and brightness contoured ATS-III satellite photographs of the Florida region. The latter product has been described by Woodley and Sancho (1971). Enlarged ATS-III positive transparencies were subjected to a color densitometer after partial brightness normalization to account for picture handling and printing changes using the dens-

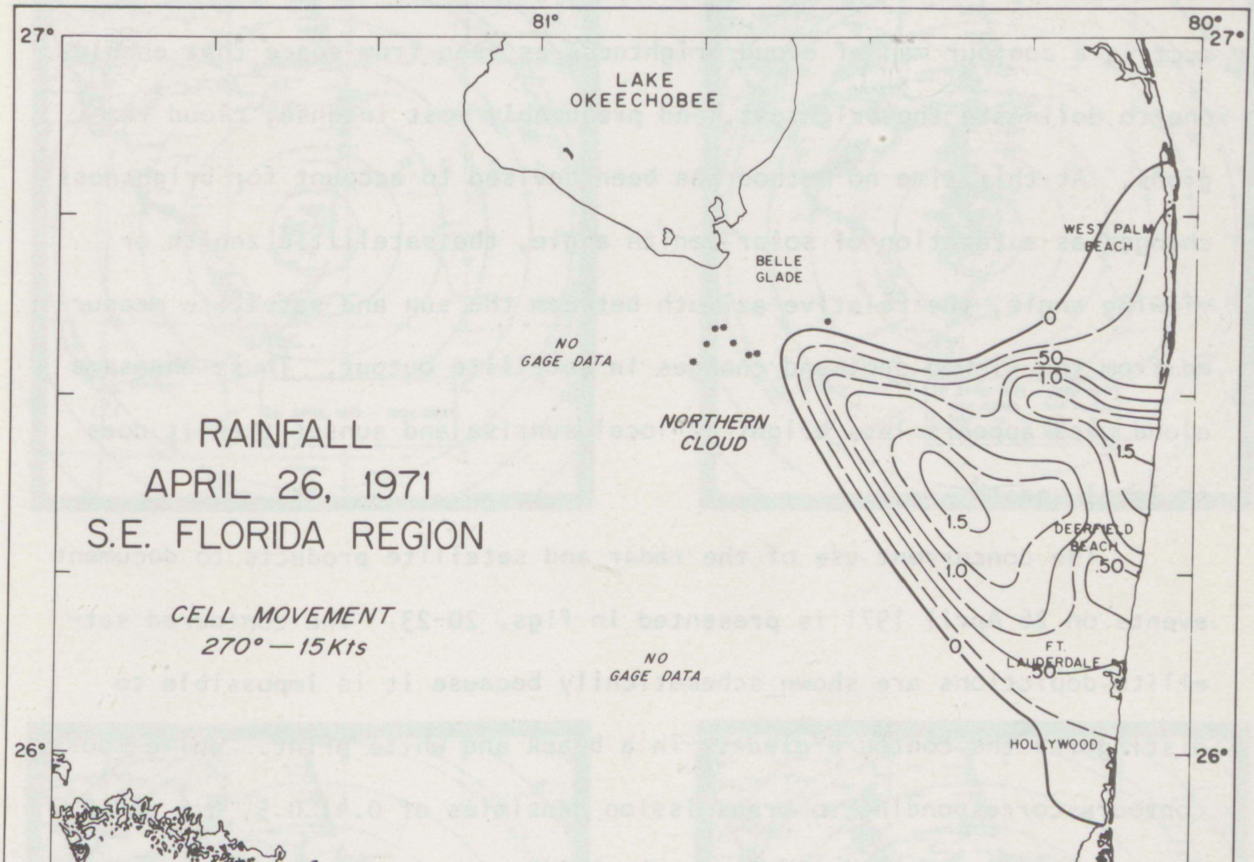
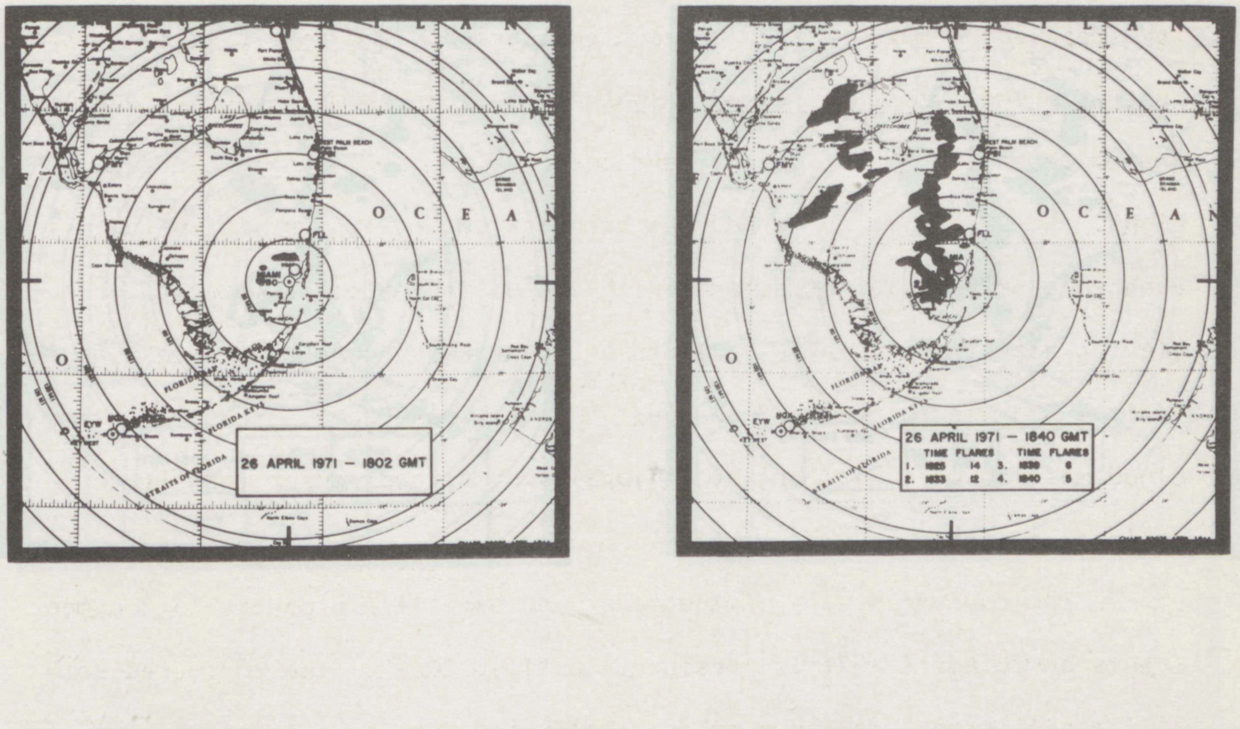


Figure 19. Isoheyetal analysis for 26 April 1971. Dots are positions of seeding passes.

ity step wedge that appeared on each photograph. The resultant color product is a contour map of cloud brightness as seen from space that enables one to delineate the brightest, and presumably most intense, cloud regions. At this time no method has been devised to account for brightness changes as a function of solar zenith angle, the satellitie zenith or viewing angle, the relative azimuth between the sun and satellite measured from the viewed spot and changes in satellite output. Thus, the same cloud mass appears less bright at local sunrise and sunset than it does at local zenith.

The concurrent use of the radar and satellite products to document events on 26 April 1971 is presented in figs. 20-23. The contoured satellite depictions are shown schematically because it is impossible to distinguish the contours clearly in a black and white print. While four contours corresponding to transmission densities of 0.4, 0.5, 0.6 and 0.7 are possible in these depictions, the brightest contour (transmission density 0.4) never appears. Because of the late time of day, the cloud masses were not bright enough to warrant the highest brightness contour. The satellite photographs have been gridded as accurately as possible, although errors of five to ten miles are possible. Seeding positions have been plotted on the satellite depictions with times and number of flares expended in the legend.

The brightest cloud masses (transmission density of 0.5) were just west of the Miami area at 1802 GMT. Very light showers may have been falling from the clouds at this time, but the WSR-57 radar could not detect them because of ground clutter. Seeding commenced in this area at 1826 GMT. By 1840 a more extensive region of the first brightness



Figures 20-23. WSR-57 radar and ATS-III satellite documentation of the weather events over south Florida on the afternoon of 26 April 1971. Those panels not specifically marked "WSR-57 radar" are the brightness-contoured satellite depictions. Numbers on satellite depictions correspond to numbers in panel legend. For details, see text.

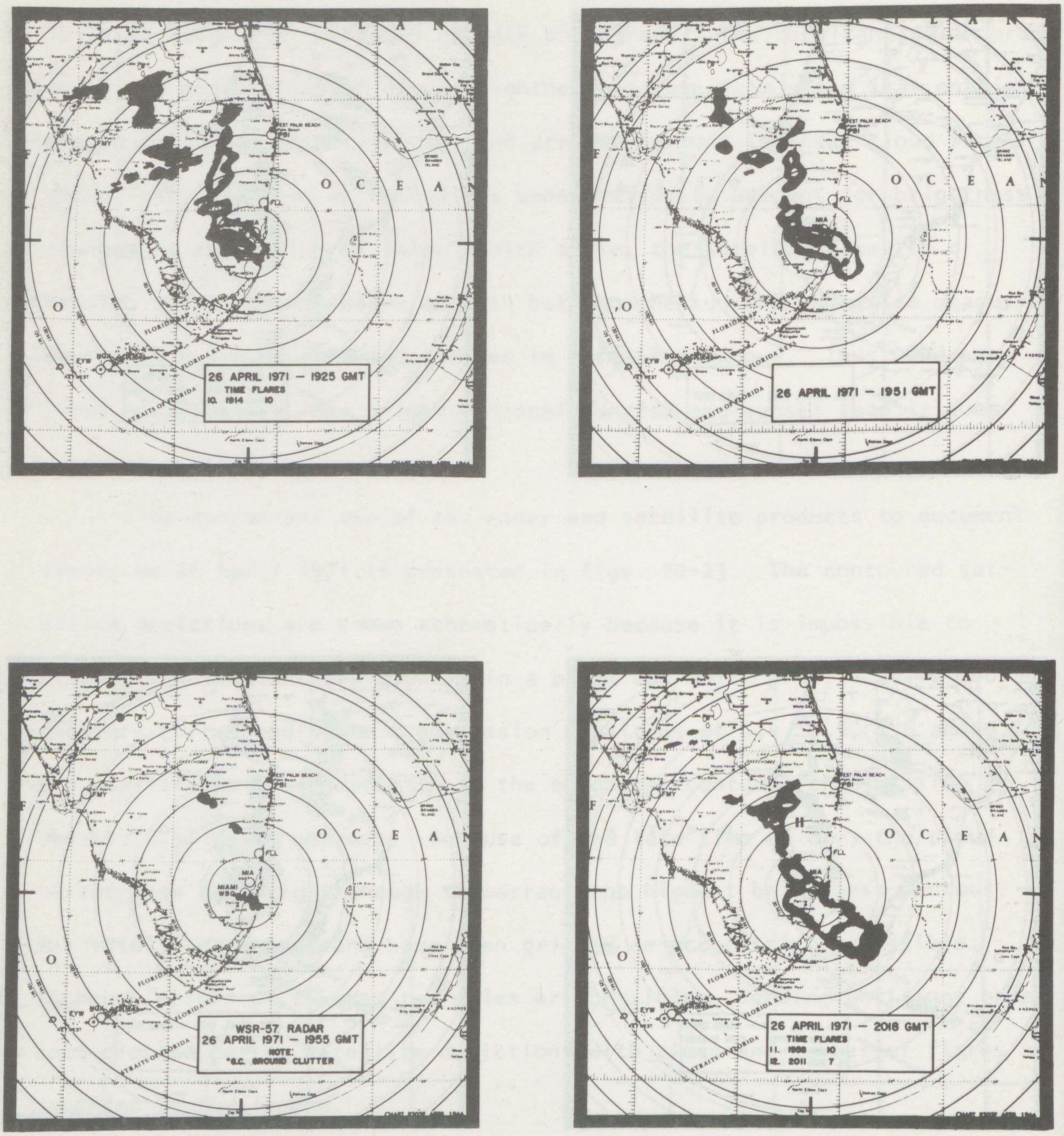


Figure 21. See caption for figure 20.

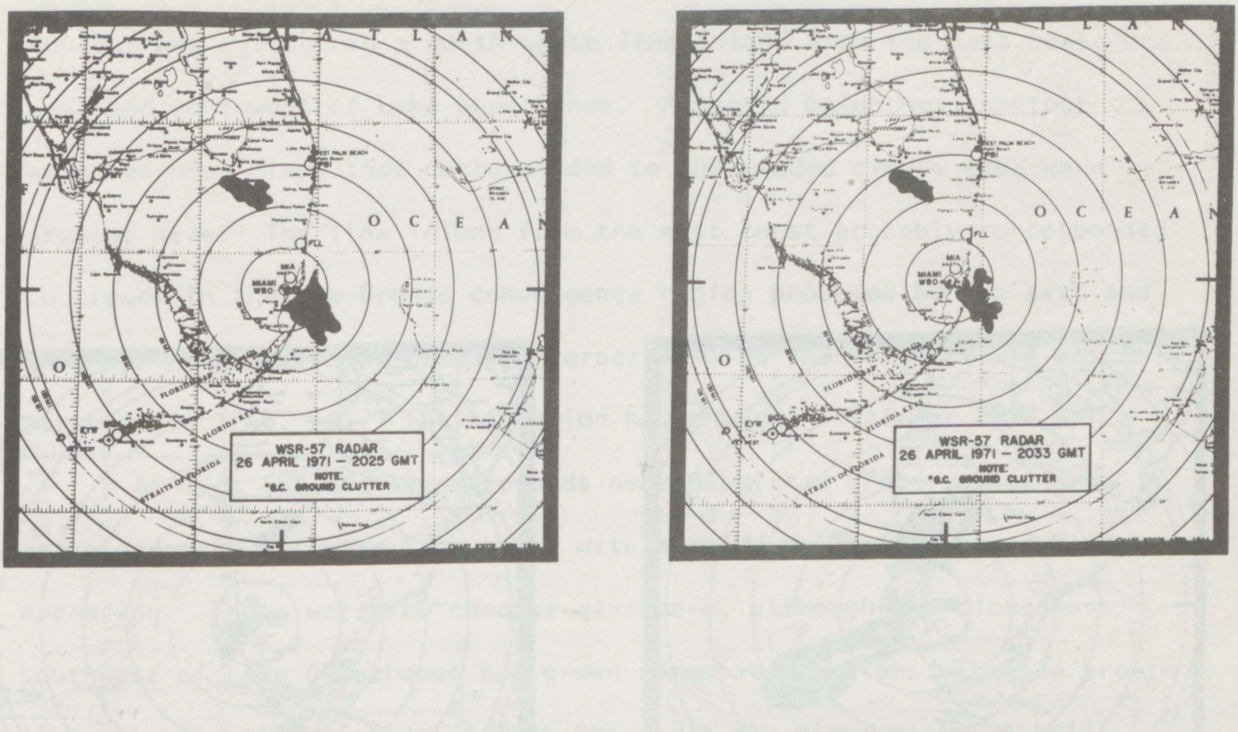
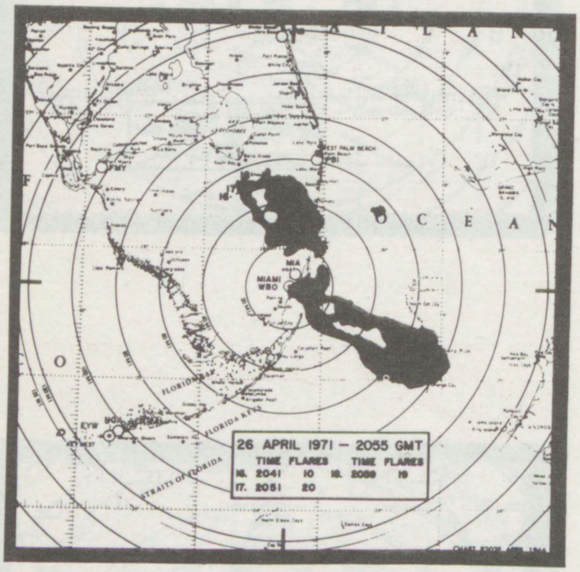


Figure 22. See caption for figure 20.



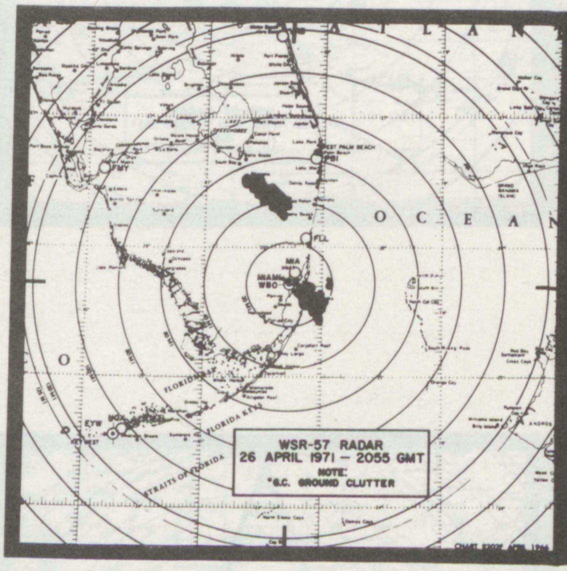


Figure 23. See caption for figure 20.

contour was evident in a north-south line inland from the east coast and west and southwest of Lake Okeechobee. A second brightness contour appeared near Miami that corresponded to the seeded clouds that were growing here. The line inland from the east coast probably corresponded to clouds in the sea breeze convergence region produced by the east and southeast low-level sea breeze interacting with the larger-scale westerly circulation (fig. 10). The situation had changed little at 1856 GMT.

At 1912 GMT the seeded clouds near Miami had grown taller and hence appeared brighter from space with a third brightness contour now appearing. There were few changes elsewhere, although the cloud mass southwest of Lake Okeechobee had grown somewhat brighter. The sea breeze line was slightly brighter at 1925 GMT while the Miami mass was still brighter. Heavy precipitation was falling in the Miami area at this time, but none was falling elsewhere.

The depiction seven minutes before initial seeding of the second cloud group southeast of Lake Okeechobee suggests that the sea breeze line had weakened somewhat and that some of the precipitation and the anvil from the Miami cloud was spreading into Biscayne Bay and the Atlantic. (One should remember that if it were possible to brightness normalize these depictions to local zenith, the brightness contours would change considerably for the later depictions). The 1955 WSR-57 radar depiction shows some of the precipitation from the Miami cloud moving out of the ground clutter into Biscayne Bay and several other showers, one west of Pompano Beach, one south, and two 40 to 60 miles northwest of Lake Okeechobee.

The Miami cloud continued to move into the Atlantic between 2018 and 2033 GMT while the cloud echo south of Lake Okeechobee had increased in area over fivefold in this period. The disappearance of the third brightness contour from the Miami cloud was probably due in part to actual weakening of the system and to the increasing sun angle. The increased intensity of the northern cloud despite the later time of day is evident in the 2040 and 2055 GMT satellite depictions. The areal coverage of this echo changed little during this period while drifting southeastward. Satellite coverage terminated after this time. The later movement of the complex can be inferred from fig. 15.

The concurrent use of the radar and satellite observations indicates that satellite photographs can be usefully quantified to delineate the most intense cloud areas that correspond to precipitation. The near perfect fit (despite gridding problems) of the radar echo over the most radiant portion of the 2040 GMT satellite photograph is a good illustration. More specific to understanding the events of 26 April 1971, their use has shown that:

1) only two major precipitation systems formed on this day, both of which were seeded, and they did not achieve massive stature until some time after the initial seeding.

2) both cloud groups were precipitating lightly before seeding, which is the usual case for clouds with tops near 20,000 ft. Obviously, some of the precipitation would have fallen without seeding.

3) there were other cloud areas in the period 1800 to 2000 GMT

with the same initial radiance as the seeded system that could have, but did not, grow into large precipitation systems.

4) sea breeze forcing was probably a factor in the meteorological events of the day. The clouds that were seeded were apparently in the sea breeze convergence zone that favored some natural cloud growth and precipitation.

The numerical cumulus model of EML was used in an attempt to delineate the effect of seeding on this day. However, its application to clouds that are growing in a strongly shearing environment is certainly open to question. Nevertheless, it is felt that the larger the predicted seedabilities for clouds that were monitored and seeded on 26 April, the more confident one can be that seeding was the prime mover in the formation of the two large cumulonimbus systems.

The Miami radiosonde for 0000 GMT on 27 April 1971 was nearest in space and time to the seeded clouds. The model run in real time using this sounding, a 915m base and a hierarchy of cloud radii, suggests (Table 3) that the effect of seeding on this day is strongly dependent on the radii of the cloud towers at seeding. If the towers were small (<1000 m) at seeding, the model predicts that seeding would cause them to grow substantially higher than they would have had they not been seeded. On the other hand, if they were large (>1000 m) initially, the model indicates that their subsequent behaviors would have been the same regardless of whether they had been seeded or non-seeded. This uncertainty could only be resolved by measurement of the radii of the cloud towers prior to seeding. A radiosonde observation closer in time and space to the seeded clouds might also be required.

The horizontal sizes of the cloud towers were measured by photogrammetry using the time-lapse film from the two 35mm side cameras on the RFF DC-6 and the method of analysis developed by Herrera-Cantilo (1970). All clearly defined cloud towers that were reaching the flight level of the DC-6 were measured and the results plotted in fig. 24. All measurements made over a minute are centered at the appropriate time, the vertical line gives their spread, and the number is the number of measurements. A photograph of the tower that was measured appears as an inset above the plot; the tower radius measured is clearly marked. The letter identifiers on the towers correspond to the letters in the plot. The distance of the aircraft from the cloud tower is entered below the picture.

Towers A, B, E, F, G and I were measured when they were at or slightly above the level of the DC-6, so they provide an estimate of the tower sizes that were seeded by the DC-6. Towers A and B are of the Miami complex, tower E is that of the cloud 8-9 complex before seeding, tower F is that of cloud 7 just before seeding, tower G is an upshear tower of the 8-9 complex during seeding, and tower I is an unseeded cloud northwest of the 8-9 complex. With the notable exception of tower F, all these tower radii were 1000 m or less, having seedabilities in the 1.5 to 4.0 range, suggesting that the growth behaviors of the seeded clouds may have been in large measure due to the seeding.

Tower F was the largest tower measured prior to seeding and the model suggests that it would grow to cumulonimbus by itself with or without seeding. It did, in fact, do just this, but then it died while

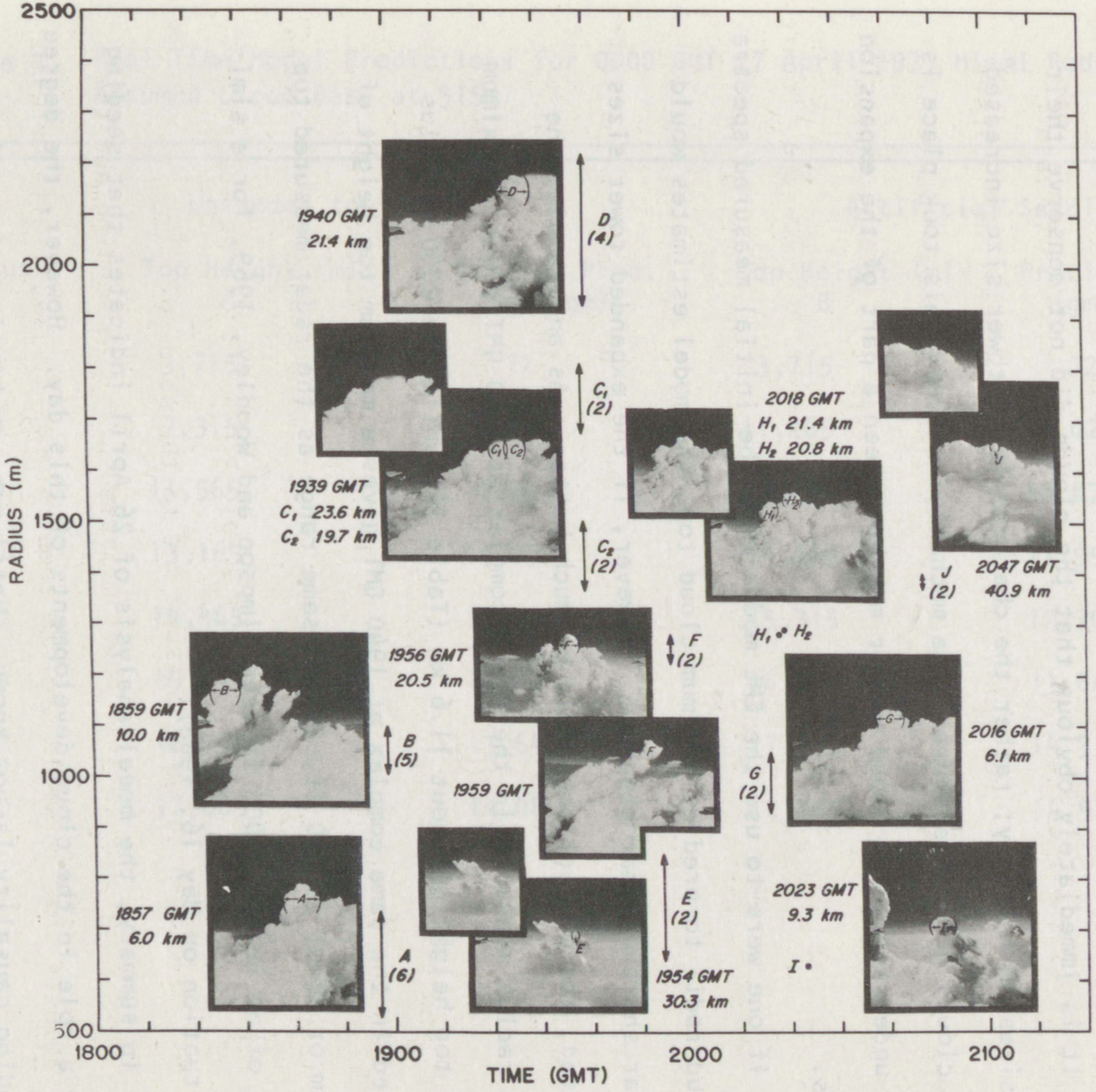


Figure 24. Plot of cloud radius measurements versus time for 26 April 1971. The vertical line gives the spread of the measurements; the number along side is the number of measurements. The tower measured is shown as an inset; the tower radius is marked. Distance from the cloud appears below the Greenwich time.

smaller seeded towers grew and merged. Obviously, initial tower size is only a part of the problem. On a day with high shear the close proximity of several smaller seeded towers may be more important than a large seeded cloud standing alone. The old adage of "united we stand, but divided we fall" seems most appropos for the events of 26 April 1971.

Towers C, D, H and J are towers in the large cumulonimbus systems, C and D in the Miami complex, and H and J in the 8-9 or Okeechobee complex. It is immediately obvious that the clouds did not conserve their tower sizes on this day; rather the characteristic tower size increased as the clouds grew in stature. The mechanism whereby this took place is poorly understood, but cloud merger may have been a part of the expansion process.

If one were to use the EML model with the initial measured spectra of cloud radii to predict maximum cloud top, the model estimates would fall far short of that observed. However, if the expanded tower sizes were used, the predictions would be much better. As an example, the 1000 m radius measured in the Miami complex at 1900 GMT gives a maximum seeded top height of about 11.6 km (Table 3), while the 2000 m radius measured in the same complex at 1940 GMT gives a maximum top height of 16.7 km or about 55,000 ft, in the same range as the radar measured top height of at least 53,000 ft (see Simpson and Woodley, 1969, for a similar situation on May 16, 1968).

In summary, the model analysis of 26 April indicates that seeding played a role in the cloud developments of this day. However, the degree of seeding causality is not known. Until more sophisticated models are

Table 3. Real Time Model Predictions for 0000 GMT 27 April 1971 Miami Radiosonde, Assumed Cloud Base at 915m

	Unseeded to -40C		Artificial Seeding -4C to -8C		
Radius (m)	Top Height (m) A	Precip. Prod. (gm/kgm)	Top Height (m) B	Precip. Prod. (gm/kgm)	B-A (km)
500	3,715	.72	3,715	.72	0
750	7,315	6.08	11,265	9.02	3.95
1000	11,565	9.62	13,165	10.87	1.60
1250	13,165	11.07	14,465	11.95	1.30
1500	14,465	11.99	15,315	12.70	0.85
2000	15,815	13.02	16,715	13.66	0.90
2500	16,915	13.64	17,865	14.37	0.95
3000	17,865	14.08	18,965	14.97	1.10

in hand, there is little more that can be said about the role of seeding on this day.

The severe weather potential of dynamic multiple cloud seeding needs more discussion. Seeding by itself cannot generate severe weather unless the induced cumulonimbus is growing in an environment that favors its generation. The seeded cumulonimbus clouds of 26 April 1971 approached severe limits, producing pea-sized hail, because they were induced in an environment with high kinetic energy, strong shear and an unstable upper troposphere as seen in the Miami 1200 GMT sounding on this day (fig. 25a). This sounding is not too different from a typical Midwestern hail sounding, as shown in fig. 25b. Hail two inches in diameter fell very close in space and time to this Omaha, Nebraska sounding. In the Midwestern case, the trigger for cumulonimbus generation is usually frontal uplift or convergence in a squall zone ahead of the front. For the south Florida case of 26 April 1971 the apparent trigger was dynamic seeding. Whatever the trigger, the end result can be storms that approach severe limits.

If it were always easy to recognize the environment that favors the generation of severe storms, one would simply not seed clouds in that environment. In the most pronounced cases this recognition is relatively simple. However, in many instances severe weather occurs in Florida from clouds that form in what appears to be a "benign" environment. The events of 10 May 1971, discussed later, is one such case. Unfortunately, the rather high frequency of such unanticipated strong to severe storm formation in a "benign" environment with resultant minor to moderate damages

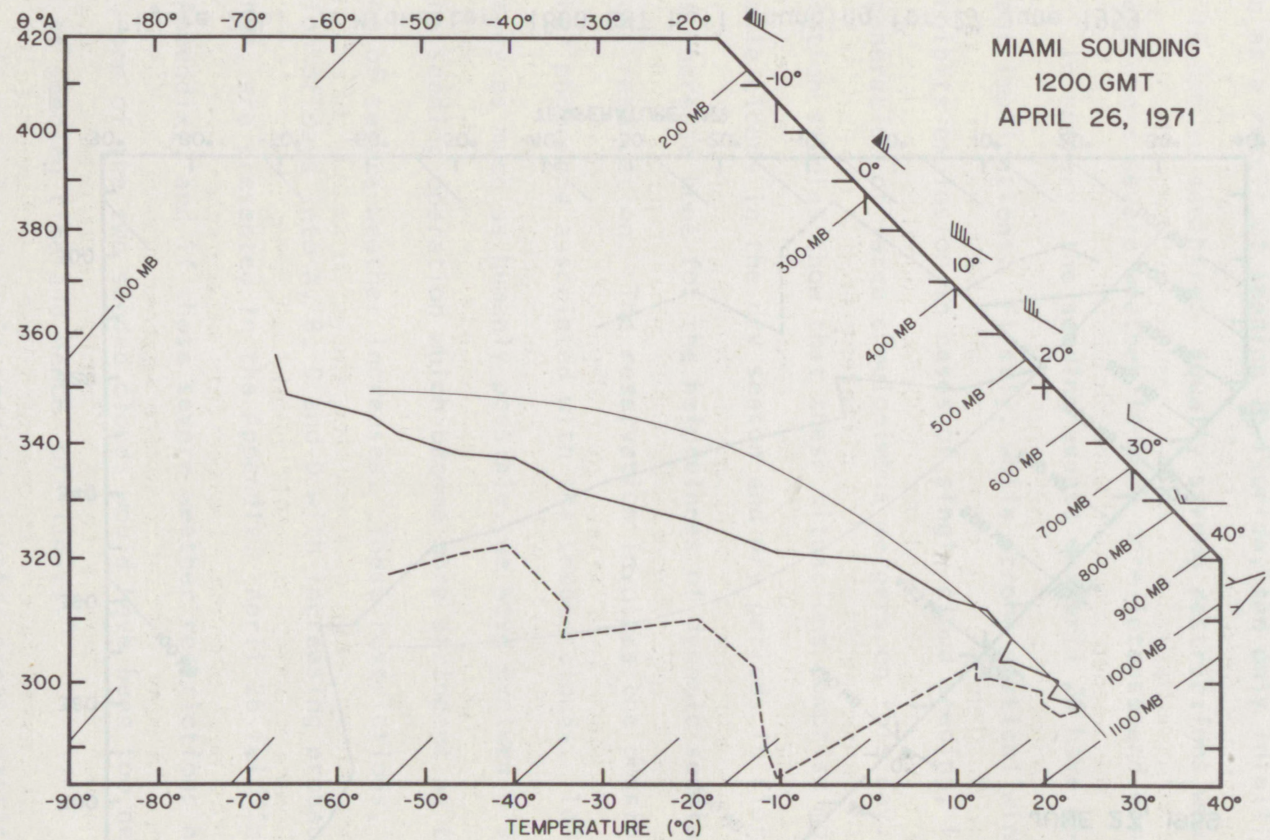


Figure 25a. Miami 1200 GMT sounding for 26 April 1971.

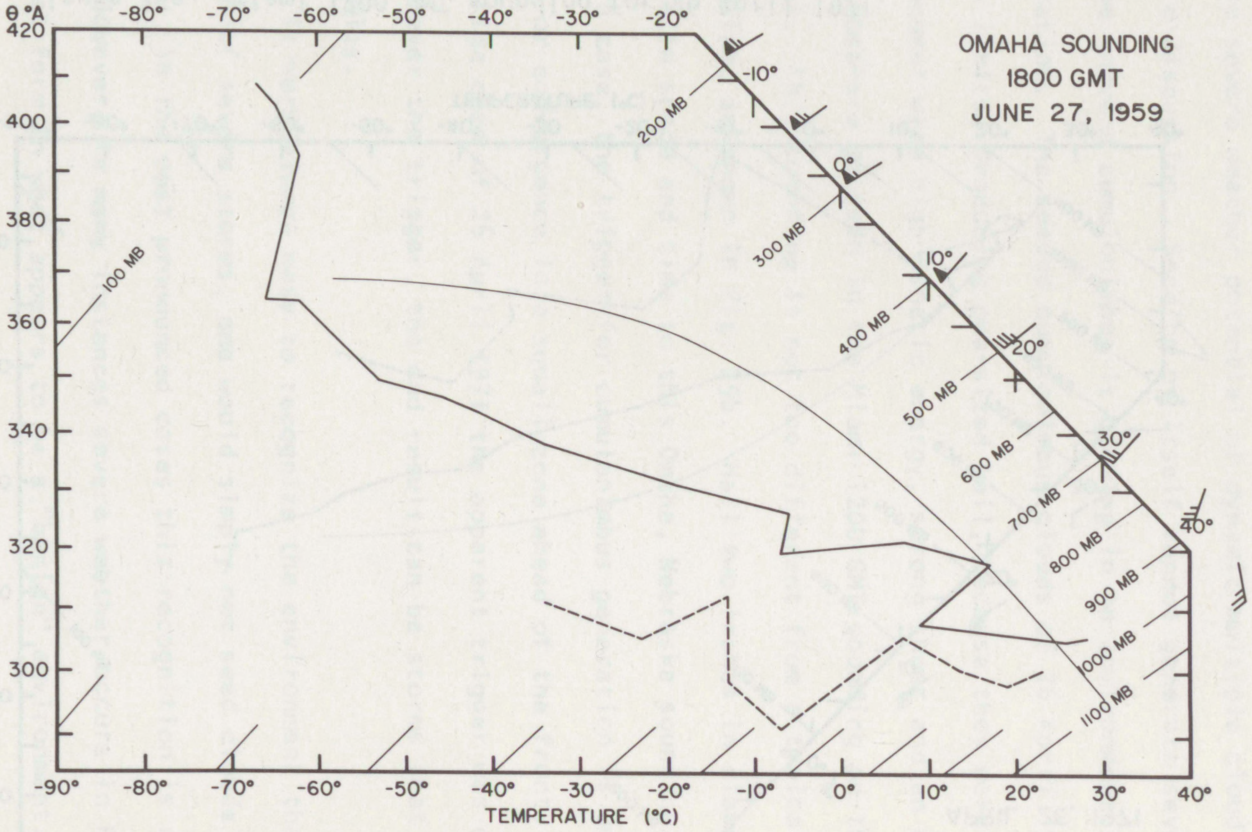


Figure 25b. A Midwestern 1800 GMT hail sounding for 27 June 1959.

makes one despair of ever forecasting severe weather accurately in Florida. Therefore, if one wishes to preclude any possibility of severe storm formation as a result of seeding in Florida, the only infallible recommendation is not to seed here. Equally strong restrictions would apply in the Midwest where severe weather is much more intense and damaging.

In summary, the seeding events on April 26 have possibly some important implications. Firstly, while strong vertical wind shear apparently inhibits explosion in cases of single cloud seeding, it may have aided the generation of large cumulonimbus mergers on this day. Since our cloud population studies show that these situations comprise more than half the seedable clouds in the dry season and dry periods in Florida, these results increase hope for the helpfulness of dynamic seeding, with one important reservation. The reservation involves the possibility of severe weather phenomena associated with the seeded clouds. To avoid this contingency as much as humanly possible, we have evolved a set of restrictions on the seeding operation which become more stringent as the expected likelihood of severe weather increases. These restrictions, involving categorization of days into A, B, C and D with increasing probability of severe weather, are presented in the Appendix. April 26 fell in category C (see the Appendix), and if those severe weather restrictions had been in effect, one of the two seeded clouds would have been too near the populated area at seeding time and hence "off limits."

In applying dynamic seeding in other areas, particularly in the Midwest, care must be taken to avert the risk of severe storms on high shear days, which in a drought unfortunately may be almost the only occasions of seedable clouds. Conversely, seeding these cloud conditions away from populated areas could provide extremely valuable information about the development and structure of severe storms and their eventual modification. It is hoped that EML will be able to conduct such a program with proper statistical controls in the future.

Most siginificant finding on 24-26 April 1971: Seeding was apparently spectacularly successful during this perod under conditions of high vertical shear of the horizontal wind. Nearly 40 percent of the rainfall from seeded clouds during the entire seeding program was produced during this period.

May 1, 1971 - The next opportunity for seeding operations was on 1 May 1971. Flight operations had been cancelled during mid-morning when it appeared that weather conditions would not warrant a seeding operation, but they were rescheduled later in the morning when weather conditions became more favorable. If it had not been for the ability and willingness of the RFF flight crew to regroup after initial cancellation, this day would have been lost to the program.

A weak, diffuse front over central Florida early in the day drifted southward in the Keys by late evening. The position of the main cloud band ahead of the front can be seen in the 1935 GMT ATS-III satellite photograph (fig. 26). The stronger elements in the line are the brighter masses in this photograph. Although the line drifted southward during the day, individual echoes moved from 280° 20 to 30 kts.

At the time of the 1820 GMT takeoff of the seeder aircraft, large sections of the Everglades were burning west of the airport and the smoke

Figure 26. 1935 GMT ATS-III satellite photograph on 1 May 1971.

was drifting over the runway. This situation is depicted in the first photograph of fig. 27. The seeding flight on this day had been rescheduled with the understanding that if suitable clouds formed upwind of these fires, they would be seeded preferentially in an attempt to douse the fires. Such an opportunity did present itself late in the day, and it is described below.

After takeoff, the aircraft proceeded north of Lake Okeechobee on the north side of the broken frontal cloudiness. There were already some mature cumulonimbus clouds in the line at this time. Seeding was carried out in the west or upshear sides of the cloud complexes, but cloud development was rather slow at first. Cloud water contents were low and updrafts were weak during the first two hours of seeding operation. However, during the latter half of the operation the upshear towers were increasingly more turbulent during aircraft penetration.

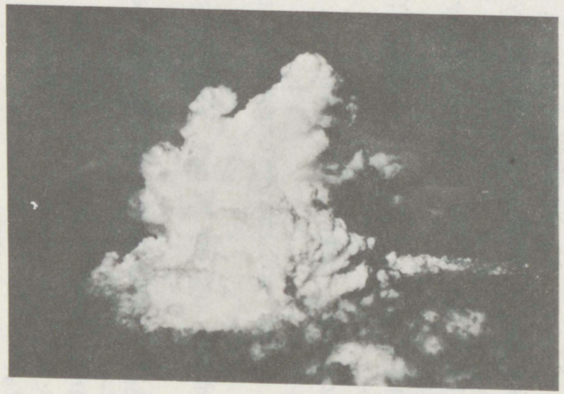
Cloud complex 13 was the last and most interesting of the day. At the time of selection it was a small cumulonimbus cloud that was upwind of the fires burning near Miami International Airport. Upon seeding, the cloud appeared to change character as the upshear towers took on a very hard cauliflower shape as shown in panels 3 and 4 of fig. 27. Aircraft penetration verified the great vigor of these towers. Seventy-one flares were dropped into this complex; it reached a maximum height of 52,000 ft, had a maximum radar-determined rainfall rate in excess of 2.00 inches per hour and dropped one to two inches of precipitation in North Miami. However, other unseeded cloud complexes on this day exhibited similar behaviors. The seeded cloud coupled in conjunction with heavy rain from un-

MAY 1, 1971

FIRE WEST
OF MIAMI INTL.
AIRPORT
ON CLIMBOUT

1909 GMT
FRONTAL CLOUDINESS

2228 GMT T+7



2237 GMT T+16

CLOUD 13 WNW OF MIAMI INTL.

Figure 27. Airborne photographic sequence for 1 May 1971. Rest of caption same as figure 16.

seeded clouds late in the evening did douse the fires west of the airport. However, these fires flared anew two days later.

Rather general showers fell over the southeast of Florida's coastal area on 1 May and the early morning of 2 May 1971. Little, if any, rain fell in this region after sunrise on 2 May 1971. The isohyetal map for this period is presented in fig. 28. Seeded clouds accounted for some of the rainfall shown.

The volumetric precipitation estimates from the subject clouds were made using Miami WSR-57 radar observations and the rain nomogram, while the regional estimate was made by space integration of the isohyetal analysis. The volumetric estimates for the seeded clouds (~9000 acre-feet), while substantial, are small compared to the 63,000 acre-foot total for the region of analysis. Two seeded cloud complexes (numbered 10 and 13 for the day) accounted for almost all of the seeded precipitation.

The effect of seeding was probably small compared to the natural course of events on this day. Seeding apparently increased the vigor of the precipitation systems, but it was certainly not responsible for their formation. A pre-existing line of convergence was probably the prime mover in shower formation. The model-derived effect of seeding for this day is preferred because it provides the minimum estimate of the effect of seeding.

Most significant finding on 1 May 1971: Seeding apparently increased the vigor of the precipitation systems on this day, suggesting that dynamic seeding may increase precipitation from cloud systems that have already attained cumulonimbus stature.

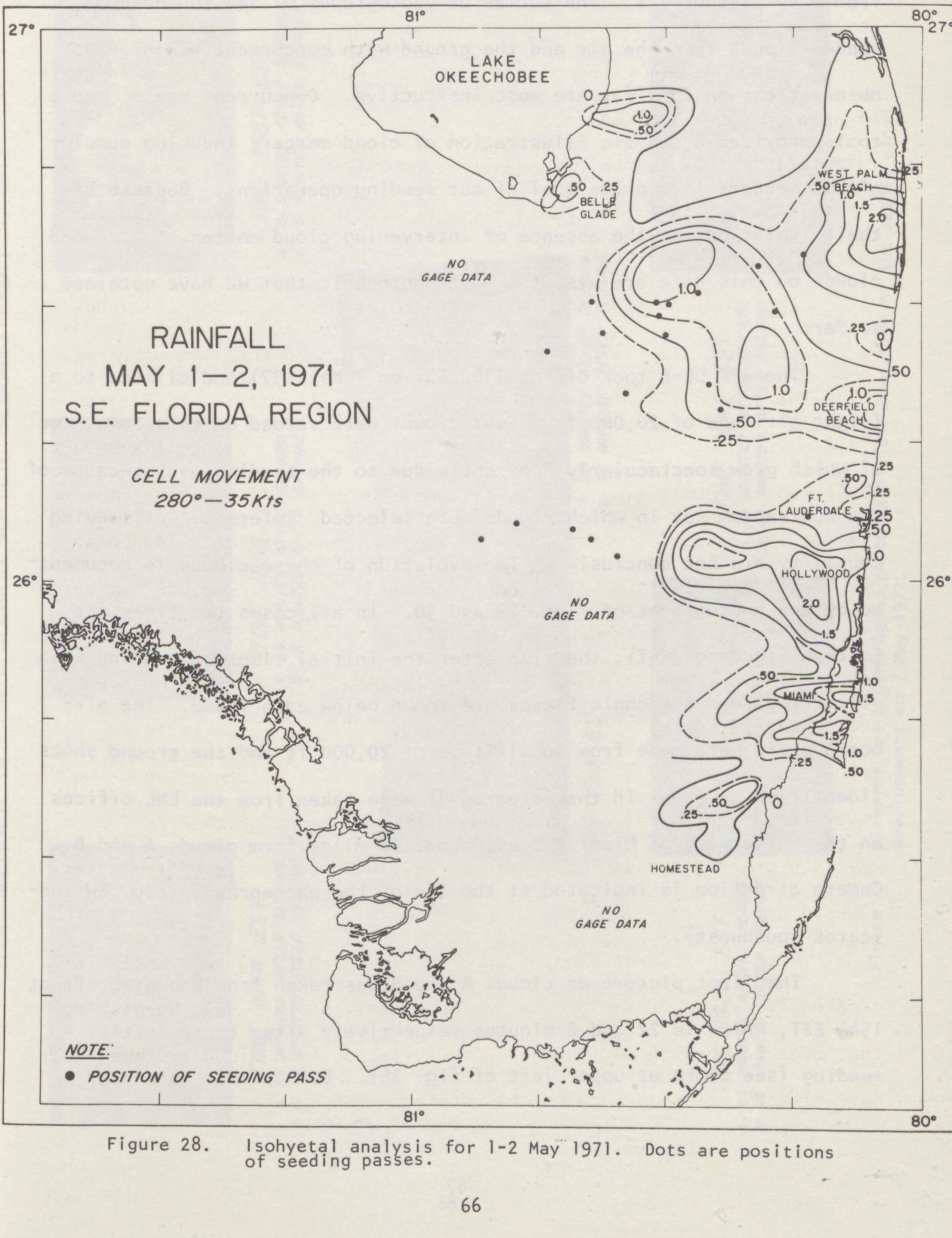


Figure 28. Isohyetal analysis for 1-2 May 1971. Dots are positions of seeding passes.

May 7, 1971 - The events of 7 May 1971 are of particular interest from many standpoints. The series of photographs of seeded and non-seeded clouds from the air and the ground with concurrent WSR-57 radar observations on this day are most instructive. Concurrent use of these tools provides a classic illustration of cloud merger; inducing cumulonimbus mergers is a prime goal of our seeding operations. Because of their isolation and the absence of intervening cloud matter, the seeded clouds on this date are also the most photogenic that we have obtained so far.

The RFF DC-6 took off at 1300 EST on 7 May 1971 and climbed to a flight altitude of 20,000 ft. Four clouds were seeded on this date, two of which grew spectacularly apparently due to the seeding, but because of the non-random way in which clouds were selected, inferences of seeding causality are not conclusive. The evolution of these clouds is documented by the photographs of figs. 29 and 30. In all cases the times are Eastern Standard (EST); the time after the initial times of seeding with silver iodide pyrotechnic flares are shown below each frame. The airborne shots were made from an altitude of 20,000 ft and the ground shots (identified by trees in the foreground) were taken from the EML offices on the University of Miami campus, about 30 miles from clouds A and B. Camera direction is indicated at the top of the photographs (e.g. SW indicates southwest).

The first picture of clouds A and B was taken from the aircraft at 1544 EST, which is 22 and 2 minutes respectively after their initial seeding (see photo at upper left of fig. 29). Both clouds were near

THE MERGER OF TWO CLOUDS AFTER SEEDING—MAY 7, 1971

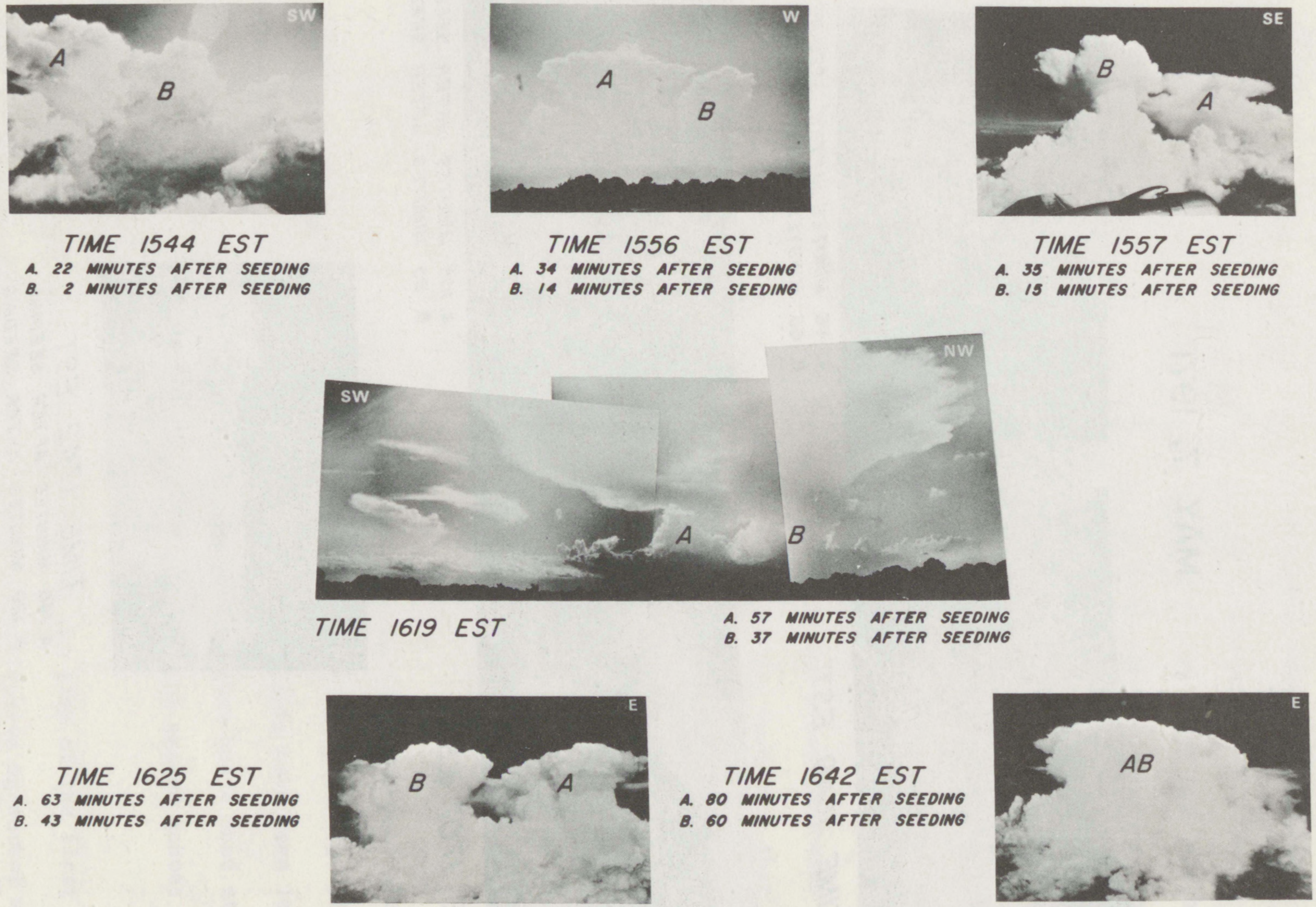


Figure 29. Airborne and ground-based photographic documentation of the seeded cloud developments on 7 May 1971.

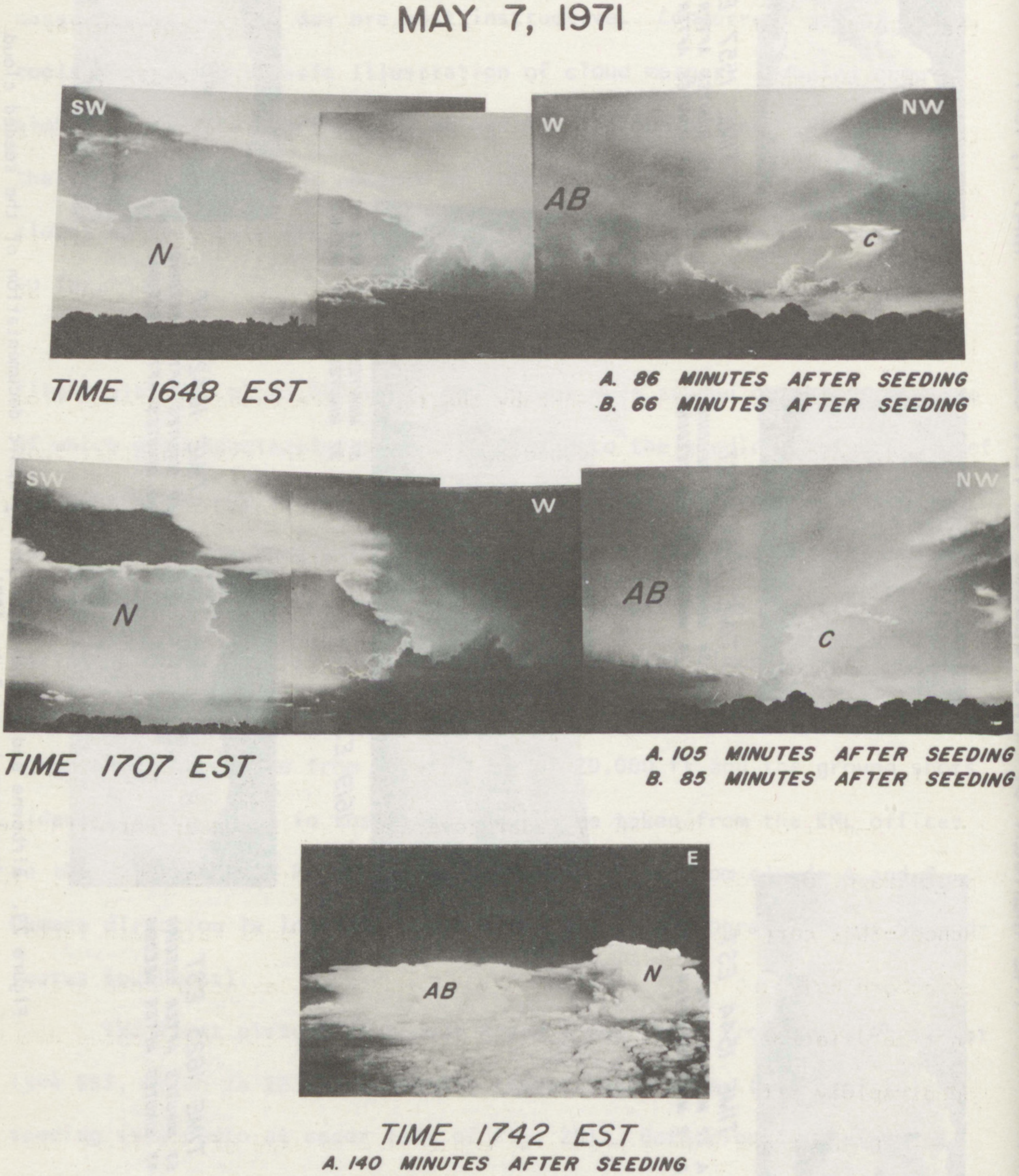


Figure 30. Airborne and ground-based photographic documentation of the seeded clouc developments on 7 May 1971.

flight level at the times of their initial seedings. Later pictures show that clouds A and B continued to grow following repetitive seeding. By 1619 EST the ground-based mosaic of photos in the center of fig. 29 shows that clouds A and B had grown closer together, with their tops now having a wind-blown anvil appearance. By 1642 EST the aircraft picture shows that clouds A and B had merged into a continuous mass (labeled AB), that was producing heavy precipitation.

Later views from the ground at 1648 and 1707 EST show the intensification of merger AB to a maxium altitude of 44,000 ft. Cloud C was an isolated seeded cloud on this day that grew in the cutoff tower mode (Simpson and Woodley, 1971), whereby the top of the cloud separates from its body below. It, too, produced rainfall, but far less than that from AB. Cloud N was a natural cumulonimbus that developed 40 miles southwest of Miami. It was not seeded because it formed outside the boundaries of secondary target S. While it produced less precipitation than the merged systems AB, the presence of cloud N indicates that one should be cautious in attributing all the precipitation from the seeded system AB to the seeding.

A portion of the WSR-57 radar coverage that is concurrent with the photographs of figs. 29 and 30 is presented schematically in fig. 31. The echoes that correspond to the clouds of the photographs have been lettered accordingly. One can see that the unseeded complex had a head start in time relative to the unseeded clouds, but that the seeded echoes developed rapidly after initial formation.

Clouds A and B were producing echoes at the time of the first photograph. They continued to grow and expand in qualitative agreement with

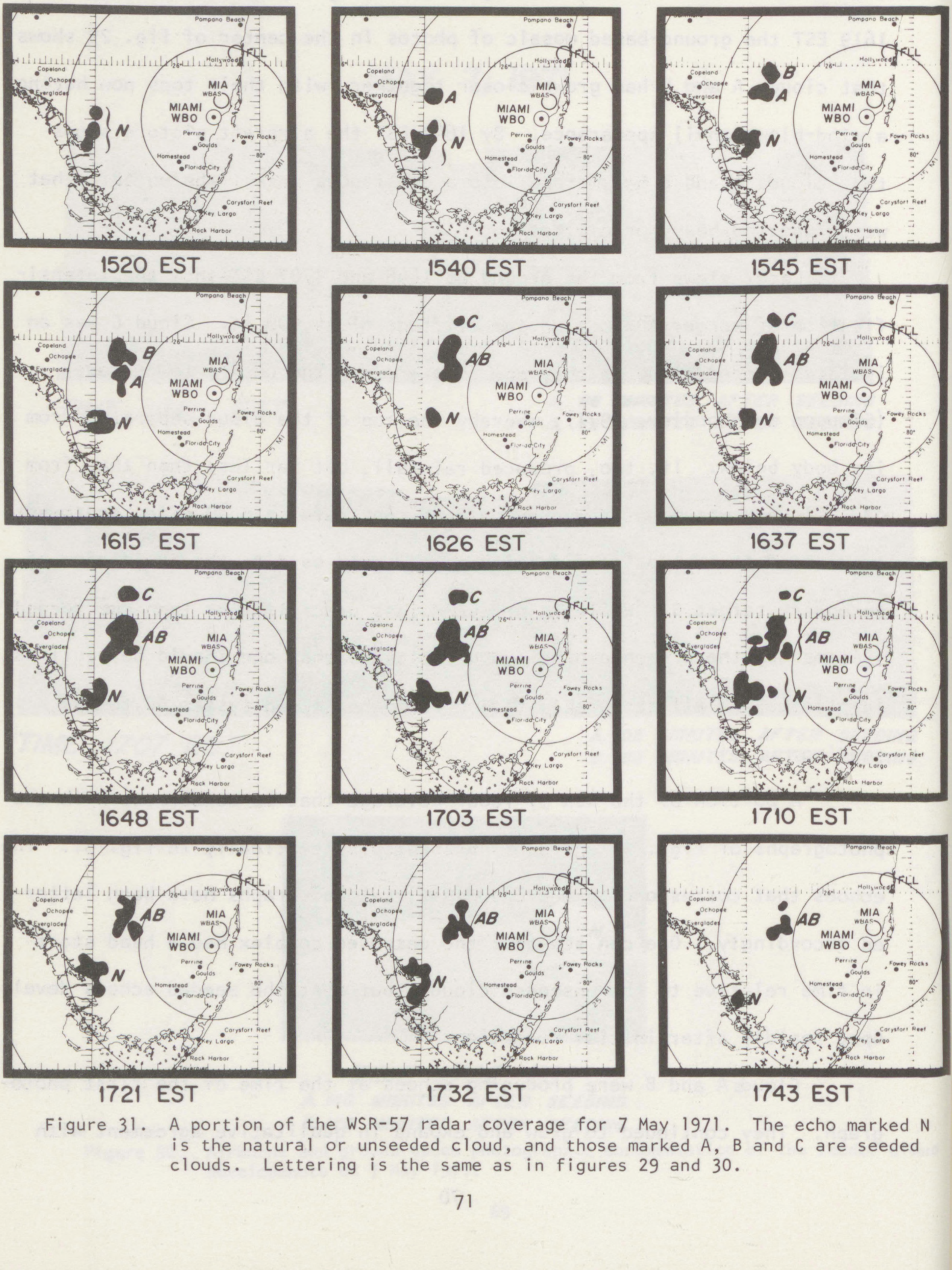


Figure 31. A portion of the WSR-57 radar coverage for 7 May 1971. The echo marked N is the natural or unseeded cloud, and those marked A, B and C are seeded clouds. Lettering is the same as in figures 29 and 30.

their change in visual appearance. By 1626 EST A and B had merged on the radar scan near cloud base, although there appeared to be a gap between the two above the flight level of the DC-6 at 1625 EST. Visual merger to the high troposphere was complete a short time later.

At 1648 EST echo mass AB was quite large (130 n mi^2), cloud N was expanding once again and the echo of cloud C had reached its maximum size (22 n mi^2). Subsequently, the echo masses appeared to fracture, shrink and eventually disappear from the radar scope, although cloud N lasted until approximately 1945 EST.

The volume of precipitation from the clouds shown in figs 29 and 30 was estimated using their complete history on the WSR-57 radar scope in conjunction with the precipitation nomogram that was discussed earlier. The rainfall calculations for clouds A, B, C and N are presented in fig. 32. The values have not been adjusted by the correction ratio (1.38). The ordinate is precipitation volume in acre-feet (1 acre-foot = 1.23×10^3 m^3 = 1.23×10^9 gm) and the abscissa is 10-min time interval. The zero (0) time is the time of initial precipitation (1520 EST) over the peninsula. Thus, the period -10 to 0 is the 10-min interval before first precipitation.

Both systems AB and N formed as the result of consolidation or merger of one or more initially separate clouds. The precipitation volumes of the components of AB are shown prior to merger, but no attempt has been made to break N into its component parts. Cloud C was an isolated seeded entity throughout its lifetime.

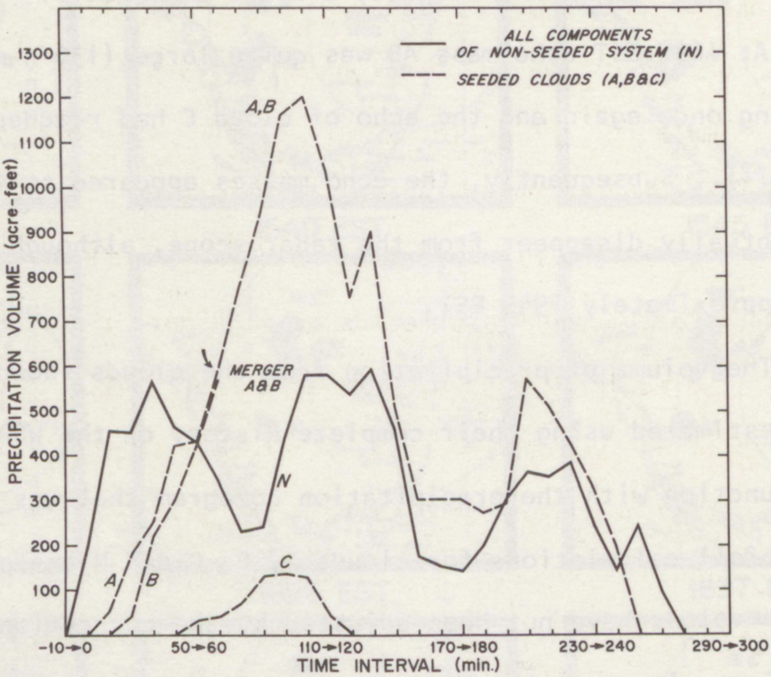


Figure 32. Volumetric rainfall calculations for clouds A, B, C and N. Values plotted have not been adjusted by the correction ratio (see text).

of AB but AB produced more precipitation. Cloud C produced much less precipitation than either merged system, once again illustrating the importance of cloud merger for the production of heavy rainfall (Woodley, Norwood and Sancho, 1971).

A summary of the calculations for clouds A , B, C and N is presented in Table 4. The corrected or adjusted rainfall was obtained by dividing the uncorrected precipitation volume by 1.4.

The sum of the precipitation volumes from AB and its components (A and B) before merger is a factor of 1.64 more than the volume from the unseeded complex N (10,195 vs. 6232 acre-feet) while the precipitation volume from C is over an order of magnitude less than that from either AB or N. It is not known with certainty that the difference in rainfall between AB and N represents a real effect of seeding or whether AB was by chance the more prolific of the two. The most reasonable effect of seeding on this day is thought to be the difference in the corrected precipitation volumes of AB and N or about 4500 acre-feet.

Most significant finding on 7 May 1971: The data from this day afford an excellent illustration of what is meant by cloud merger as documented by airborne and ground-based photographs and WSR-57 radar at Miami.

<u>May 8, 1971</u> - Weather conditions on 8 May 1971 had not changed appreciably from those on the previous day. The atmosphere over south Florida continued quite dry with rather late shower development. Cloud motion was small and propagation was dominant in most instances. None of the official raingages in south Florida reported any rain of consequence

Table 4. Seeding Summary and Precipitation Results, 7 May 1971

Cloud	Seeding Times (EST) First	Seeding Times (EST) Last	Amt. Ag I (gm)	Max. Top. Height* (ft)	Precip. Times (EST) First	Precip. Times (EST) Last	Precipitation Volume (acre-feet) Uncorrected	Precipitation Volume (acre-feet) Corrected
A	1522	—	1500	—	1530	—	1902	1378
B	1542	—	2250	—	1545	—	1560	1130
AB	—	1651	850	44,000	—	1921	10,762	7687
C	1630	1702	850	—	1626	1721	570	413
N	—	—	0	>33,000	1520	1945	8725	6232

* as determined by WSR-57 RHI

Cloud complex N precipitated before and after the birth and demise on this day, although an intense precipitation system formed over the interior by early evening.

After a 1730 GMT takeoff there was a flurry of seeding activity between 2010 and 2040 GMT in the southwestern portion of the secondary target. Three clouds were studied here, but the third was the only one seeded. Flight operations were terminated after the third pass through cloud 3 when the HF antenna broke loose from the tail of the aircraft. A total of 59 flares was used during the abbreviated operation. The seeded complex rose to a maximum height in excess of 39,000 ft and produced over 2000 acre-feet of precipitation (Table 6) as estimated from the rain nomogram.

A sequence of photographs of the seeded cloud and its environment is presented in fig. 33. A view of a group of natural cumulonimbus clouds along the southwest Florida coast 19 minutes before seeding of the cloud group marked with the number 3 is shown in panel a. The larger clouds were south of the secondary target and thus off-limits to the seeder aircraft. A better view of the cloud 3 complex, 3 minutes after initial seeding, is shown in panel b with the unmodified cumulonimbus complex in the right background, and a closer view of the 3 complex in panel c. The cloud 3 complex after it had attained cumulonimbus stature is shown in panels d, e and f. This complex was large and impressive, but no more so than the unmodificed cumulonimbus to its south and those that formed later to the north.

Shower development to the immediate north of seeded complex 3 on 8 May 1971 was most impressive. Several distinct showers formed in close

MAY 8, 1971

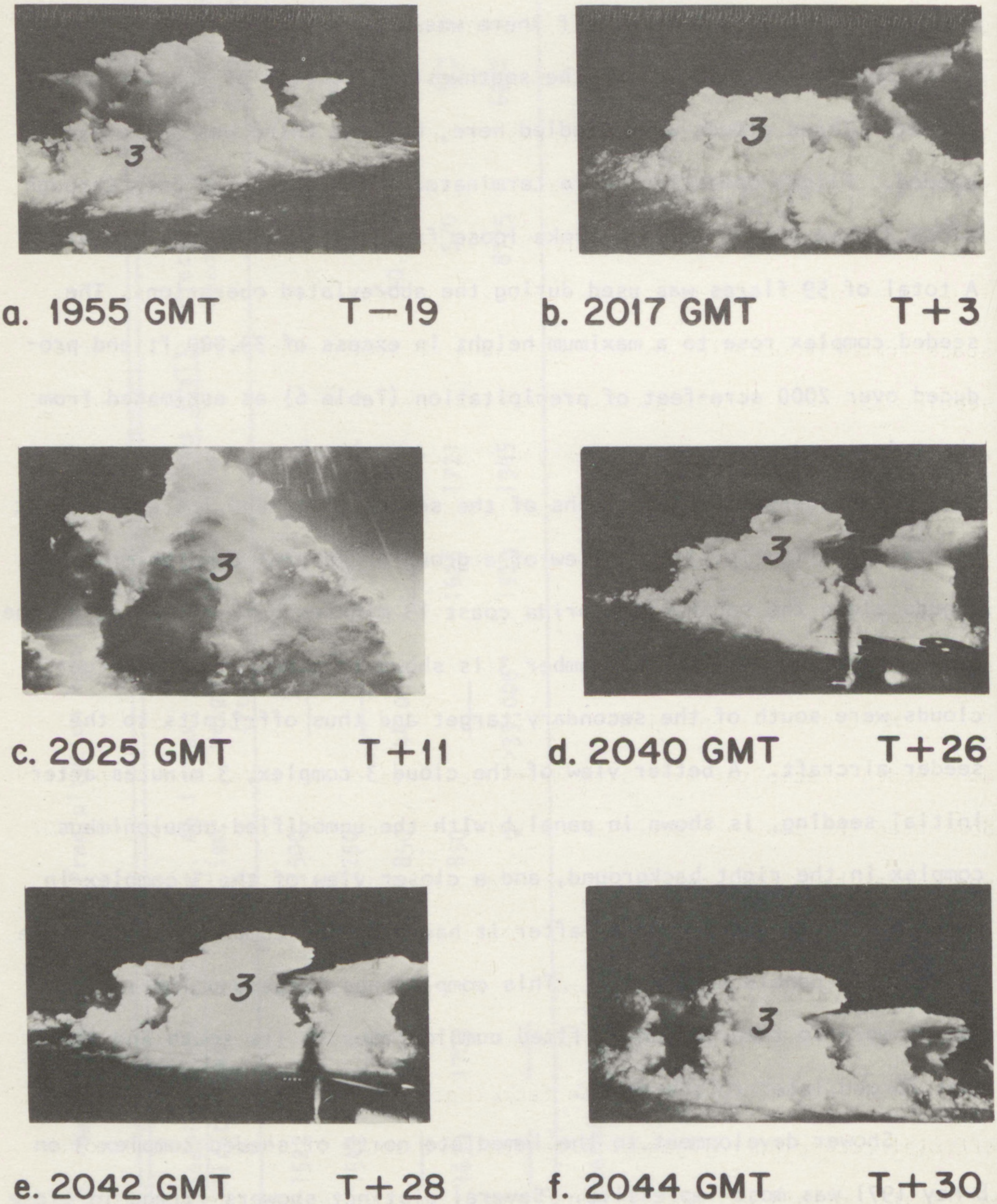


Figure 33. Airborne photographic sequence for 8 May 1971. Rest of caption same as figure 16.

proximity and grew together into a line with north northwest-south southeast orientation. At the time of its maximum development (2000 GMT) this shower complex towered to over 50,000 ft, covered nearly 900 n mi^2 and had a WSR-57 radar-determined rainfall rate of 5.00 inches per hour. This system was all the more remarkable because at the time of its formation there were no other showers of consequence anywhere within range of the Miami WSR-57 radar. Because this unmodified complex formed within five miles of the dying seeded complex and eventually took up the air space formerly occupied by it, one cannot discount the possibility that seeding may have played a causal role in the formation of the intense rain system. However, without any evidence to support such a role, none of the rain from the unmodified complex has been ascribed to the seeding. The secondary effect of dynamic cloud seeding on other cloud systems that are separate in space and time from the original subject clouds must still be determined.

Most significant finding on 8 May 1971: An intense, extensive non-seeded precipitation system developed late on this day and completely dominated the southern peninsula. While this massive system occupied space that had been taken up by seeded clouds earlier in the day, none of its precipitation has been ascribed to the seeding.

<u>May 9, 1971</u> - May 9 was a fair day with widely scattered thunderstorm activity by afternoon. This activity was centered primarily over the interior, accounting for the fact that no rain was measured by the official recording raingages in central and south Florida. Cloud motion was small on this day and, as on 8 May, propagation was the dominant

means of cloud movement. Five clouds were seeded repetitively in the center of the secondary target on 9 May, and seeded cloud complex 1-2 was the major precipitation system over the entire southern peninsula on this day.

Seeded cloud complex 1-2 grew in two stages, the first between 1900 and 1930 GMT when the seeded tower of cloud 1 grew, anviled and subsided, and the second after 2030 GMT when complex 1-2 grew to major cumulonimbus stature. The hour hiatus between the two growth phases of the complex was due to a lack of upshear cloud towers that were suitable for seeding. The seeded complex merged with an unmodified cumulonimbus complex to its south after 2120 GMT.

Portions of the developments described above are illustrated in fig. 34. In panel a the growing tower of cloud 1 is shown approximately 17 minutes after initial seeding. Note the large unmodified cumulonimbus in the distant right background. In b the seeded tower is shown 11 minutes later after having attained miniature cumulonimbus stature. The same cloud group is shown from the upshear side looking downshear in panel c, over 1 1/2 hours after initial seeding. The cloud complex was ending its dormant phase at this time. In panels d, e and f the seeded complex is shown as it grew to massive cumulonimbus size with the natural cumulonimbus (N) (right background) pacing it in a race to the stratosphere. In the last photograph the seeded complex is the dominant cloud, now having pileus-draped towers poking through the main anvil into the stratosphere. The two cloud systems merged 15 minutes later.

The combination of the seeded and non-seeded systems resulted in a

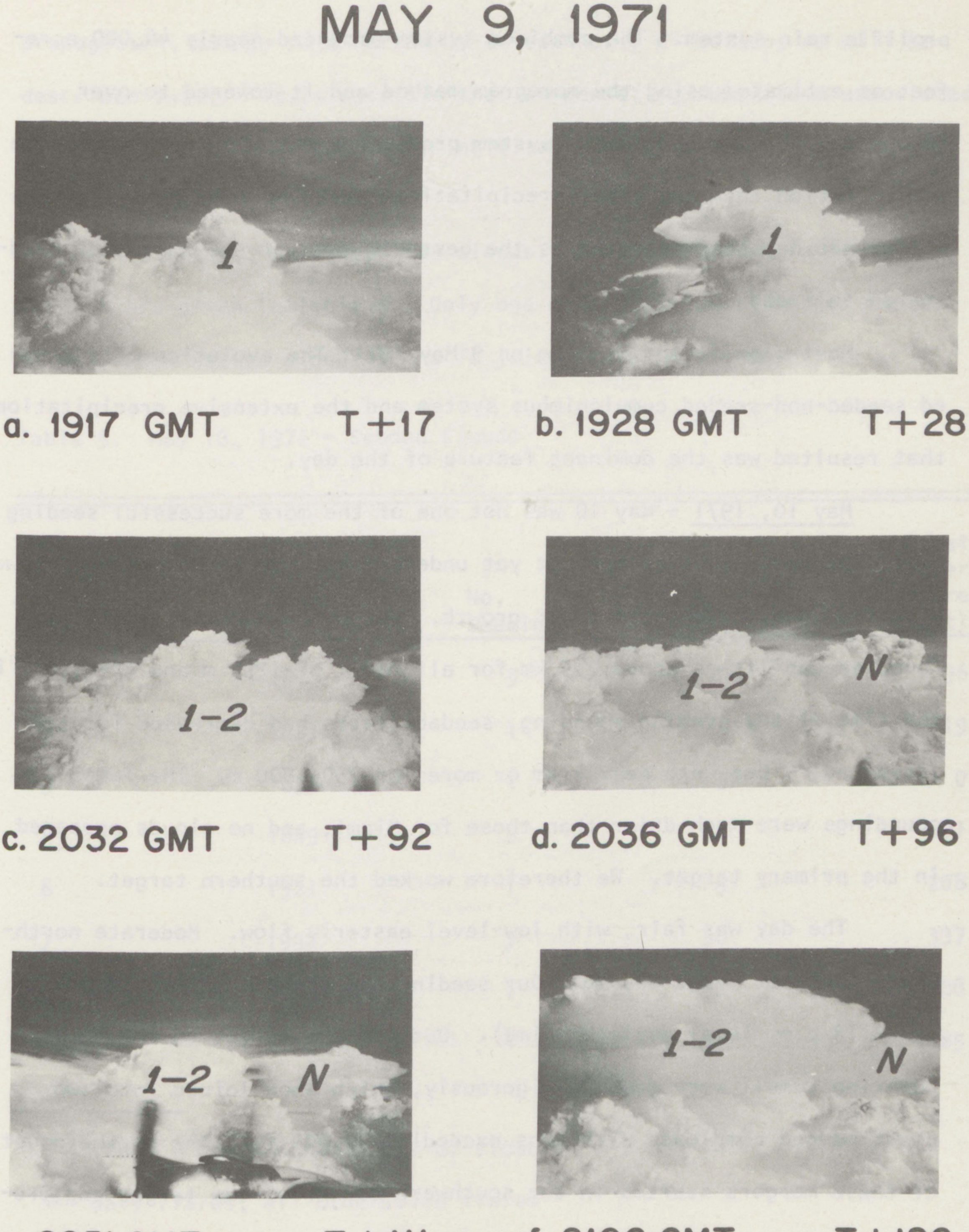


Figure 34. Airborne photographic sequence for 9 May 1971. Rest of caption same as figure 16.

prolific rain system. The combined system produced nearly 40,000 acre-feet as estimated using the nomogram method and it towered to over 48,000 ft. The merged seeded system produced about 9000 acre-feet more precipitation than any other precipitation entity on this day, and this difference has been selected as the best estimate of the effect of seeding on this day.

Most significant finding on 9 May 1971: The evolution of a merged seeded-non-seeded cumulonimbus system and the extensive precipitation that resulted was the dominant feature of the day.

<u>May 10, 1971</u> - May 10 was not one of the more successful seeding days, for reasons which are not yet understood. The morning sounding was a typical one for cut-off tower growth. Using the model with it, we found seedabilities above 2.5 km for all radii of 1250 m and greater. By the time of the evening sounding, seedabilities had decreased for the large radii, but were near 3 km or more for 750-1000 m. The Tampa soundings were much drier than those for Miami, and no clouds appeared in the primary target. We therefore worked the southern target.

The day was fair, with low-level easterly flow. Moderate northwesterlies set in at 500 mb. Our seeding operation began at 1813 GMT (or 2:13 p.m. local daylight time). Outside the target to the south, towering cumuli were growing vigorously, which soon joined into two giant merged complexes with tops exceeding 50,000 ft. The northernmost of these mergers started in the southwest corner of the target and propagated northward during the afternoon. There was no uniform drift or advection of echoes observed. On the other hand, echoes moved rapidly by propagation, mainly in a northerly or southerly direction, as will be described later. It is possible that compensating subsidence associated with the huge natural complexes inhibited the merger and growth of our seeded clouds.

Altogether, we seeded ten clouds, located as shown in fig. 35. Results are given in Table 5. Only one moderately small merger was obtained, when seeded clouds 8 and 10 joined late in the day.

Table 5. May 10, 1971 - Seeded Clouds

Cloud No.	Time First Seeding (GMT)	No. Seedings	No. Flares	Total Water (acre-feet)
1,4*	1813	5	60**	96
2	1831	1	4**	19
3	1835	1	5**	0
5	1849	5	52	101
6	1921	1	9	208
7	1932	3	38	337
9	2104	1	16	108
8-10***	2058	4	51	1685

* Cloud 4 was another tower of cloud 1

** Navy flares; all othersOlin flares

*** Merger system of cloud 8 and 10

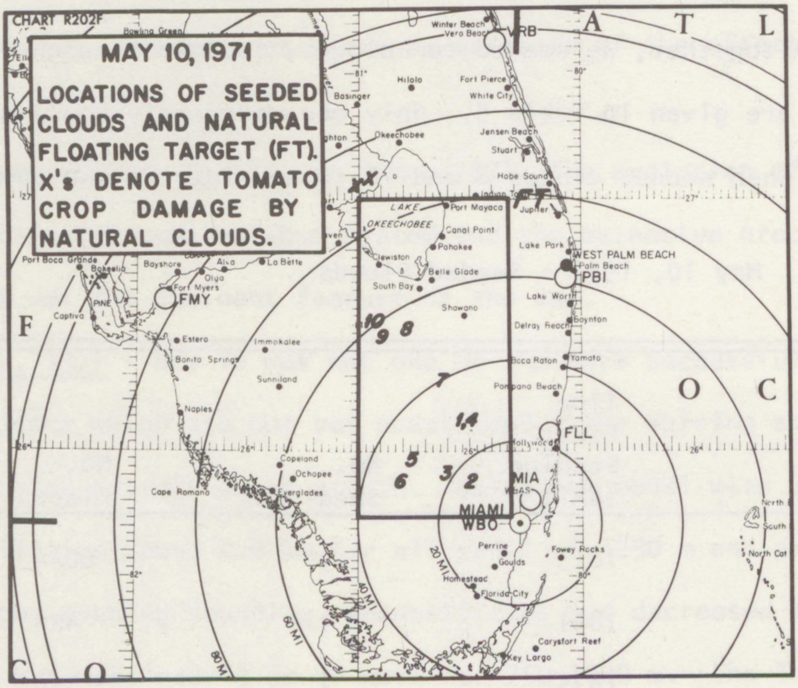
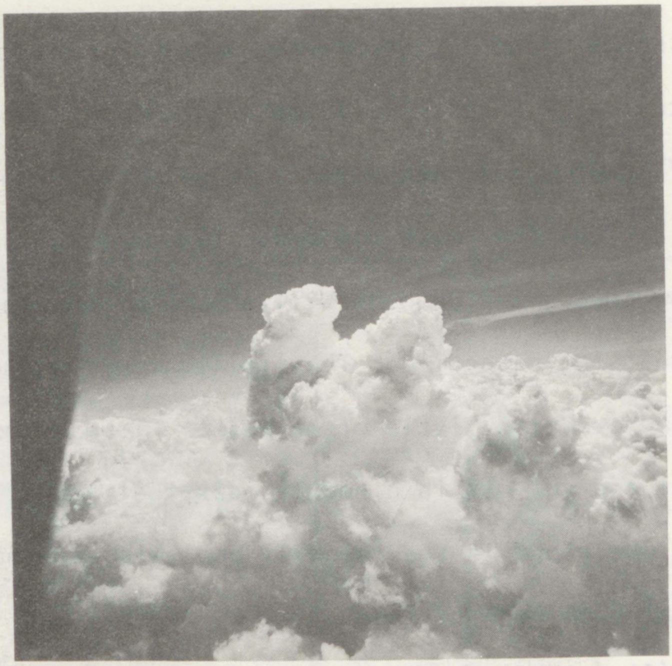


Figure 35. Locations of seeded clouds and natural Floating Target (FT) on 10 May 1971. X's denote tomato crop damage by natural clouds.

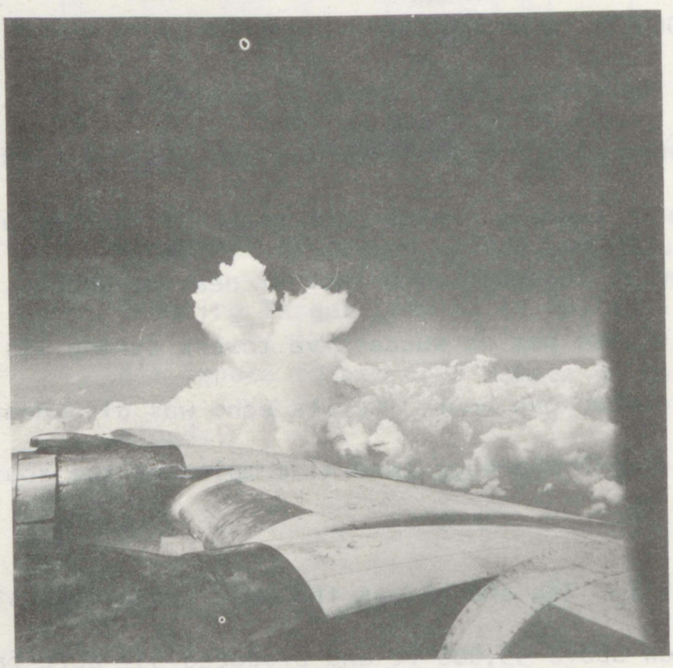
Fig. 36 shows cloud 1, two minutes after the first seeding and again six minutes later. It grew to about 31,000 ft, exhibited the typical cut-off tower regime and eventually produced 96 acre-feet of rain, which is typical for these regimes. Clouds 2 and 3 were failures, with very narrow towers and Johnson-Williams water contents barely above 0.5 gm m^{-3} at the single seeding. They failed to grow much above the seeding level and produced little or no rain. Cloud 4 was a succeeding tower of cloud 1 and cut off in a nearly identical manner. Both towers were treated as one cloud in the rainfall analysis, so that the 96 acre-feet is the total from both of them.

Cloud 5 (fig. 37) put up a succession of about five towers successively on the upshear (northwest) side. Each was seeded, grew to somewhat above 31,000 ft, cut off and dissipated as it moved off downshear. Fig. 37a shows the first tower, about five minutes after seeding; the same tower is seen six minutes later in fig. 37b. Fig. 37c shows cloud 5 after the fourth seeding, which took place 18 minutes after the first. Short-lived towers, together with lack of near neighbors, precluded a merger. Cloud 6 also put up successive towers during its echo lifetime of a little more than one hour. As its echo was disappearing from the scope, it merged with the huge natural complex at the southwest corner of the target.

Cloud 7 (fig. 38a and b) was the most successful single cloud of the day. It grew above 35,000 ft and produced 337 acre-feet of rain in the one hour lifetime of its echo. Its growth regime was somewhere between explosive and cut-off tower. As the photographs show, it lacked



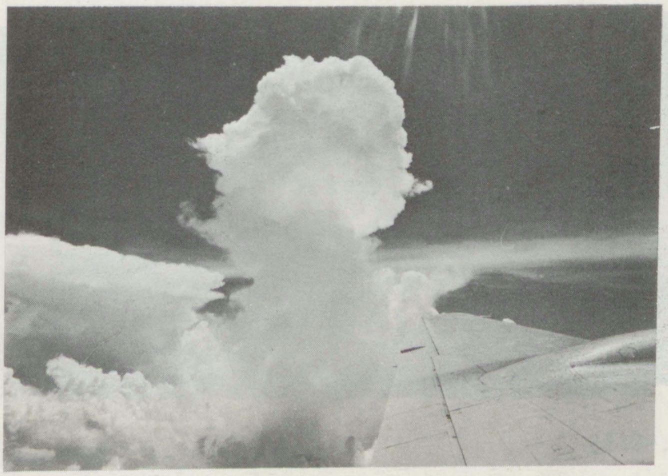
a. 18:15:00



b. 18:21:00

Figure 36. Photographs of cloud 1 on 10 May 1971.
a. - 2 minutes after seeding - 18:15:00
b. - 8 minutes after seeding - 18:21:00

a. 18:54:00

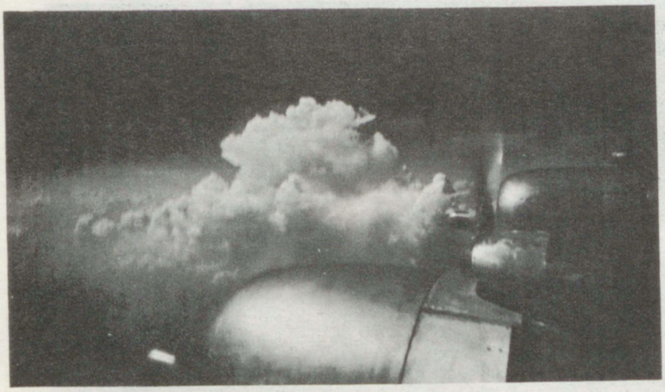


b. 19:00:00

c. 19:09:00

Figure 37. Photographs of cloud 5 on 10 May 1971.
a. - 5 minutes after seeding - 18:54:00
b. - 11 minutes after seeding- 19:00:00
c. - 18 minutes after seeding- 19:09:00

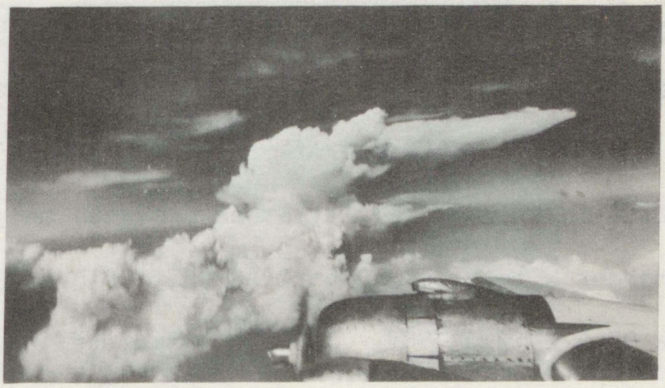
19:34:00



19:45:55

20:08:26

Figure 38a Photographs of cloud 7 on 10 May 1971.



2023 GMT

2025 GMT

2032 GMT

Figure 38 b Photographs of cloud 7 on 10 May 1971.

merger potential, since none of its neighbors reached the seeding level.

Clouds 8, 9 and 10 formed close together, and it was hoped to make all three of them merge. Cloud 8 (fig. 39) was seeded twice by the B-57, at 2058 and 2118 GMT. It grew little and produced only 15.3 acre-feet of rain before merger with cloud 10 at 2143 GMT. Cloud 9 (fig. 39) was seeded by the DC-6 at 2104 GMT. Its echo produced 108 acre-feet of rain and approached within less than a mile (on the southwest side) of cloud 8's echo at 2123 GMT. Instead of merging, however, cloud 9 died and had disappeared from the scope at 2131 GMT.

Cloud 10 (fig. 39) was seeded by the DC-6 at 2127 and 2135 GMT. It grew explosively following seeding, producing 125.6 acre-feet of rain prior to merger. The echo of cloud 10 expanded southeastward, encountering and merger with that of cloud 8 which had been very slowly weakening. The total rainfall from the 8-10 system was 1685 acre-feet; the precipitation history of the merger is shown in fig. 40.

Thus, a total of 2554 acre-feet of rain fell from seeded clouds on May 10. If we assume a seeding factor of 3 by extrapolation from our single cloud experiments, we might then attribute about 1900 acre-feet to the seeding. However, it must be pointed out that nature made four merged complexes on that afternoon in south Florida, each of which precipitated twice or more times as much as the sum of all the seeded clouds.

To illustrate, we selected one of these natural systems as a "Floating Target" and dispatched the B-57 to inspect it. Although it as yet had no echo, it was eligible for seeding at 2010 GMT which was designated as the simulated seeding time. The location of the "Floating Target"

a. 2059 GMT

b. 2110 GMT

c. 2132 GMT

Figure 39. Photographs of clouds 8, 9 and 10 on 10 May 1971.

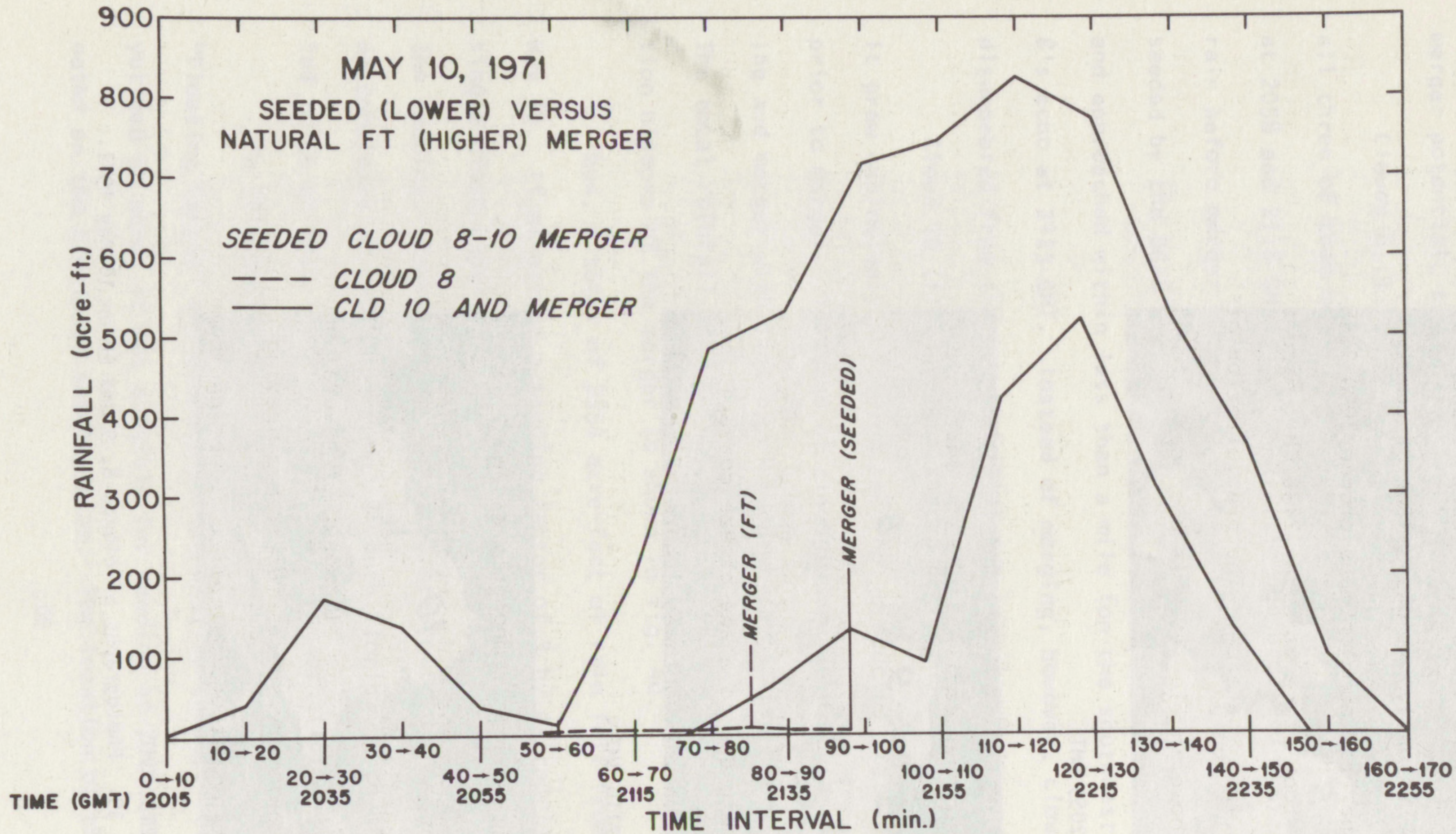


Figure 40. Precipitation histories of the seeded 8-10 merger and the Floating Target merger.

is designated by FT and its early history is shown by the photographs in fig. 41 (arrow). Visually, it was a line of cumuli, some of which merged to make a large natural cumulonimbus around 2030-2055 GMT. On radar, the only echo merger took place at about 2130 GMT, more than an hour after our aircraft had left the area. The precipitation history of the "Floating Target" is shown in fig. 40. It produced a total of 5663 acre-feet of rain, 1085 before echo merger and 4578 after.

The "Floating Target" was the smallest and least rain-productive of the four giant natural mergers of May 10. In addition to the two southern ones mentioned earlier, a most remarkable development occurred long after the end of our seeding operation. A larger natural echo on the west-northwest side of Lake Okeechobee propagated rapidly southeast, while another large natural echo on the south side of the lake propagated northwest, possibly due to a sea breeze convergence. They met at 2330 GMT near Moorehaven, on the southwest shore of the lake, forming a giant merger which produced severe hail and rainfall rates in excess of three inches per hour. At 2345 GMT, this huge merger split in two, with a "right-moving" and "left-moving" component, at least superficially similar to many severe storms in the Midwest. The "right-moving" storm was the most severe. It allegedly did rain and hail damage to tomato crops in the areas marked X in fig. 35 in an amount of several hundred thousand dollars.

Although not very successful from a seeding point of view, May 10 is very interesting meteorologically. It brings home the point that many natural severe weather occurrences in Florida simply cannot be forecast in our present state of knowledge. On the 1200 GMT (0800 local daylight)

a. 20:22:28

b. 20:51:27

Figure 41. Photographs of the "Floating Target" clouds.

Miami sounding the Showalter stability index was +4.6 and the 850-200 mb shear was only 16 kts from 270°. On the 00 GMT May 11 (8 p.m. local daylight, May 10), the stability index was still +3.1. Although the shear had increased to 33 kts (from 312°) it was still modest and well below the 50 kts required for the weakest of our restricting criteria (see Appendix).

Most significant finding on 10 May 1971: Seeded clouds produced little precipitation on this day when compared to unseeded cloud developments. An unseeded cumulonimbus merger showed many of the characteristics often exhibited by severe splitting thunderstorms of the Midwest. This storm did damage to the tomato crops along the west and north shores of Lake Okeechobee.

<u>May 21 and 22, 1971</u> - These days are grouped together for coherence of discussion. A weak, diffuse convergence region that was approaching south Florida on 21 May moved into the Florida Straits by 22 May. This line was clearly evident in the cloud patterns (arrows) in the 1640 GMT ATS-III satellite photograph on 21 May 1971 (fig. 42), but not in the 1915 GMT photograph on 22 May 1971 (fig. 43). Florida was dominated by a strong northwesterly airflow at middle and upper levels that was moving about an anticyclone centered in the Gulf of Mexico. While neither day can in any way be considered disturbed, 21 May was the more disturbed of the two. The Showalter stability was lower, the shear stronger and cloud base lower on 21 May. Maximum seedabilities were 3 to 4 km on both days, suggesting rather good seeding potential.

There were widely scattered showers over the south Florida penin-

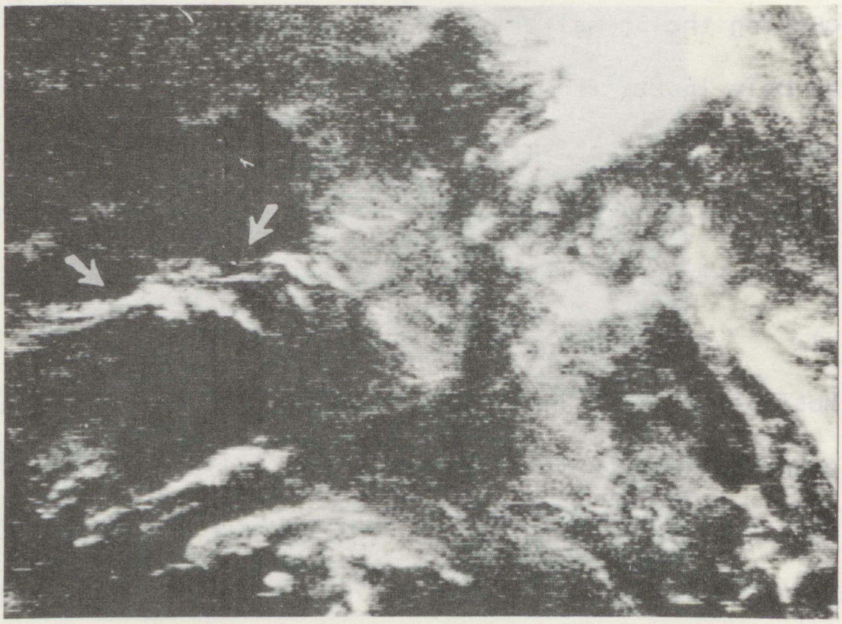


Figure 42. 1640 GMT ATS-III satellite photograph on 21 May 1971.

Figure 43. 1915 GMT ATS-III satellite photograph on 22 May 1971.

sula on 21 May when the single seeder aircraft became airborne for flight operations. Only clouds in the secondary target were worked because those in the primary target were embedded in middle-level stratiform clouds. Seven separate clouds or cloud complexes were seeded with a total of 208 flares on this day. These clouds grew slowly at first, but their growth accelerated as they neared the east coast, suggesting that sea breeze convergence may have played a role in enhancing cloud growth and precipitation. Most of the rain from the seeded system fell in the populated areas (fig. 44) and over the Atlantic. A second rain area, superficially similar to the seeded system, developed along the east coast between Palm Beach and Vero Beach. It, too, moved into the Atlantic.

Partial photographic documentation of the life histories of some of the seeded clouds on 21 May is provided in fig. 45. Cloud 1 is shown in panels a, b and c; in a, less than a minute after its initial seeding; in b, 37 minutes later, after it had attained small cumulonimbus stature; and in c, after it had merged with an unmodified cloud to its west. Cloud 2 is shown in panels b and d; in b, two minutes after seeding, and in d, over one hour after its initial seeding. Cloud 2 never grew explosively after seeding, but rather remained a small shower system. Cloud 6 is shown in panels e and f, slightly before and slightly after its initial seeding. This cloud was rather large at seeding and it grew explosively thereafter.

The upshear or western side of the organized seeded system is shown in panel g. At this time cloud 8 anchored the western edge, 10 minutes after its initial seeding and 152 minutes after the initial seeding of cloud 1. The clouds in the right background are the other seeded

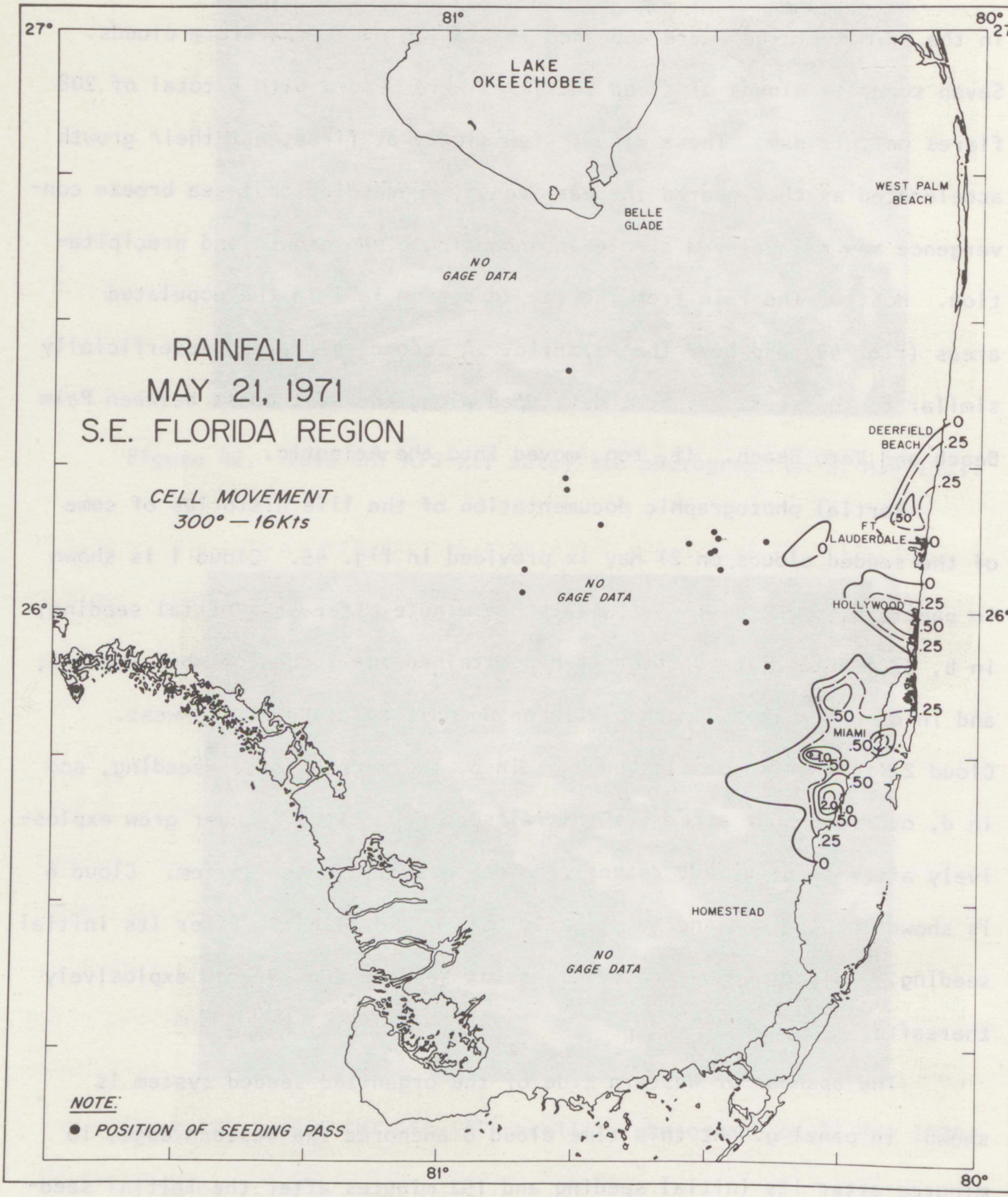


Figure 44. Isohyetal analysis for 21 May 1971. Dots are positions of seeding passes.

MAY 21, 1971

a. 1858 GMT T+3

b. 1904 GMT T_1+9 T_2+2

c. 1934 GMT T+39

d. 2010 GMT T+67

e. 2031 GMT T−1

f. 2034 GMT T+2

g. 2127 GMT T+11

h. 2150 GMT CLD. LINE

Figure 45. Airborne photographic sequence for 21 May 1971. Rest of caption same as figure 16.

clouds of the line. A much better view of the seeded system at a right angle to its northwest-southwest orientation is provided in the last photograph of fig. 46. This system is clearly very organized at this time.

It was not possible to calculate the precipitation histories of every seeded cloud on this day because of their movement into the ground clutter of the UM/10-cm radar. Rather, the total contribution from all the clouds was computed using raingages in the Miami-Ft. Lauderdale area. Fortunately, almost all of the clouds that precipitated in this region had been seeded, so no great errors are introduced by this procedure.

Over 6000 acre-feet of precipitation were produced over land areas by the seeded clouds. Much more precipitation fell over the water areas to the east where it was not needed. Single cloud extrapolation has been selected as the most reasonable estimate of the effect of seeding on this day, giving nearly 5000 acre-feet as the result of seeding. An estimate by comparison would have been more desirable, but there were no other comparison systems within either range of the UM/10-cm radar or in a dense raingage network.

Shower activity continued in the Bahamas most of the night, decreasing around sunrise on 22 May as new showers formed in the Straits of Florida. Shower activity was slower to develop over the peninsula on 22 May than on 21 May, although there was some isolated shower activity here when the DC-6 aircraft took off for seeding operations. As on 21 May, the more suitable clouds formed over the secondary target area on 22 May. Eight clouds or cloud complexes were seeded on this day. The DC-6 aircraft was used to seed all the clouds except cloud complex 5, which was seeded repetitively by the B-57. Cloud growth and precipitation production was slow at first, becoming explosive later in the day. Precipitation from the seeded system continued over the southwest sections of Miami well into the night. The evaluation of this system is treated in some detail here.

Clouds 1 and 2 are shown in pictures a through d of fig. 46. These clouds were isolated initially, but later grouped together into one mass. Their rain production was small, amounting to a total less than 100 acre-feet as determined using UM/10-cm radar observations. Clouds 3 and 4 were even less prolific. Clouds 5 through 8 were quite another matter.

The B-57 joined the DC-6 for seeding operations while the DC-6 was making its last seeding runs on complex 1-2. Both aircraft then proceeded southbound in search of favorable clouds. Cloud 5 was selected at a distance and the B-57 was sent ahead to do the seeding. Once again, the greater speed of this aircraft proved invaluable because it enabled the pilot of the B-57 to seed cloud 5 during its active growth phase. A photograph of this cloud at the time of seeding is shown in picture e of fig. 46. The lone cumulonimbus in the distant background is an unseeded cloud over the extreme south Florida peninsula. While the B-57 made repeated seeding passes through cloud 5, the DC-6 aircraft seeded cloud 6 to the west. Both clouds are shown in picture f of fig. 46. Cloud 5 (left) had already become a cumulonimbus and cloud 6 was well on its way. Five minutes later, cloud 6 had become a cumulonimbus and was still

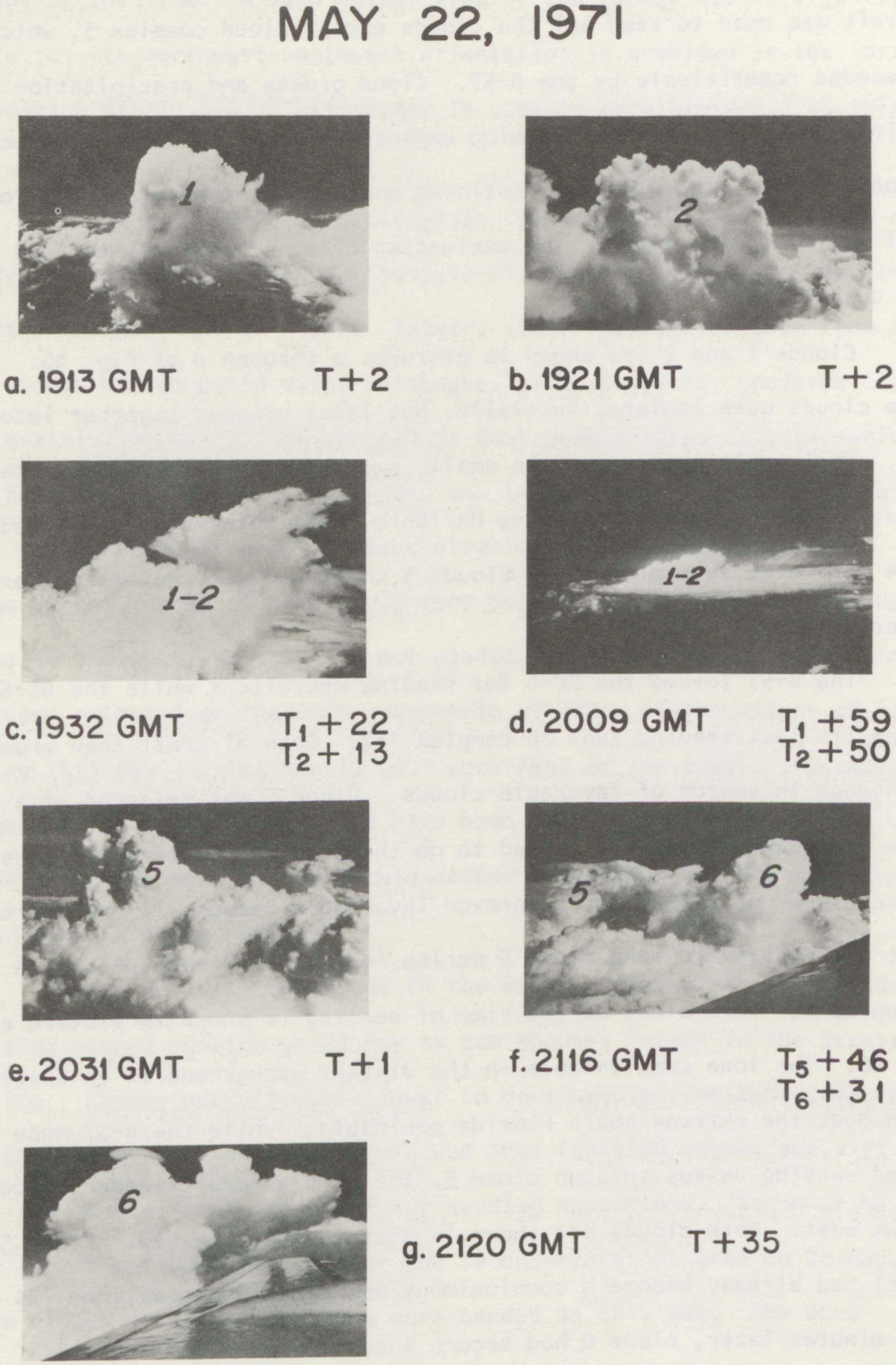


Figure 46. Airborne photographic sequence for 22 May 1971. Rest of caption same as figure 16.

growing on its upshear side as evidence by the pileus cap over the tower (panel g of fig. 46). Cloud 7 was seeded by the DC-6 on the west side of cloud 6 and by 2130 GMT a line of cumulonimbus had formed, consisting of clouds 5, 6 and 7 (picture a of fig. 47). Over an hour later this line was visually continuous and more mature (fig. 47b). Subsequently, this line fractured with a portion of the split moving southeastward into the western sections of Miami. It is believed that this transport of intense shower activity with its associated dome of cool, downdraft air into a region where there was a strong onshore sea breeze resulted in a nearly self-perpetuating shower mechanism. Heavy rains in excess of five inches fell in the convergence region.

The evolution of the seeded precipitation system on the UM/10-cm radar scope is depicted schematically in figs. 48 and 49. Only the first and third contours are shown in this depiction, the latter corresponding to a rainfall rate of over 0.50 inches per hour. Cloud 5 is shown in the first panel at the time of its initial seeding. Its development can be followed in subsequent panels. Cloud 6 appeared at 2049 GMT. It was seeded at 2056 GMT and had intensified considerably by 2103 GMT. Unmodified shower activity continued 20-30 n mi southwest of the radar and was building northward. By 2115 GMT clouds 5 and 6 formed a broken line, while the natural cumulonimbus about 30 n mi west-southwest of the radar had reached its maximum intensity. By 2134 seeded clouds 7 and 8 had made their appearance on the radar scope as cloud 5 propagated southeastward.

Some interesting developments were taking place by 2150 GMT. Clouds

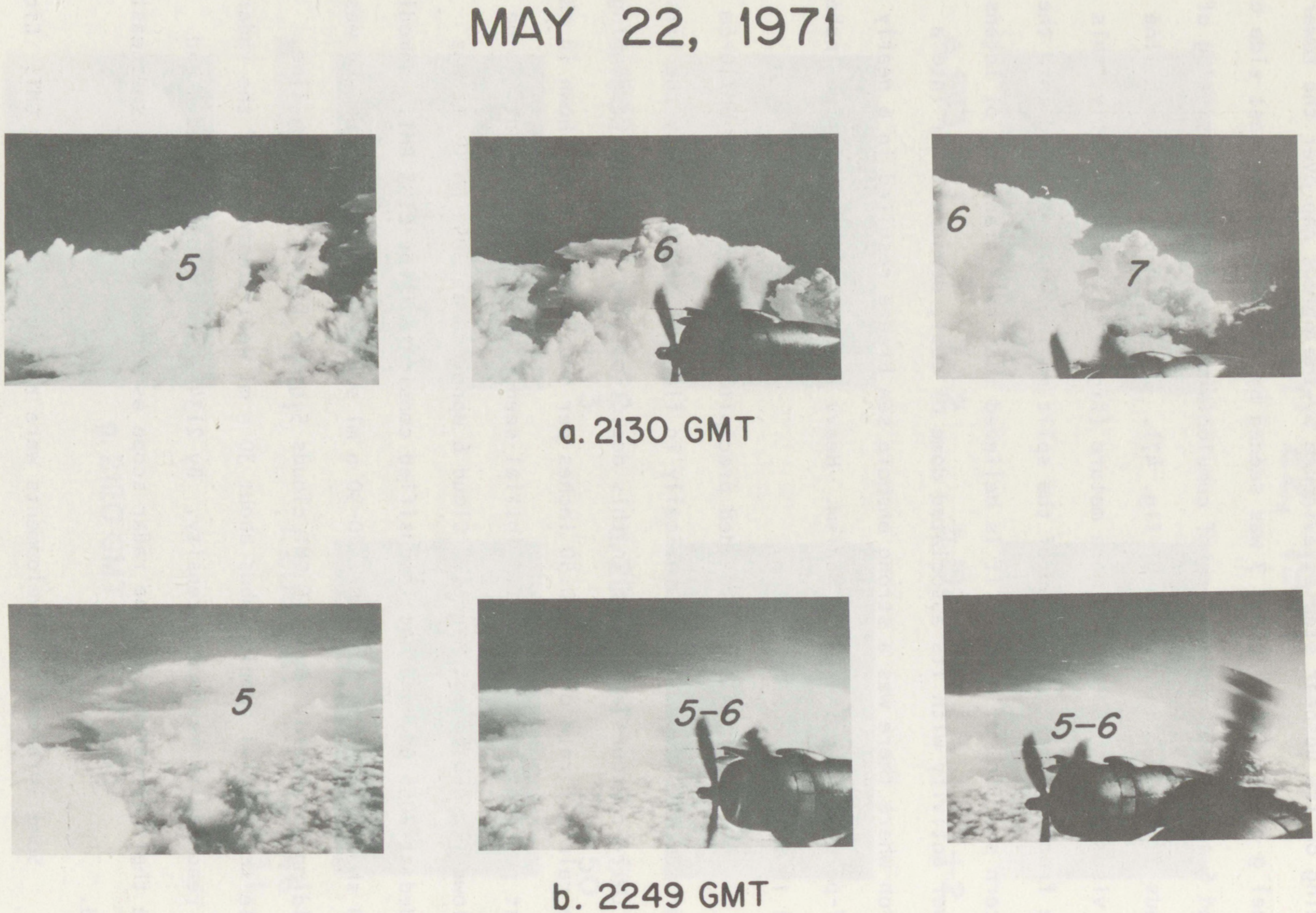


Figure 47. Airborne photographic sequence for 22 May 1971. Rest of caption same as figure 16.

MAY 22, 1971 — UM/10cm RADAR

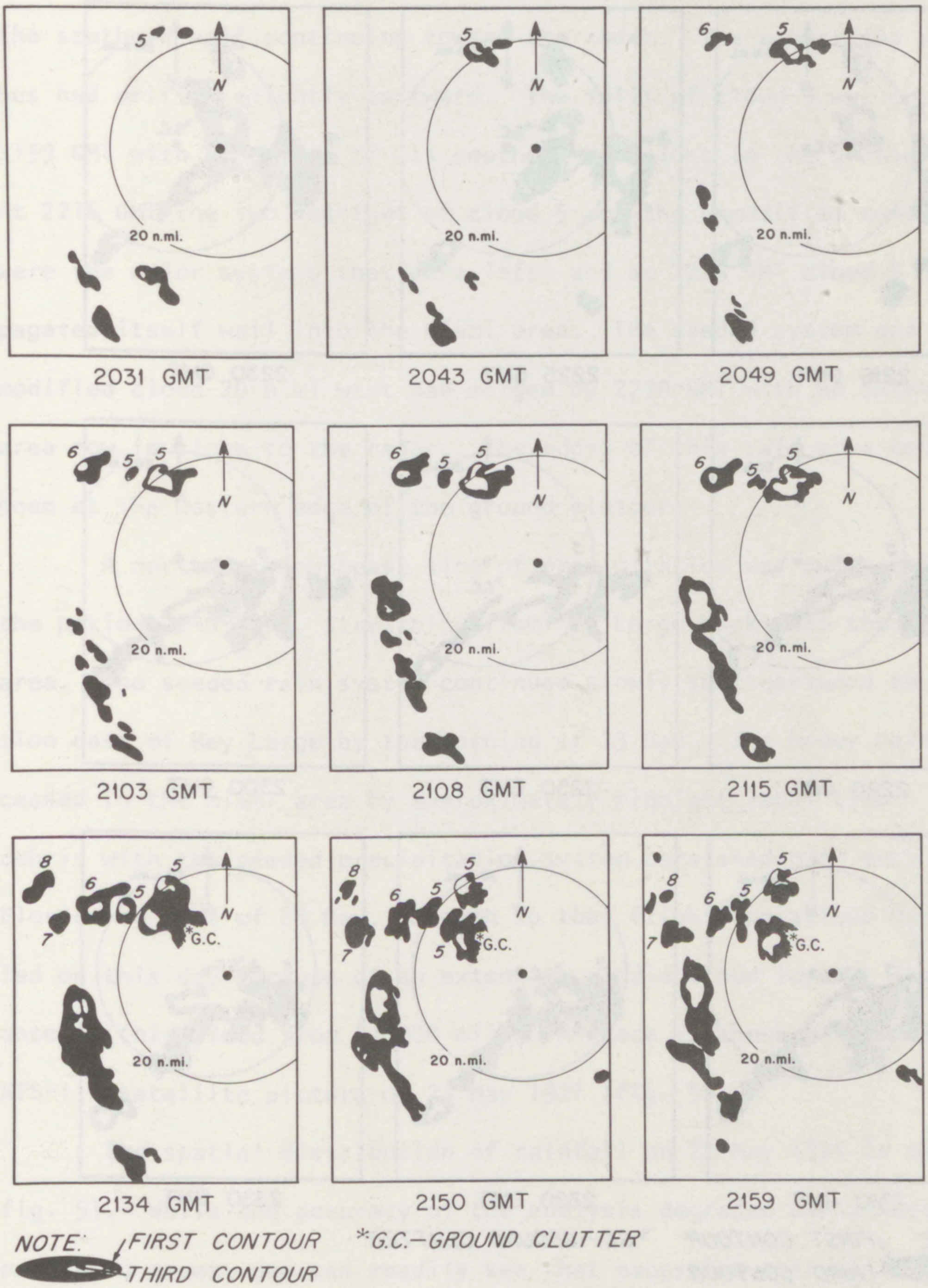


Figure 48. Evolution of the seeded precipitation system on the UM/10-cm radar scope. Only the first and third contours are shown in this depiction; the former corresponds to the minimum discernible signal and the latter to a rainfall rate of 0.50 inches per hour.

MAY 22, 1971 — UM/10cm RADAR

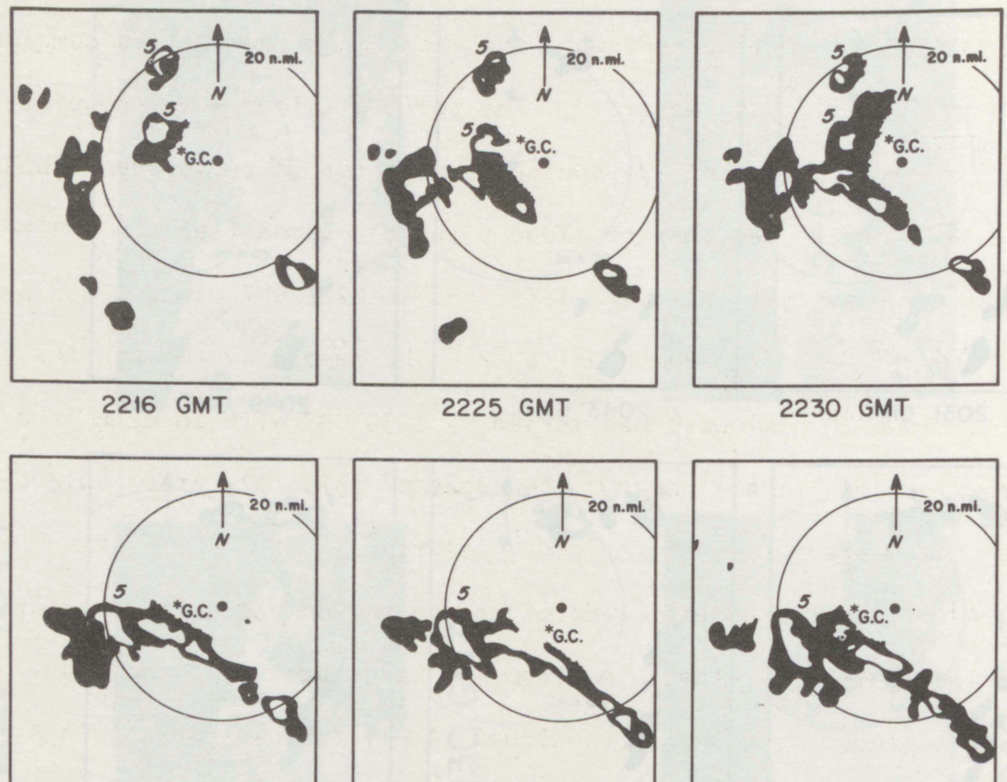


Figure 49. Evolution of the seeded precipitation system on the UM/10-cm radar scope. Only the first and third contours are shown in this depiction; the former corresponds to the minimum discernible signal and the latter to a rainfall rate of 0.50 inches per hour.

5, 6, 7 and 8 formed a broken east-west line, but 5 was splitting with the southern half continuing toward the radar. The unmodified cumulonimbus had drifted slightly eastward. The split of cloud 5 was complete by 2159 GMT with a portion of its southern half lost in the ground clutter. At 2216 GMT the two sections of cloud 5 and the unmodified cumulonimbus were the major systems that were left, and at 2225 GMT cloud 5 had propagated itself well into the Miami area. The seeded system and the unmodified cloud 20 n mi west had merged by 2230 GMT with an extensive rain area now in close to the radar. The edges of this rain area could be seen at the western edge of the ground clutter.

A northwest-southeast line of precipitation was quite evident in the period 2240-2310, stretching from Key Largo back into the Miami area. The seeded rain system continued slowly southeastward to a position east of Key Largo by the morning of 23 May. The heavy rain had ceased in the Miami area by approximately midnight local time. The cloud debris with the seeded precipitation system persisted over much of south Florida on most of 23 May, so much so that flight operations were cancelled on this day because of an extensive middle cloud layer. The appearance of this cloud from 22,000 miles in space is shown on the 1526 GMT ATS-III satellite picture on 23 May 1971 (fig. 50).

The spatial distribution of rainfall on 22 May 1971 is shown in fig. 51. While the accuracy of the analysis degrades badly west of the populated areas, one can readily see that excessive rain fell three to five miles southwest of the radar in the area traversed by the intense line of echoes. Rain gradients are impressive over many areas of the

Figure 50. 1526 GMT ATS-III satellite photograph for 23 May 1971.

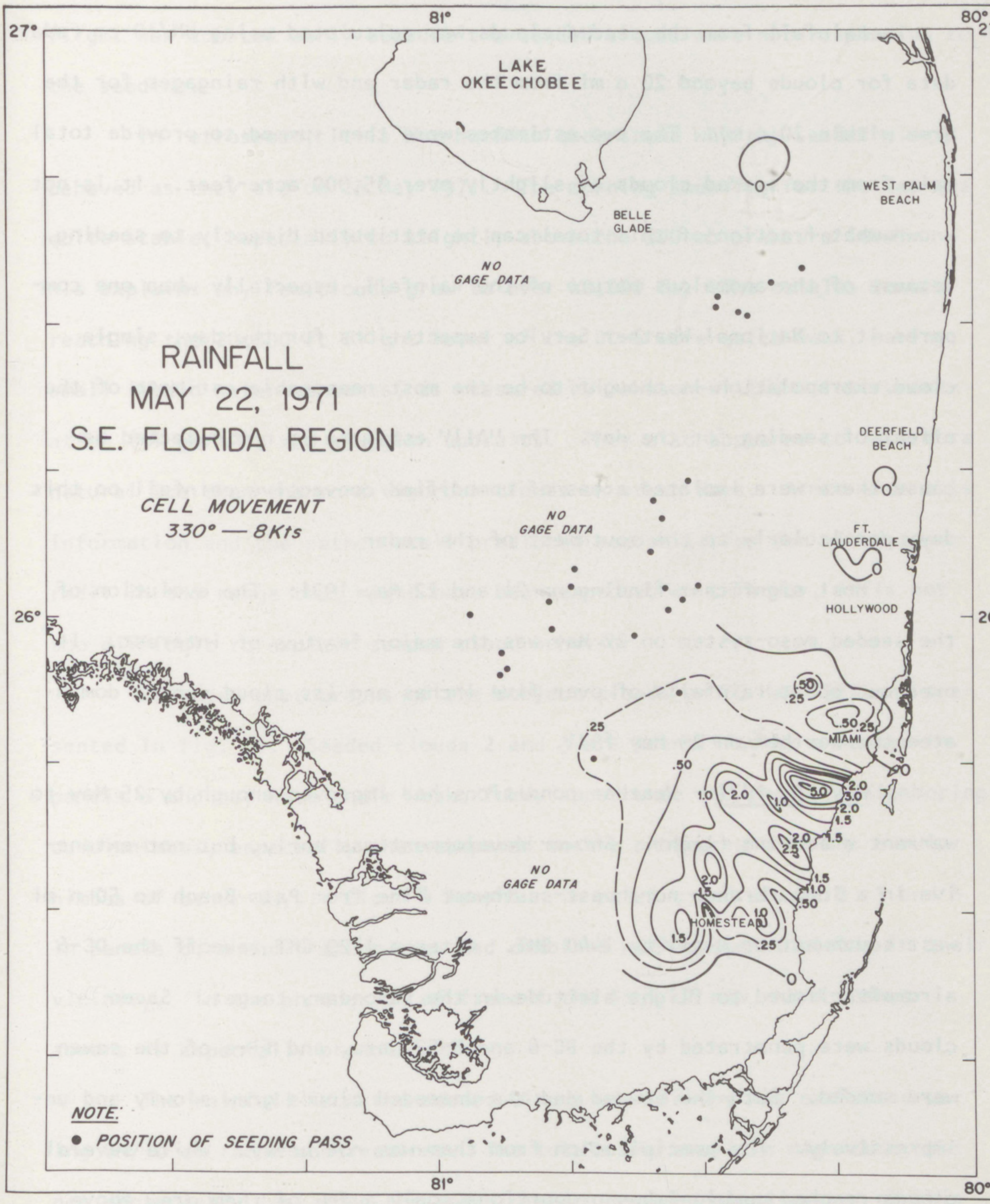


Figure 51. Isohyetal analysis for 22 May 1971. Dots are positions for seeding passes.

analysis, especially northeast of the five inch maximum.

Rainfall from the seeded clouds was calculated using UM/10-cm radar data for clouds beyond 20 n mi from the radar and with raingages for the area within 20 n mi. The two estimates were then summed to provide total rain from the seeded clouds of slightly over 35,000 acre-feet. It is not known what fraction of this total can be attributed directly to seeding. Because of the anomalous nature of the rainfall, especially when one compares it to National Weather Service expectations for the day, single cloud extrapolation is thought to be the most reasonable estimate of the effect of seeding for the day. The "All" estimate is not selected because there were isolated areas of unmodified convective rainfall on this day, particularly to the southwest of the radar.

Most signficant finding on 21 and 22 May 1971: The evolution of the seeded meso-system on 22 May was the major feature of interest. It produced point rainfalls of over five inches and its cloud debris dominated the weather on 23 May 1971.

May 25, 1971 - Weather conditions had improved enough by 25 May to warrant a seeding flight. Shower development was early, but not extensive in a long, broken northeast-southwest line from Palm Beach to 50 n mi west-southwest of Miami by 1440 GMT. After a 1729 GMT takeoff the DC-6 aircraft climbed to flight altitude in the secondary target. Seven clouds were penetrated by the DC-6 and B-57 here, and five of the seven were seeded. Both the seeded and the unseeded clouds grew slowly and unimpressively. The precipitation from them was not heavy. While several clouds reached cumulonimbus proportions, only a few of them grew above

40,000 ft. Shower movement was erratic throughout the day. The seeding flight was aborted early because the seeded clouds were not responding to the seeding.

In retrospect, it is not hard to understand why the seeded clouds behaved as they did on 25 May 1971. The morning sounding for the day was quite stable, especially so slightly above the 300 mb pressure level. This explains why few clouds grew to over 40,000 ft. The cumulus towers reaching the 20,000 ft flight level of the DC-6 were quite weak, having small liquid water contents, as measured by Johnson-Williams instrumentation (<1 gm/m^3), and sluggish updrafts. They also appeared to have more natural ice than the more vigorous clouds on other days. Armed with this information and the rather small predicted seedabilities for cloud tower radii in the range that might have been expected on this day, it is not too difficult to explain seeded cloud behavior.

Selected photographs of the subject clouds on 25 May 1971 are presented in fig. 52. Seeded clouds 2 and 3 are identified by a number in panels a and b. Note their weak, fuzzy appearance and that of neighboring cumulonimbus, especially when compared to the photographs of the cumulonimbus of other days. Cloud 4 is shown in panel c and clouds 2, 3 and 4 in panels d, e and f after they had combined with unseeded clouds in their vicinity. In the photograph of frame f the lack of new, hard upshear towers is especially pronounced.

The rainfall from the seeded clouds on this day was evaluated using UM/10-cm radar observations. The totals are small in magnitude, but not appreciably less than the most intense unseeded cloud system on this

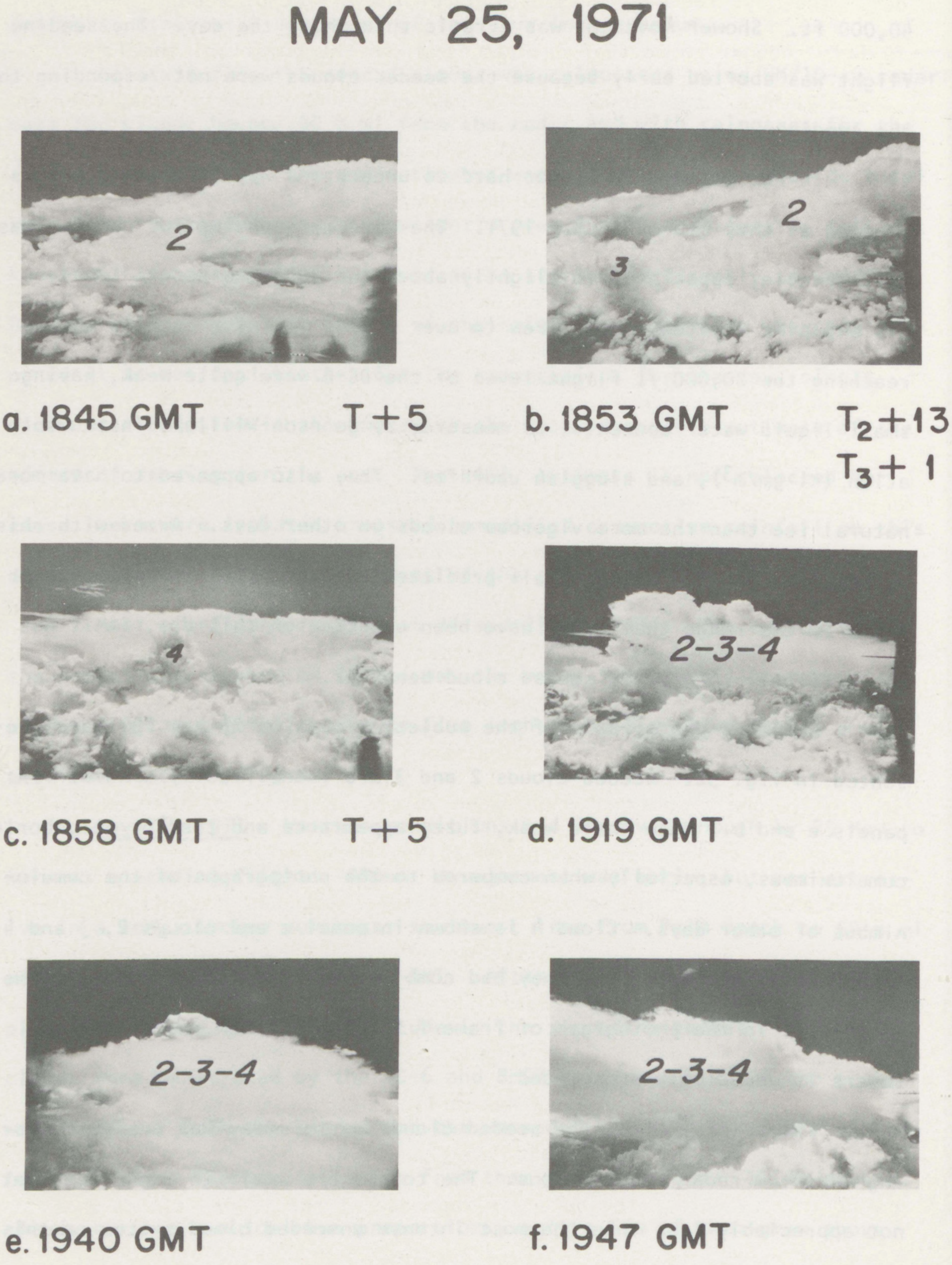


Figure 52. Airborne photographic sequence for 25 May 1971. Rest of caption same as figure 16.

day. The most reasonable assessment of the effect of seeding on 25 April 1971 is thought to be that derived from the EML numerical model.

Although the clouds of this day were comparatively weak, over an inch of rain was measured near the southeast shore of Lake Okeechobee, and rain was also reported near Homestead (fig. 53). Rain also fell in the southern interior of Florida, but it was not sampled by raingages.

Most significant finding on 25 May 1971: Seeding apparently had little effect on the clouds of this day. The troposphere was stable and cloud developments were weak and unsuitable for seeding.

May 26, 1971 - May 26, 1971 was the last day of seeding operations during the April-May drought mitigation program. The atmosphere was still rather stable and dry on this day as evidenced by the zero predicted seedabilities for the 1200 GMT and 0000 GMT (27 May) Miami soundings for the 915m cloud base and cloud radii in the interval $750m \leq R \leq 1500m$. Except for the largest and rarely found radii (>2000m) no cloud was predicted to grow much above the -8C level of assumed glaciation. Despite these predictions, some clouds did grow above this level, some of them explosively.

First shower development on 26 May was over the south Florida peninsula 40 miles southwest of Miami. After a 1800 GMT takeoff, flight operations were confined to the secondary target because of extensive cirrus cloudiness in the primary target. Dr. Robert Sax directed most of the flight on 26 May and did most of the seeding following essentially the same procedures that were used on earlier flights. He did, however, use 10 to 20 percent more silver iodide flares per cloud pass than were used on earlier flights. The apparent response of the seeded clouds was

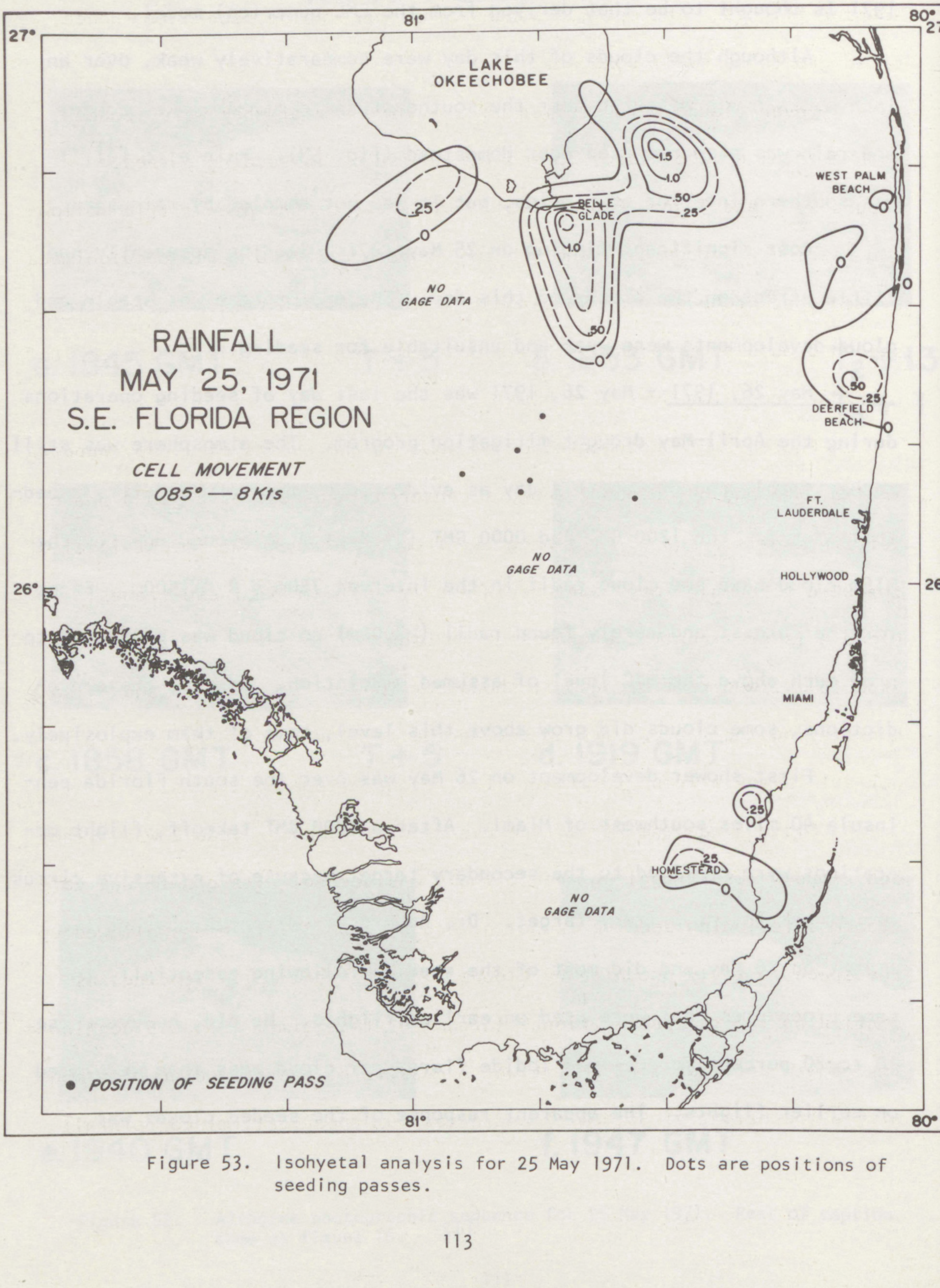


Figure 53. Isohyetal analysis for 25 May 1971. Dots are positions of seeding passes.

dramatic in several instances, but no more so than on some of the earlier seeding flights. The optimum amount of silver iodide needed to induce cloud growth is still unknown.

Seven clouds were studied on this day; six of them were seeded with a total of 208 flares during the course of 16 seeding passes. Clouds 2, 4 and 5 grew impressively, while the others grew little following seeding. Clouds 2, 4 and 5 grew and merged into a large cumulonimbus system that produced over 90 percent of the measured precipitation from seeded clouds on this day. This cloud complex was visible on the UM/10-cm radar scope for over five hours.

Photographic documentation of some of the events of 26 May appears in fig. 54a and b. Cloud 2 appears centered in panels a, b and d and on the left in panels c and e. Its progress from a cloud at the flight level of the DC-6 to cumulonimbus stature is easily followed in these frames. Cloud 4 is prominent as a congestus in panels c, e and f. Frame f is especially important because it shows portions of clouds 2, 4 and 5, demonstrating their proximity to one another. Cloud proximity is most important in any attempt to promote the merger of seeded clouds.

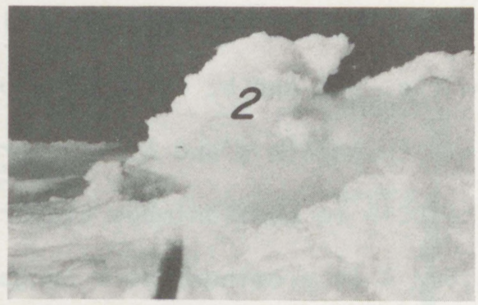
Cloud 5 was the key to the events of the day. Cloud 2 was dying and cloud 4 was struggling when cloud 5 was seeded. Its growth was very vigorous following seeding (panel g) and by 2100 GMT it had swallowed up the space formerly occupied by clouds 2 and 4 (panel h). Seeding was continuing in its upshear flanks (arrow) at this time. Cloud 5 continued its growth until at 2142 GMT it was a massive pileus-draped cumulonimbus with a top height of 50,000 ft and a maximum radar-determined rainfall

MAY 26, 1971

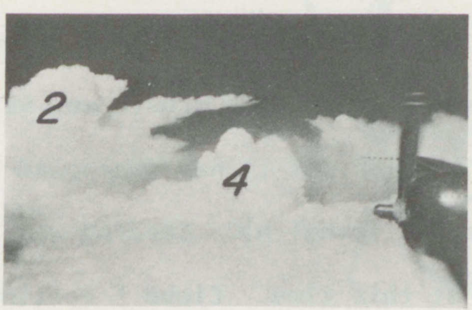
a. 1913 GMT $T+2$

b. 1916 GMT $T+5$

c. 2004 GMT T_2+53
T_4+1



d. 2014 GMT $T+63$

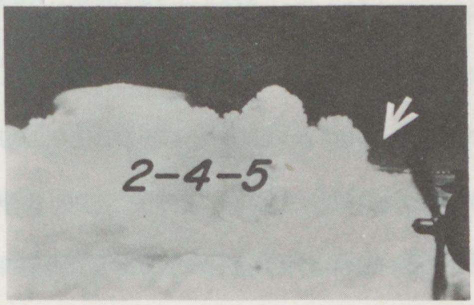


e. 2015 GMT $T+12$

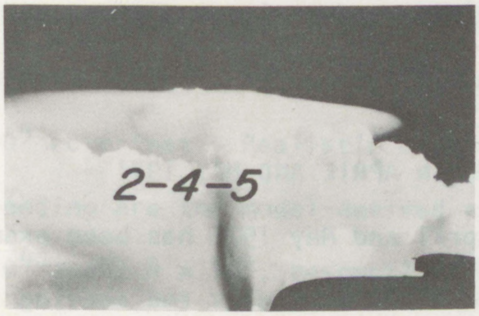
f. 2016 GMT T_4+13
T_5+4

Figure 54a. Airborne photographic documentation for 26 May 1971. Rest of caption same as figure 16.

MAY 26, 1971



g. 2032 GMT T+20 h. 2101 GMT



i. 2143 GMT

Figure 54b. Airborne photographic documentation for 26 May 1971.
Rest of caption same as figure 16.

rate of 3.00 inches per hour (panel i).

The seeded clouds of 26 May produced nearly 7000 acre-feet of precipitation as determined by UM/10-cm radar observations. This figure may be too low because a portion of the main contributor, cloud 5, was in the blind cone of this radar during a part of its five hour lifetime. Because there was a good comparison cloud on this day, the comparison difference (3853 acre-feet) has been selected as the most likely effect of seeding on this day.

Most significant finding on 26 May 1971: Seeding by another individual on this day was apparently as successful as those that preceded it. This suggests that trained individuals can learn dynamic seeding procedure with little difficulty.

7. THE OVERALL EFFECT OF SEEDING IN APRIL AND MAY 1971

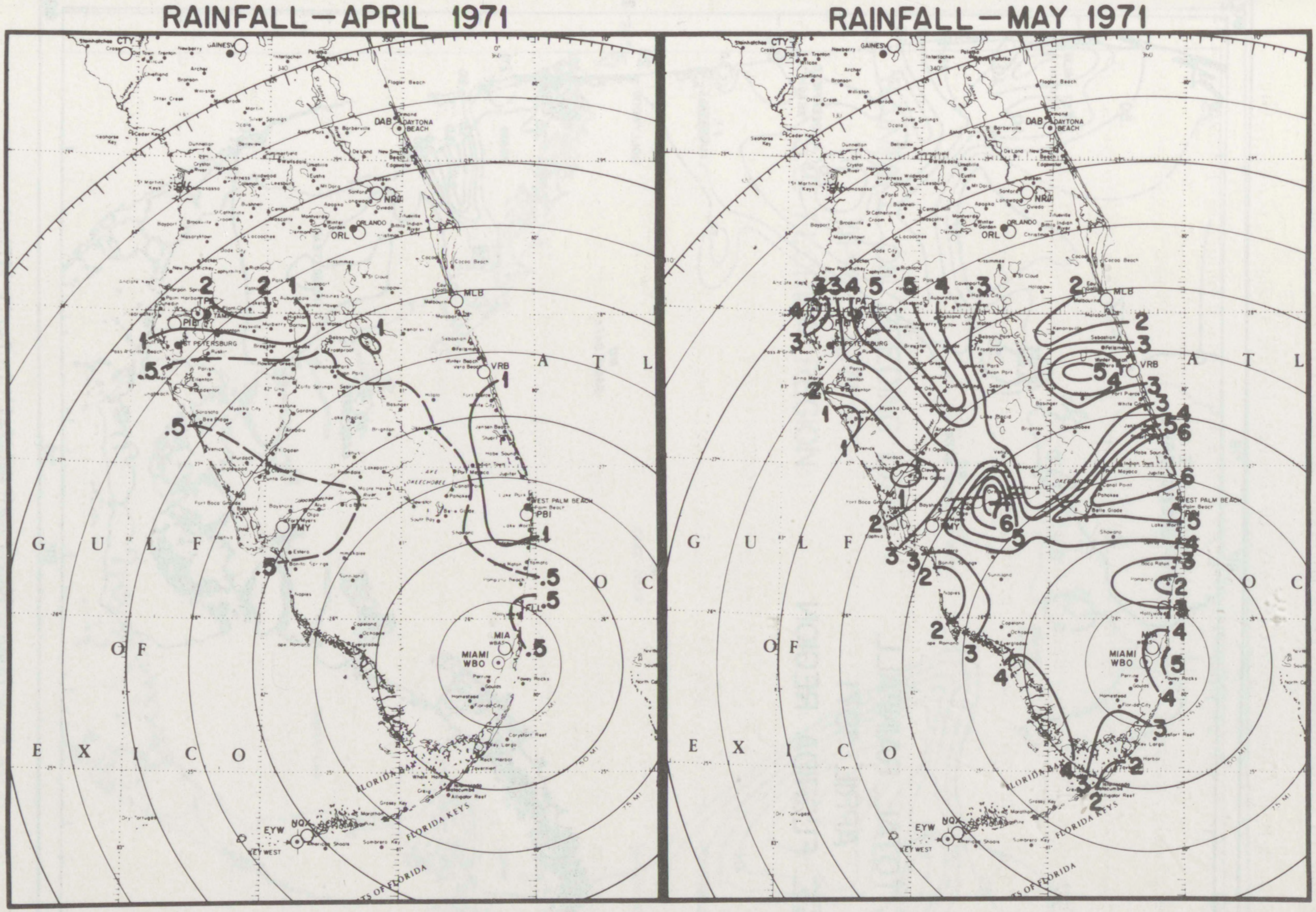
Each day of seeding operation in April and May 1971 has been examined in some detail in the previous section. On some days the seeding was apparently spectacularly successful; on others it appeared to have no effect at all. These daily calculations are synthesized and an assessment of the overall effect of seeding is made in this section.

Seeding had little, if any, effect on the precipitation in the primary target simply because no seeding was done there with the exception of 24 April 1971. It is not known whether this target would have been just as unsuitable in the April-May periods of other years. While it is felt that the unsuitability of target P was peculiar to April and May 1971, it does demonstrate the danger of designating a single target for a rain augmentation program. Without the secondary target, little seeding would have been done in April and May 1971. Further, the non-uniformity of suitable convection in targets P and S emphasizes the impracticability of the cross-over design for randomized multiple cloud seeding in Florida.

Several estimates of the overall effect of seeding in April and May 1971 are tabulated in Table 6. While magnitudes of these estimates are undoubtedly in error, they represent the best that could be done with the observations at hand. Accuracy is certainly well within a factor of two. Besides the estimate termed "most reasonable" by the authors, there are estimates for almost any other persuasion. While the "0" and All estmiates do provide minimum and maximum limits of the effect of seeding, they are considered unrealistic in all cases. Thus, the maximum amount of precipitation that could have been produced by the seeding is 1.8×10^5 acre-feet. Realistic maximum and minimum estimates of the effect of seeding are the model-derived and single cloud extrapolations of 2.5×10^4 and 1.4×10^5, respectively. The comparison estimate is unrealistic because it is incomplete due to the inability to form comparisons on all days.

The "most reasonable" estimate of approximately 10^5 acre-feet was obtained by summing the estimate thought most reasonable for each day of seeding operation (the asterisked figure). As we have seen, on some days it might have been the comparison estimate; on others it might have been single cloud extrapolation. While the 10^5 acre-foot estimate represents a large amount of water that easily justifies the cost of the program, (discussed below), it falls far short of the water that was needed by nearly an order of magnitude, suggesting that "dynamic seeding" or any other seeding technique, for that matter, will not be effective in breaking in a drought. When compared to the rainfall for a "normal" April and May (when approximately 10 inches falls south of 27°N), the "most reasonable" and All estimates represent only two and three percent, respectively, of the 6.4×10^6 acre-feet two month normal for this region. For 1971, when less than half normal rain fell over this area, (figs. 55a and 55b) these figures become five to seven percent. The comparison for the region south of 27°N is probably not a fair one because a large fraction of this area was off-limits to the seeder aircraft. Although seeding apparently increased rainfall by less than ten percent for this region, the localized increases were much greater. This statement is supported by the rain analyses for the Florida east coast region for April and May that were made possible in large part by the observations of the C&SFFCD and the private sector. These analyses appear in figs. 56, 57 and 58. In panel a of each figure is the total rainfall for the designated period, in b is the rainfall on days of seeding in this period, and in c is the ratio of total rainfall on days of seeding to total rainfall in the period. The dots are all the seeding passes in the designated period. It would have been better to plot the surface rainfall from seeded clouds in b, but it was not possible to segregate seeded rainfall from non-seeded rainfall on days of seeding. The reader should keep this reservation in mind in interpreting these figures.

The interpretation for the April period is a relatively simple one. There was only one day of seeding (26 April) over this area for the month, and most of the April rainfall fell on this day as can be seen in the ratio map. Thus, only one day of seeding operation apparently had a



Figures 55a. and 55b. Isohyetal analyses for Florida for April and May 1971.

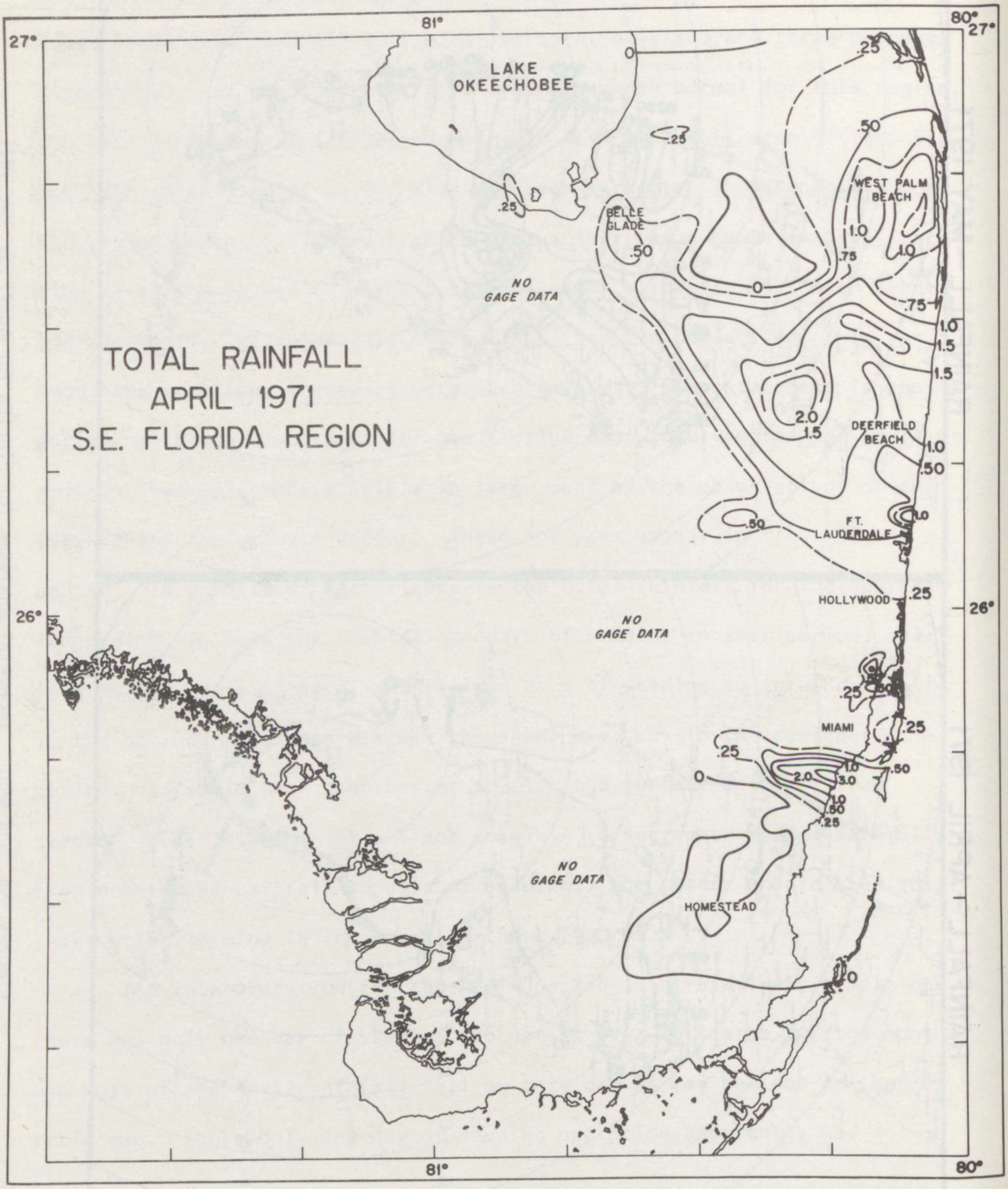


Figure 56a. Total rainfall in April 1971.

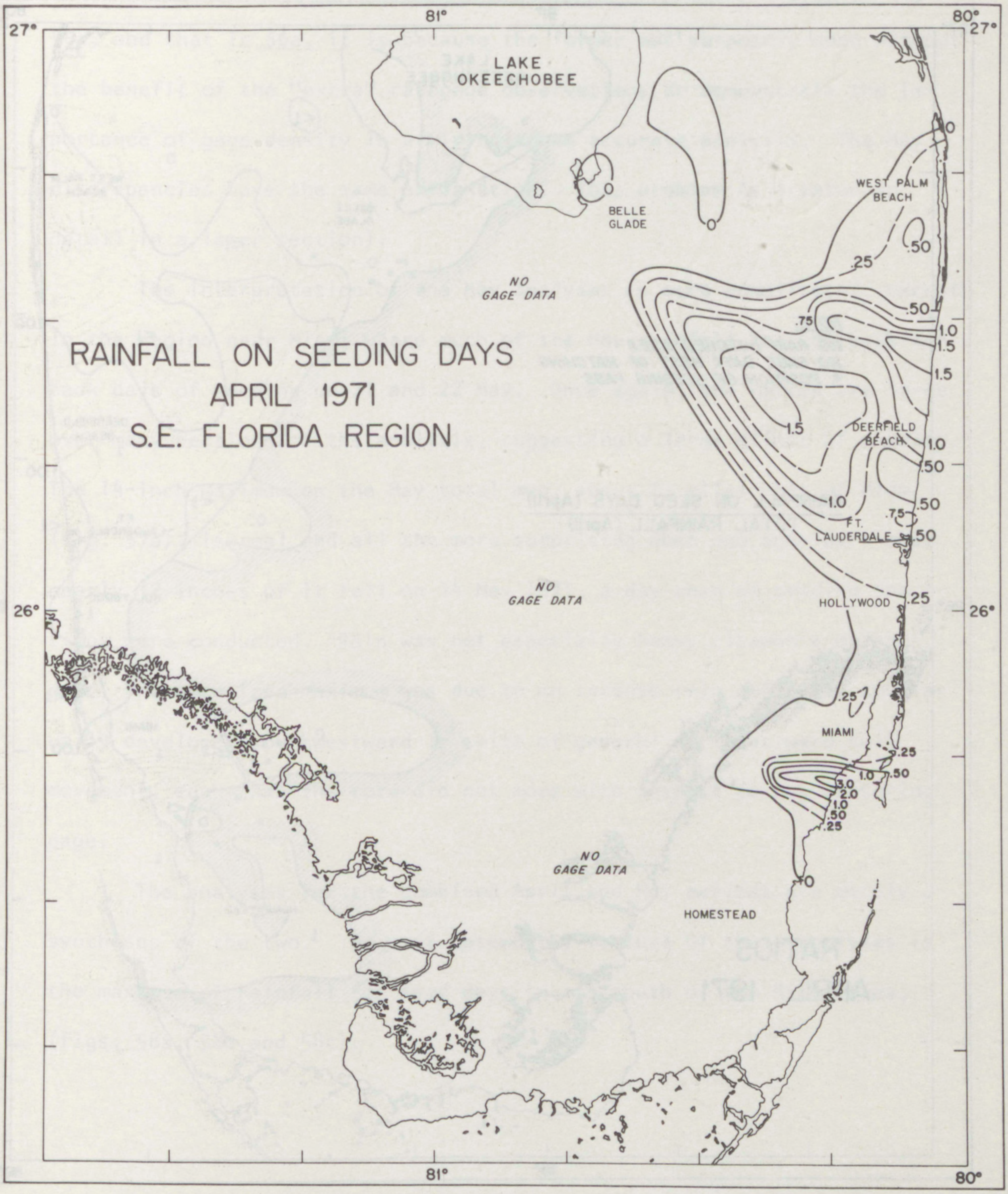


Figure 56b. Total rainfall on days of seeding in April 1971.

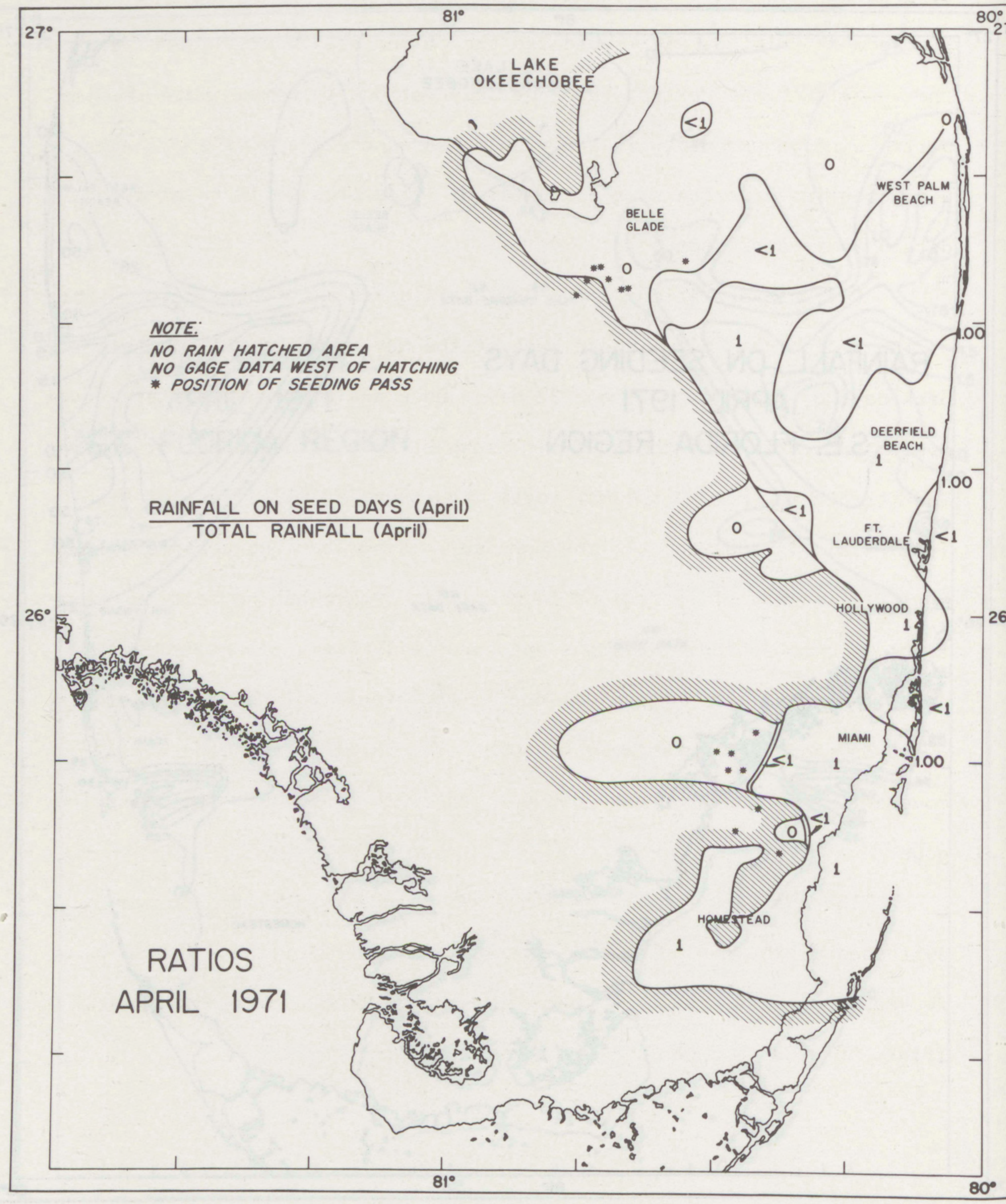


Figure 56c. Ratio of b to a (b/a). Dots are positions of all seeding passes in April 1971

profound effect on the April rainfall. (If the reader wonders about the discrepancy between the rain analysis for the east coast region of fig. 55a, and that in 56a, it is because the former was purposely done without the benefit of the "extra" raingage observations to demonstrate the importance of gage density in arriving at an accurate analysis. The May discrepancies have the same explanation. This problem is treated in detail in a later section).

The interpretation of the May analyses is more complicated, except in the region near Miami where much of the May rainfall fell on back-to-back days of seeding on 21 and 22 May. Once again, the ratios are large over many sections of the analysis, suggesting a large effect of seeding. The 14-inch maximum on the May total map, about 23 miles west of Miami (fig. 57a), is real and all the more surprising when one considers that nearly 12 inches of it fell on 14 May 1971, a day when no seeding operations were conducted. Rain was not especially heavy elsewhere on this day. The localized maximum was due to an intense rain core that continually developed southwestward in spite of general northeastward cell movement, such that the core did not move with respect to the measuring gage.

The analyses for the combined April and May periods are merely syntheses of the two. The most noteworthy feature of these analyses is the maximum of rainfall for seed days in and south of the Miami area, (figs. 58a, 58b and 58c).

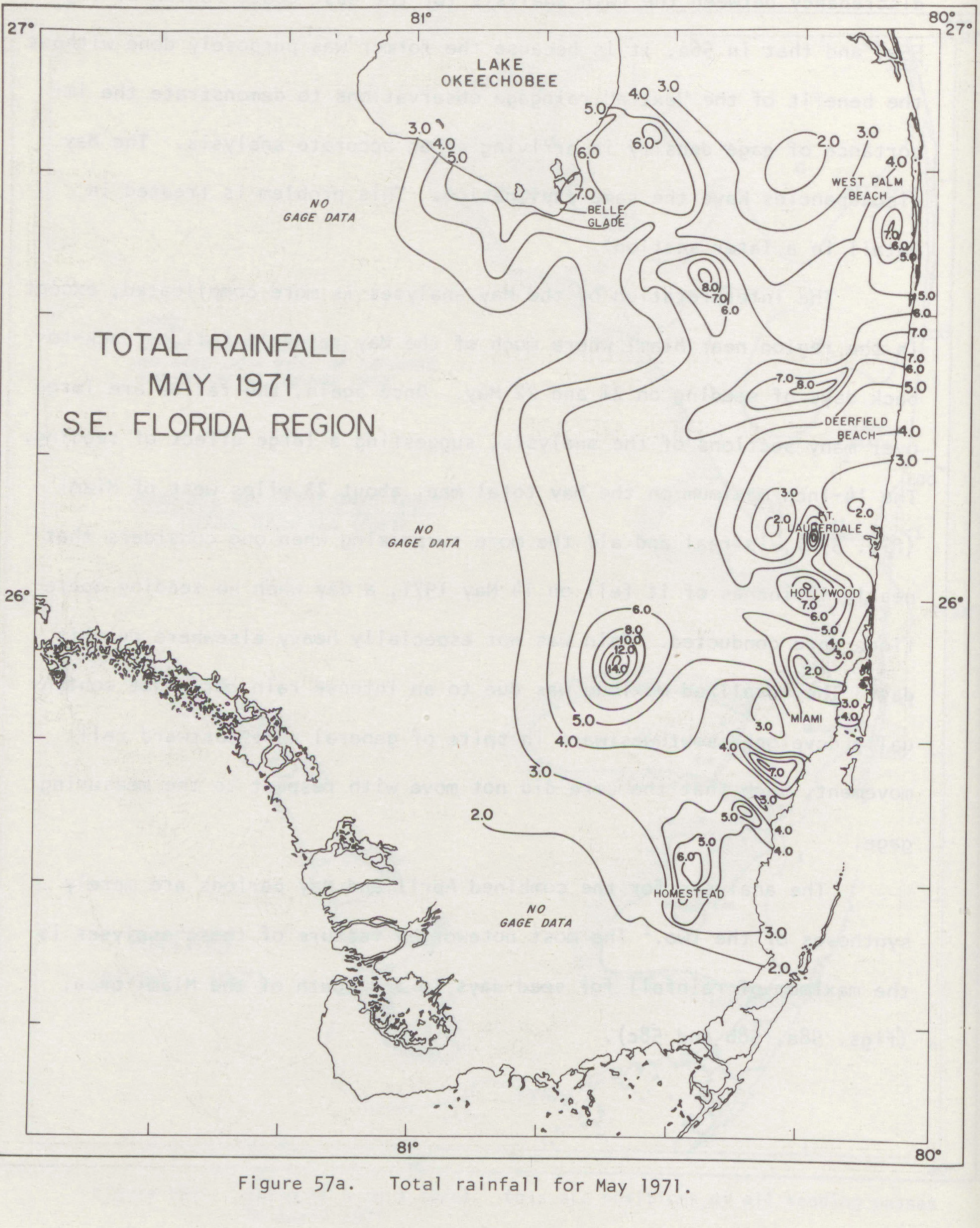


Figure 57a. Total rainfall for May 1971.

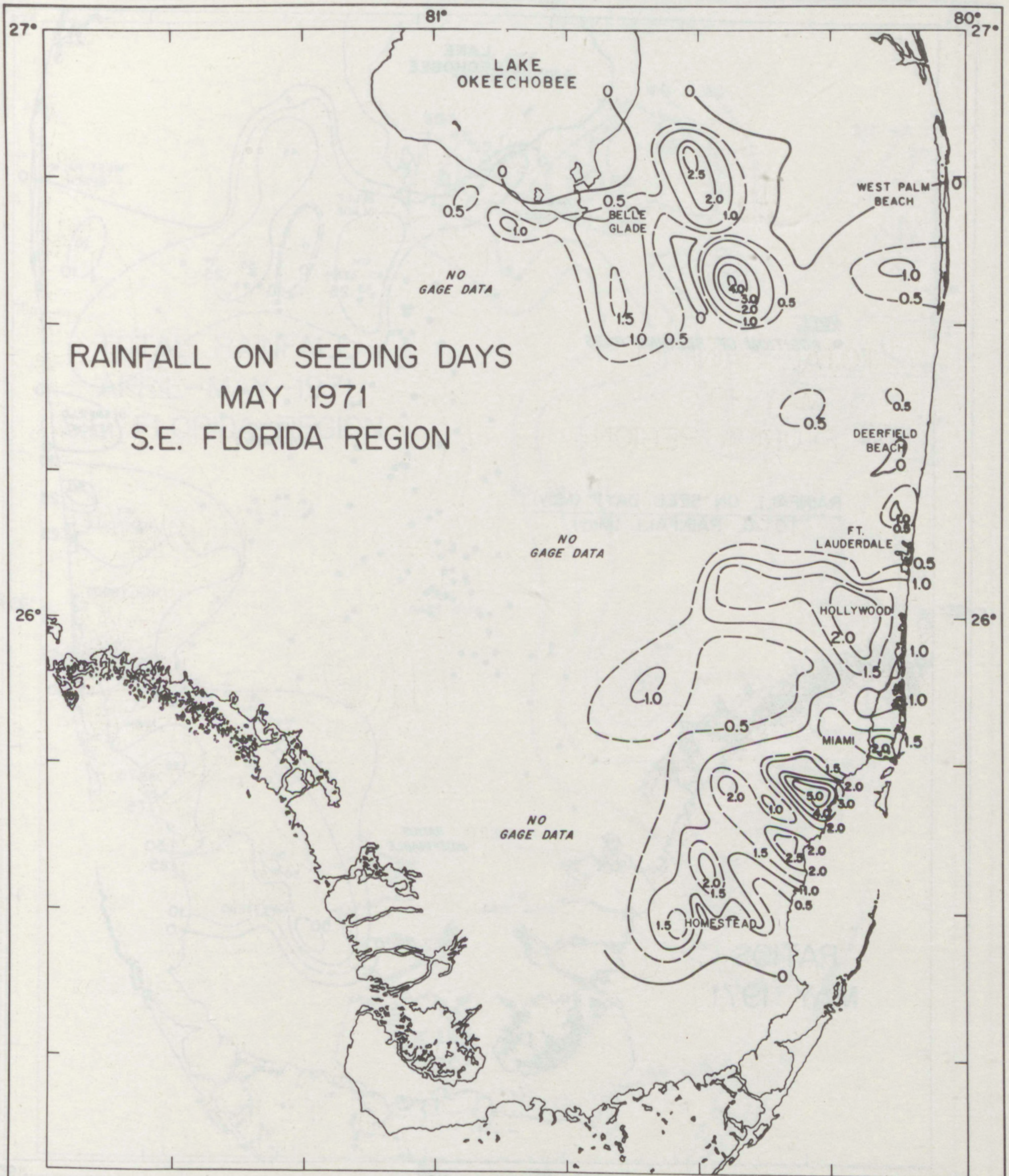


Figure 57b. Rainfall on days of seeding in May 1971.

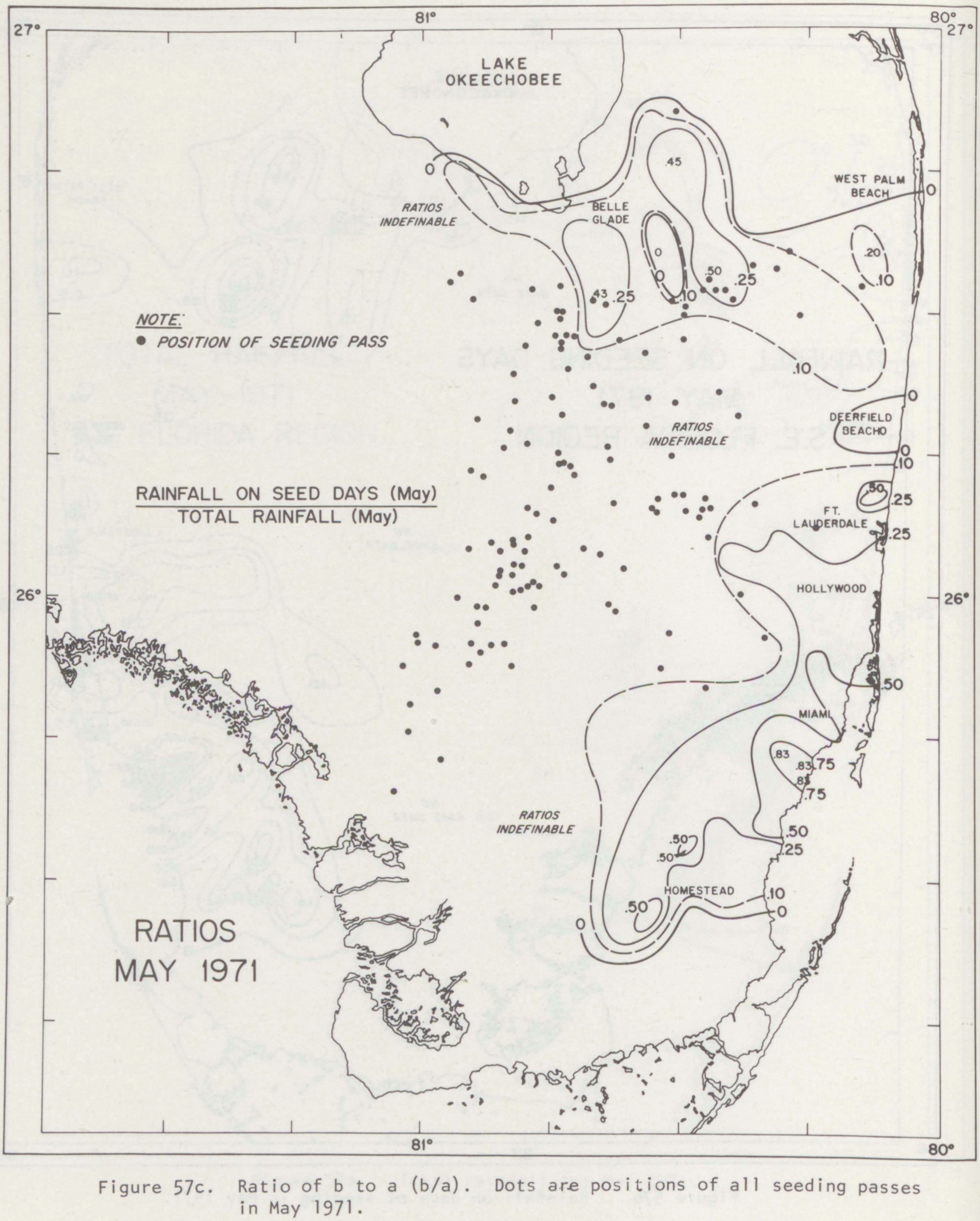


Figure 57c. Ratio of b to a (b/a). Dots are positions of all seeding passes in May 1971.

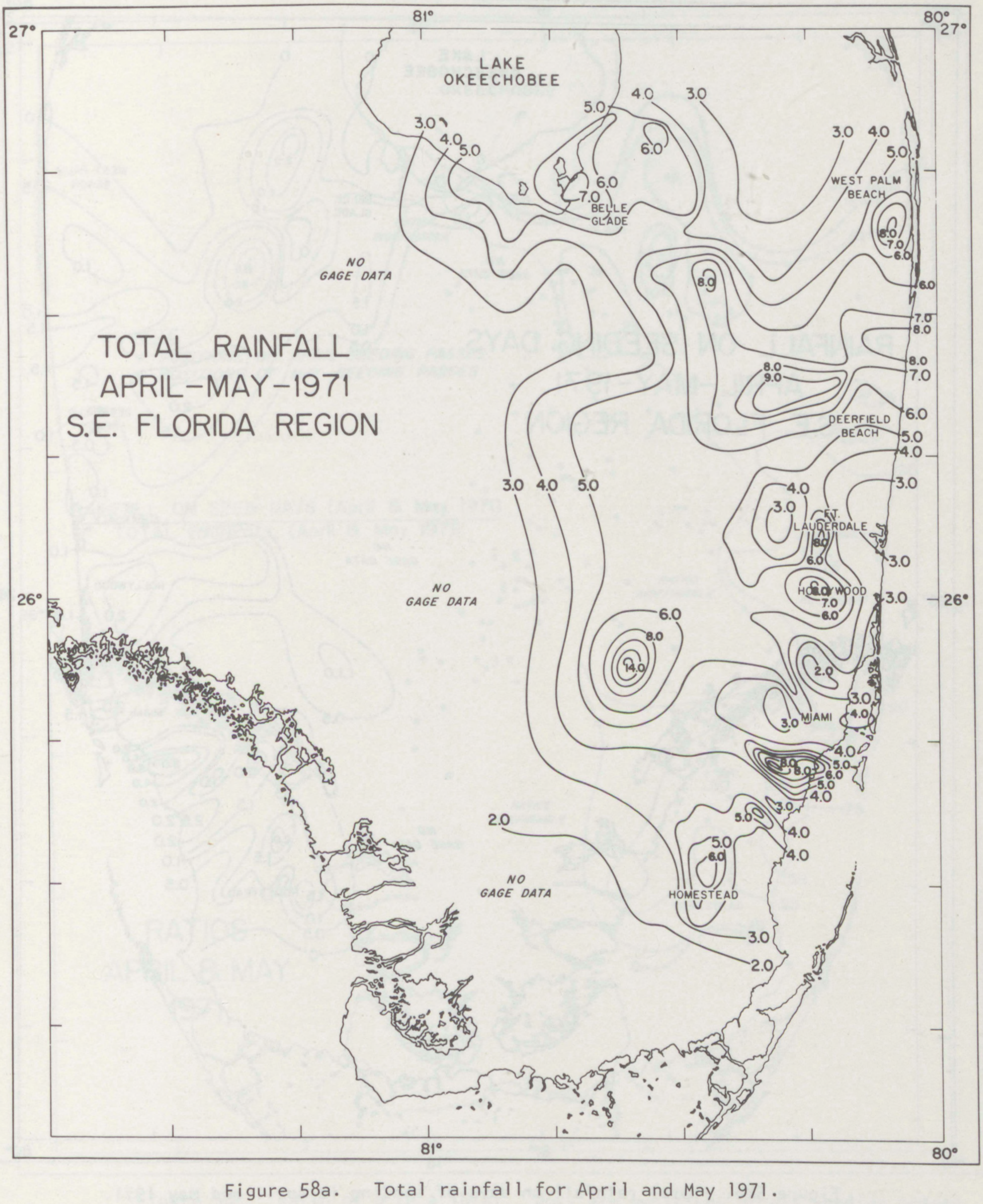


Figure 58a. Total rainfall for April and May 1971.

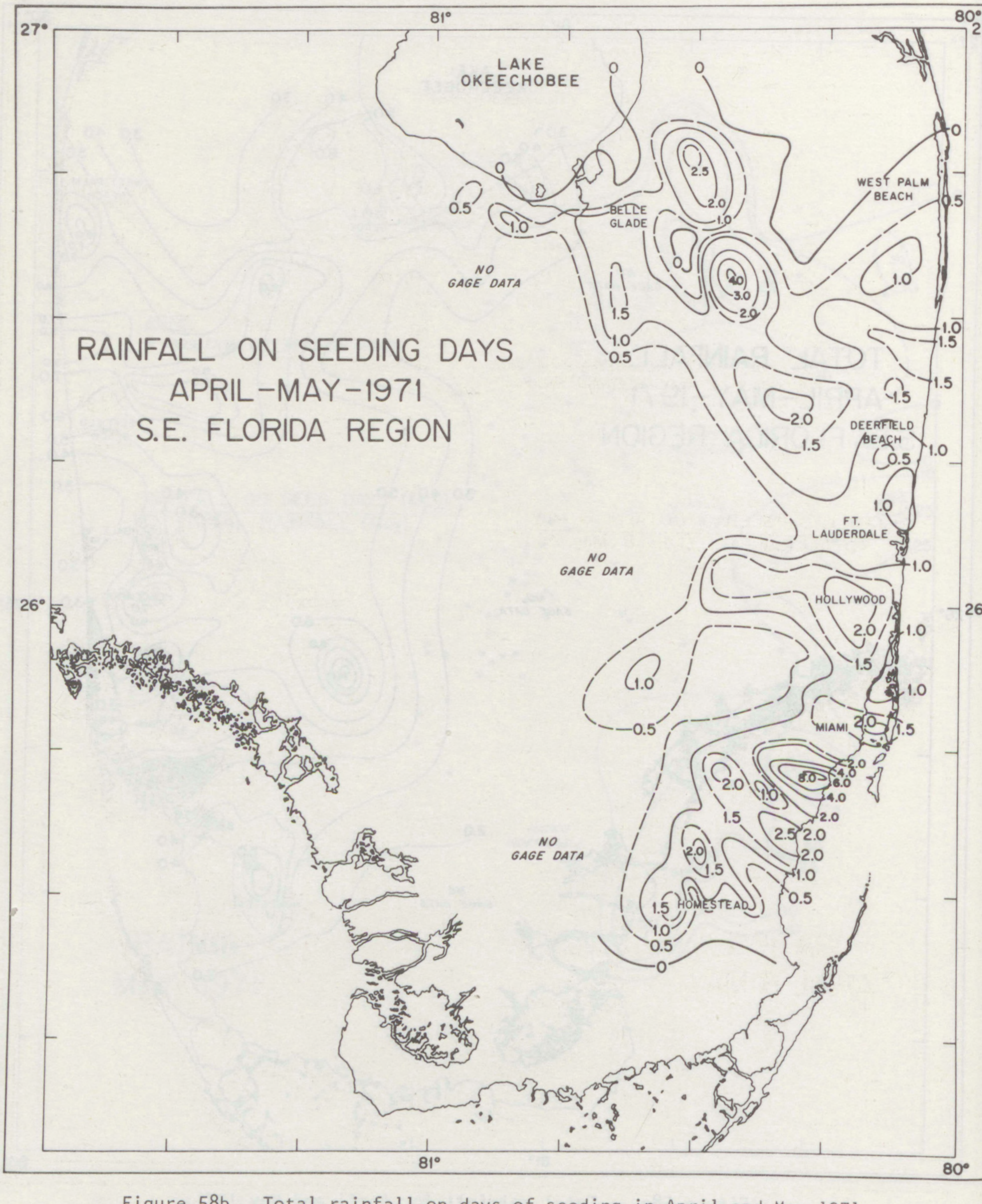


Figure 58b. Total rainfall on days of seeding in April and May 1971.

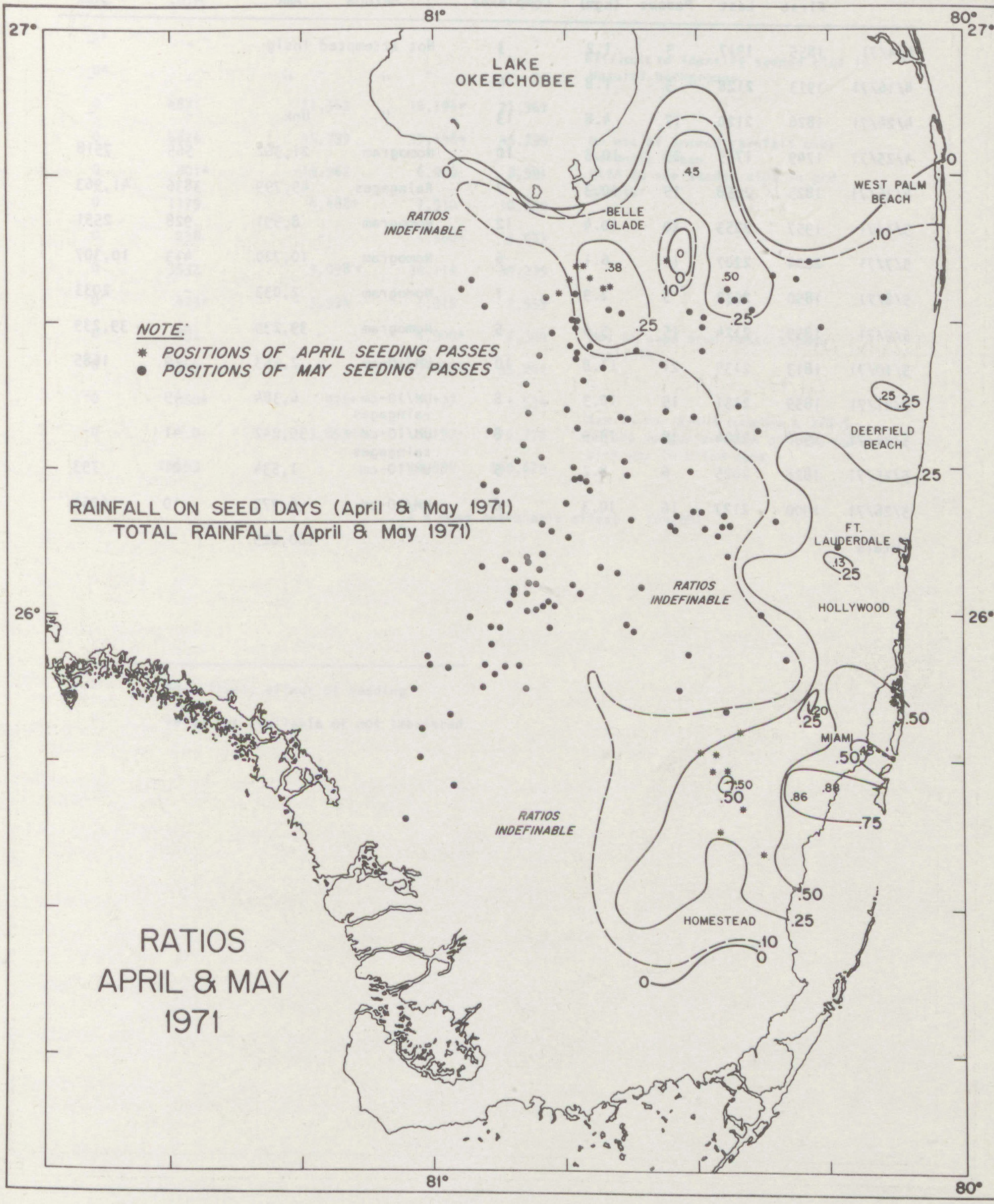


Figure 58c. Ratio of b to a (b/a). Dots are positions of all seeding passes in April and May 1971.

Table 6 . Precipitation Estimates (acre-feet) for the April-May 1971 Seeding Program

Date	Seeding Times First	Seeding Times Last	No. Passes	AgI (kgm)	No. Seeded Clds or Cld Complexes	Rain Estimates Method	Total Amt	Rain Amt per Complex Min.	Rain Amt per Complex Max
4/4/71	1855	1917	3	1.2	3	Not attempted	Insig	-	-
4/16/71	1913	2128	5	1.8	4	"	"	-	-
4/24/71	1826	2120	17	4.8	13	"	Unk	-	-
4/25/71	1749	1755	25	10.3	10	Nomogram	21,362	565	7518
4/26/71	1825	2058	19	10.3	7	Raingages	45,799	3836	41,963
5/1/71	1957	2253	20	10.4	12	Nomogram	8,991	928	2551
5/7/71	2004	2207	12	6.1	6	Nomogram	10,720	413	10,307
5/8/71	1850	2032	3	2.9	1	Nomogram	2,033	-	2033
5/9/71	1859	2124	15	5.6	5	Nomogram	39,239	-	39,239
5/10/71	1813	2135	21	11.8	10	UM/10-cm	2,553	19	1685
5/21/71	1855	2131	15	10.3	8	UM/10-cm + raingages	6,384	49	-
5/22/71	1906	2204	19	13.9	8	UM/10-cm + raingages	35,242	41	-
5/25/71	1828	2025	6	8.2	5	UM/10-cm	1,534	21	793
5/26/71	1900	2127	16	10.3	6	UM/10-cm	6,772	10	6051
Totals							180,629		

	Effect of Seeding				
None	Model Derived 8pm Mia Sounding	By Comparison	Sgle Cloud Extrapolation	All	Comments
0*	-	-	-	-	
0*	-	-	-	-	
0*	-	-	-	-	Difficult to identify seeded clds in Natural background
0	4871	21,362	16,394*	21,362	
0	6824	45,799	35,148*	45,799	No est of seeded rainfall over Atlantic Ocean
0	801*	-19,962	6,900	8,991	Diff to see seeded clds in grd clutter
0	1179	4,488*	7,910	10,720	
0	238	-	1,560*	2,033	
0	3532	9,098*	30,114	39,239	
0	423*	- 3,994	1,915	2,553	
0	891	-	4,900*	6,384	May be gaps btwn radar & gage analysis
0	6344	-	27,046*	35,242	
0	350*	- 926	1,177	1,534	
0	0	3,853*	5,197	6,772	Max is for 2-4-5 complex & 2-4-5 before merger portion of this complex was in blind cone
	25453	-	138,994	180,629	

∑* = most reasonable effect = 104,061

* Most likely effect of seeding

\- Value not available or not tabulated

7. BENEFIT-TO-COST RATIOS FOR THE PROGRAM

In the previous section, we have seen that seeding during April and May 1971 probably increased the precipitation over the 9000 n mi^2 south of 27°N between five and ten percent during the entire period. The percentage increases over this region on days of seeding were undoubtedly much higher and locally (e.g. in the Miami area) the percentage increases were higher yet. These are interesting statistics, but it is also important to know whether the apparent yield of water from seeding justified the effort and money expended during the program.

It is very difficult to attach a money figure to an acre-foot of water because its value depends on many variables. An acre-foot of precipitation in the coastal margins is probably less valuable than an acre-foot of water over a parched citrus grove, because in the former instance much of the water is lost by drainage to the sea, while in the latter instance, the water stays to irrigate the citrus. Water is also much more valuable during a drought. Thus, even though the Miami cloud of 26 April 1971 reached its maximum intensity near the coastline, the nearly 4000 acre-feet of water deposited here rejuvenated residential lawns and shrubs, decreasing the load on municipal water systems for nearly a week. Certainly this rain was more valuable than one during a rainy spell in mid-June.

Two estimates of the value or cost of water, $50 and $108 per acre-foot, were used to estimate the benefit:cost ratio of the program. The first is the cost of the water from the municipal water systems in south Florida, and the second is the cost to farming interests to irrigate their fields with large overhead sprinkler systems.

The combined NOAA-C&SFFCD estimated costs for the program is $165,000, while the "most reasonable" estimate of water production due to seeding is approximately 10^5 acre-feet. At the cost of municipal water the benefit:cost ratio is 32:1, while at the cost to sprinkle water over a crop this ratio is 68:1. If all the precipitation from seeded clouds is ascribed to the seeding, the benefit ratio goes up by nearly a factor of two.

Regardless of which volumetric water estimate and which cost of water is used, the benefit:cost ratio of the April-May seeding program exceeds, by a wide margin, the 10:1 ratio that is considered desirable to justify a seeding program. If the program had been operational rather than scientific in scope, it is estimated that costs could have been cut by nearly a factor of three with a corresponding increase in the benefit: cost ratio of the program. This would be accomplished by using a smaller, less expensive aircraft and fewer personnel.

8. THE C&SFFCD RAINGAGE CONTRIBUTION --- WAS IT NECESSARY?

A large fraction of the C&SFFCD'S portion of the financial burden of the program was in renting, installing and maintaining the network of recording raingages in the target area P (fig. 59a). Because very little seeding was done here, it might appear that the C&SFFCD effort was for nought. However, this network was of considerable scientific value, because of the lesson it taught about the accuracy of rain measurements as a function of gage density. These findings are detailed below.

In any rain modification experiment one naturally wishes to measure rainfall as accurately as possible. In the analysis of EML rain augmentation experiments in Florida, rain volumes are estimated in preference to gage point estimates in the belief that the former provides a better

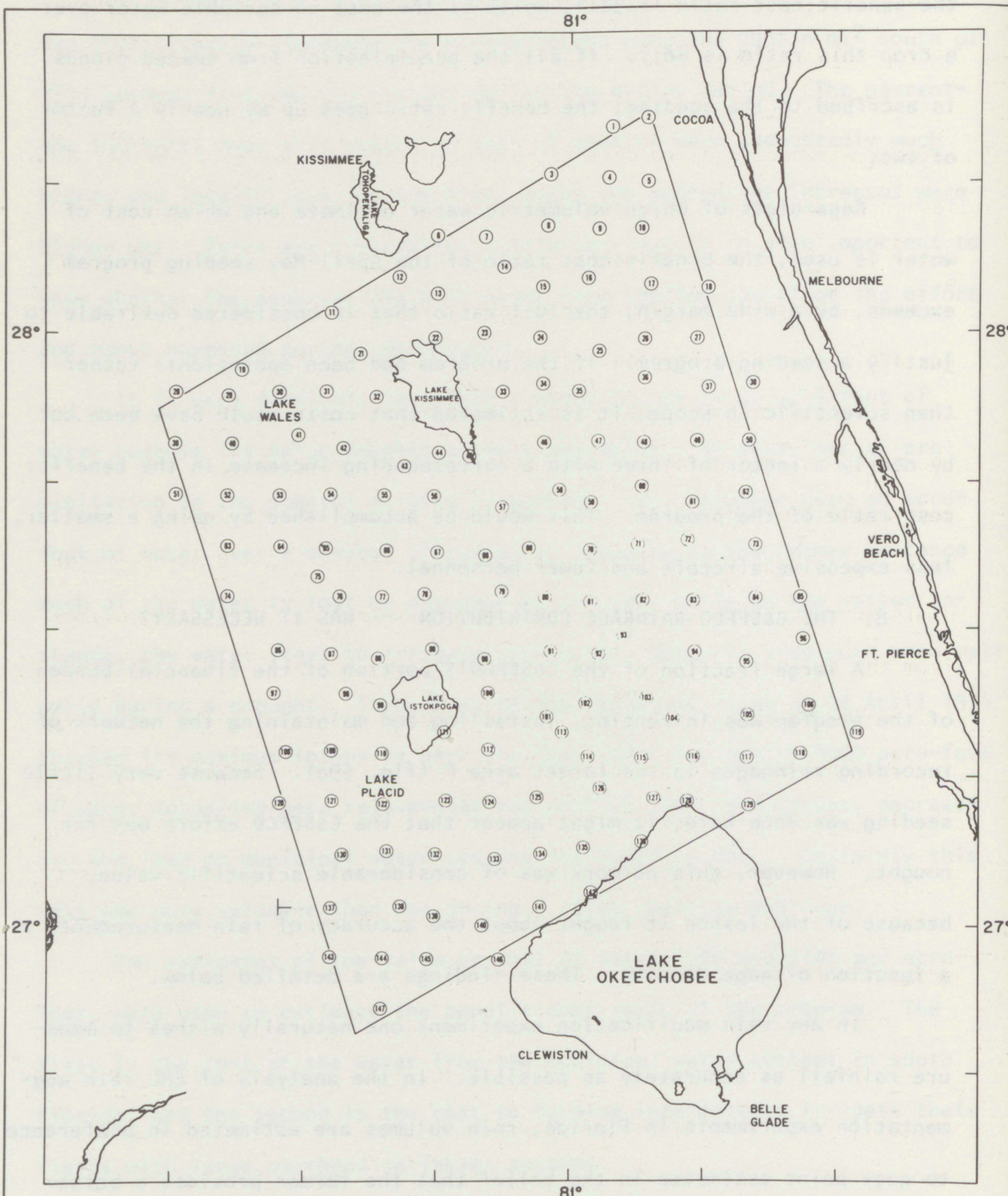


Figure 59a. Target area P showing the gage locations.

estimate of the effects of seeding than the latter. Rain volume was calculated for area P on all days that the network was in operation during April and May 1971. While little seeding was actually done here during this period, it is nonetheless important to determine whether the full network was necessary to define the precipitation volume, or whether a lesser network might have been adequate. If the answer to the latter question is in the affirmative, then it might not be necessary to expend so much effort in the future in establishing a surface network to evaluate a cloud seeding program.

This uncertainty was investigated by calculating rain volumes for the northern area using two gage densities, one gage in 77 n mi^2 (44 gages) and one gage in 25 n mi^2 (the full network of 145 gages). (The lesser gage density still exceeds by a wide margin the one gage in 350 n mi^2 of the climatological gage network in Florida). The rain volumes from the two networks were compared and tested for significant differences.

The 48 gage network was defined before any of the data were plotted and analyzed. In its definition, gages were retained that provided the best network coverage commensurate with the 48 gage restriction. One-third the number of total inoperative (12 gages) and partially inoperative (10 gages) were retained in the secondary network. Thus, the 48 gage network (fig. 59b) covered the same area and had the same proportion of inoperative gages.

The days from 13 April to 24 May were given code names to preserve objectivity. Isohyetal analyses were completed for the 48 gage plots before analysis of the more dense gage network. Once a final analysis had been made, no changes were permitted. Rain volume was calculated by area integrating the isohyetal analysis with a planimeter. These rain volume estimates are found in Table 7 where $R_{1/3}$ is the estimate for the network with one-third of the gages and R_F is the estimate from the full network. In all cases, R_F must be considered the standard or the more accurate of the two. Days with no rain in the full network do not appear in this table.

Of the 36 days with rain, 20 had rain amounts less than 500 acre-feet; five had rain amounts greater than 500 acre-feet, but less than 5000 acre-feet; nine had amounts exceeding 5000, but less than 50,000 acre-feet, and there were two days with amounts more than 50,000 acre-feet. However, the two heavy rain days accounted for nearly 75 percent of the rainfall during this period. This emphasizes the importance of a few intense rain events in producing the bulk of Florida's rainfall.

The estimates provided by the two gage densities differ substantially in many cases. This is quantified in the frequency histogram of the ratio $\frac{|R_{1/3} - R_F|}{R_F}$ (fig. 60). In only seven of the 36 comparisons was this ratio less than 0.25, while in 14 of the 36 it was 1.00 or greater. Thus, in nearly half of the comparisons, the error $|R_{1/3} - R_F|$ is as great as the standard estimate (R_F) itself. This result has serious ramifications for cloud seeding experiments. Unless one makes an extensive gaging effort to minimize the error level that is the result of inadequate distribution, he can be unlucky enough that the errors may mask any effect of seeding.

Table 7. Rain Volume Estimates (acre-feet)

Date n	$R_{1/3}$	R_F	$R_{1/3}-R_F$	$\frac{\lvert R_{1/3} - R_F \rvert}{R_F}$
April:				
13	240.0	41.6	198.4	4.77
14	0	42.7	- 42.7	1.00
15	14,183.6	8,345.6	5,838.0	0.70
16	9,075.7	4,041.9	5,033.8	1.25
17	15.5	9.6	5.9	0.61
18	33.1	41.6	- 8.5	0.20
19	0	305.6	- 305.6	1.00
20	1,515.6	3,936.3	- 2,420.7	0.61
21	0	3.7	- 3.7	1.00
22	0	5.3	- 5.3	1.00
23	0	16.5	- 16.5	1.00
24	3,345.4	3,524.0	- 178.6	0.05
25	25,486.4	15,763.8	9,722.6	0.62
26	147.7	311.4	- 163.7	0.53
27	14,913.2	10,853.7	4,059.5	0.37
29	0	5.3	- 5.3	1.00
May 1	2,996.1	5,240.7	- 2,244.6	0.43
2	0	15.5	- 15.5	1.00
3	0	6.9	- 6.9	1.00
5	1,134.3	724.7	409.6	0.57
6	0	7.5	- 7.5	1.00
7	0	19.2	- 19.2	1.00
8	51.2	147.2	- 96.0	0.65
9	121.1	265.0	- 143.9	0.54
10	42,697.1	46,682.4	- 3,985.3	0.09
11	6,232.1	11,152.9	4,920.8	0.44
12	128.5	124.3	4.2	0.03
13	39,765.5	43,265.0	- 3,499.5	0.08
14	138,814.3	186,098.8	47,284.5	0.25

Table 7. Rain Volume Estimates (acre-feet) - Continued

Date n	$R_{1/3}$	R_F	$R_{1/3}-R_F$	$\frac{\|R_{1/3} - R_F\|}{R_F}$
15	288,861.9	304,081.3	-15,219.4	0.05
16	14,946.8	12,774.7	2,172.1	0.17
17	44.3	59.7	- 15.4	0.26
19	0	57.6	- 57.6	1.00
20	0	134.9	- 134.9	1.00
21	5,691.4	8,123.2	- 2,431.8	0.30
22	14.9	568.9	- 554.9	0.90

$n = 36$

$\sum R_{1/3} = 610,455$

$\sum R_F = 666,799$

$\sum (R_{1/3} - R_F) = -56343$

$\sum |R_{1/3} - R_F| = 111,180$

$\overline{R}_{1/3} = 16957$

$\overline{R}_F = 18522$

$\overline{(R_{1/3}-R_F)} = -1565$

$\overline{|R_{1/3}-R_F|} = 3088$

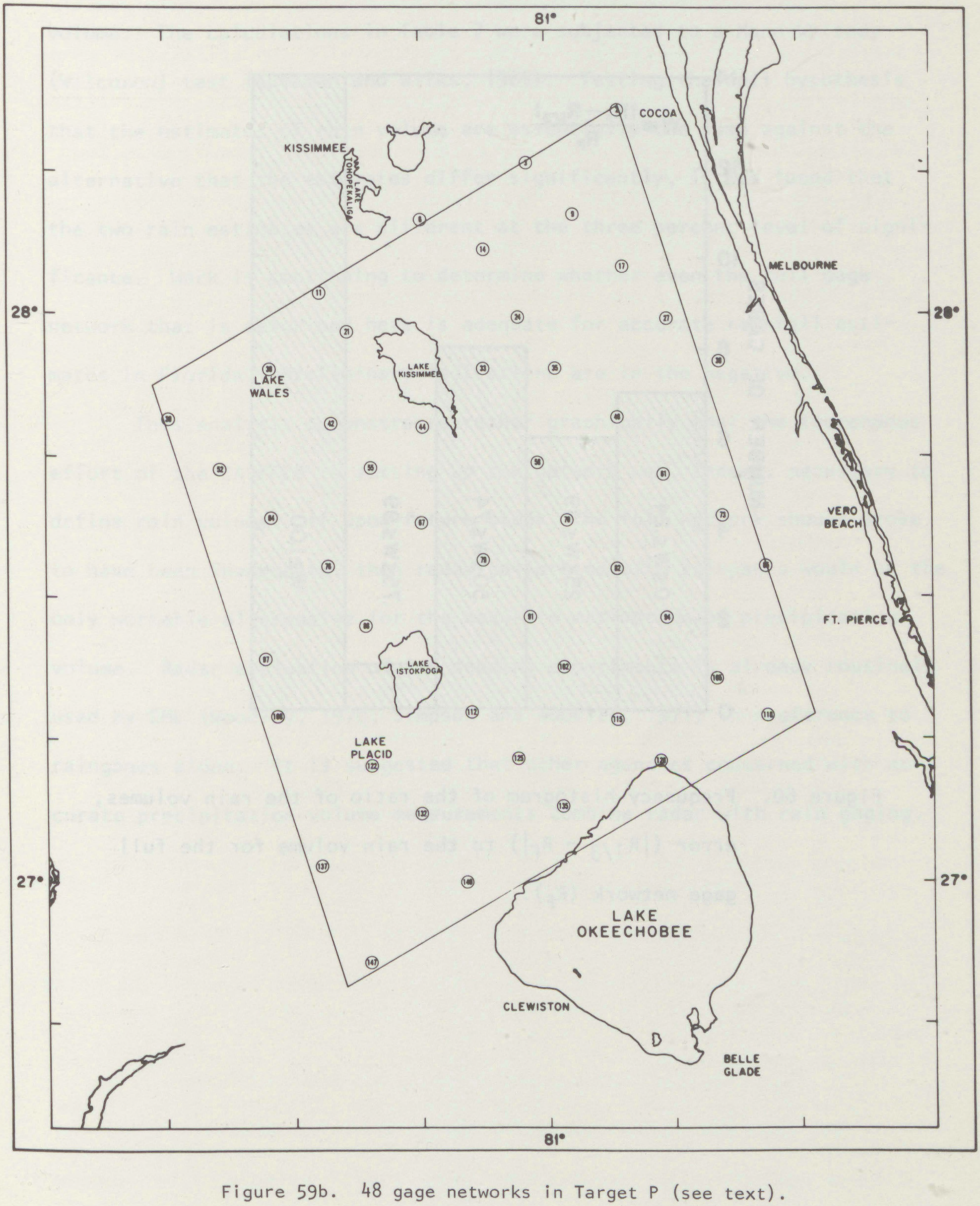


Figure 59b. 48 gage networks in Target P (see text).

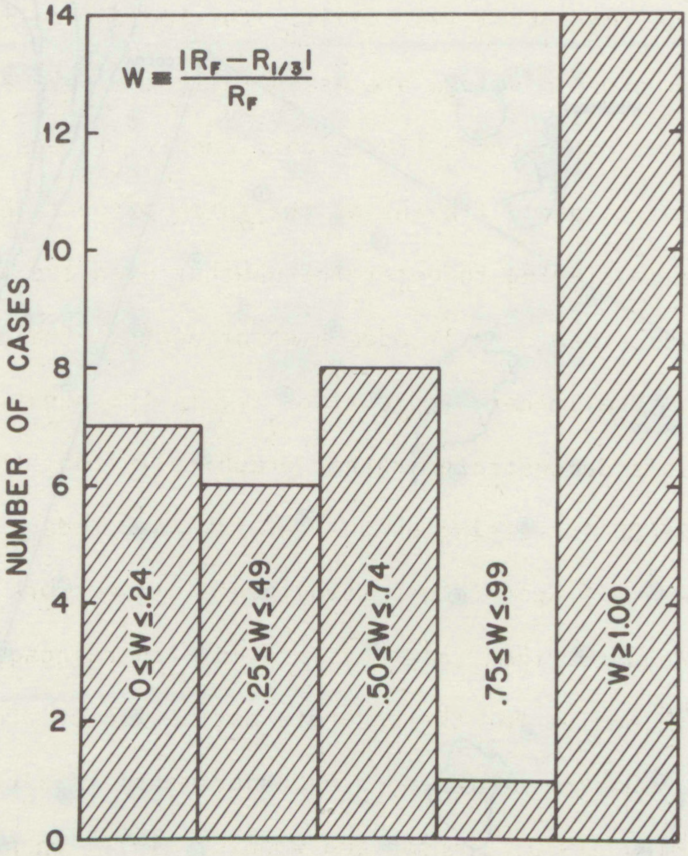


Figure 60. Frequency histogram of the ratio of the rain volumes, error ($|R_{1/3} - R_F|$) to the rain volume for the full gage network (R_F).

An attempt was made to determine whether the two raingage networks were providing statistically significant different estimates of the rain volume. The calculations in Table 7 were subjected to a Mann-Whitney (Wilcoxon) test (Guttman and Wilks, 1965). Testing the null hypothesis that the estimates of rain volume are essentially the same against the alternative that the estimates differ significantly, it was found that the two rain estimates are different at the three percent level of significance. Work is continuing to determine whether even the full gage network that is described here is adequate for accurate rainfall estimates in Florida. Preliminary indications are in the negative.

This analysis demonstrates rather graphically that the tremendous effort of the C&SFFCD in setting up the network was, indeed, necessary to define rain volume. If upon future study, the full network should prove to have been inadequate, then radar calibrated with raingages would be the only workable alternative for the accurate estimation of precipitation volume. Radar evaluation of its seeding experiments is already routinely used by EML (Woodley, 1970; Simpson and Woodley, 1971) in preference to raingages alone. It is suggested that other agencies concerned with accurate precipitation volume measurements combine radar with rain gaging.

9. ECOLOGICAL EFFECTS OF SILVER IODIDE

Silver iodide is used exclusively for the seeding of supercooled convective clouds in Florida. Questions concerning the toxicity of this material are rather common. While no specific toxicity data are available for silver iodide, hazard analysis is still possible based on data for silver compounds and iodides. The ensuing hazard analysis of silver iodide draws very heavily on reports by Douglas (1968) and Cooper and Jolly (1969). Details are found in these reports:

9.1 IODINE

> "All available evidence indicates little likelihood of environmental effects from the iodine in AgI. A human consumer would have to drink 130 gallons of precipitation from a storm seeded with AgI to obtain as much iodine as in eggs flavored with iodized table salt. The role of iodine in physiological processes has been well documented, and instances of toxicity from naturally occurring iodine are very rare. Iodine is ubiquitous in organic and inorganic environments. Up until 1934 it was commonly produced along the Atlantic seaboard of Europe by the burning of seaweed with concomitant escape of iodine vapor to the atmosphere. Vaporized iodine was regularly detected over most of Europe during this period, but no biological effects were ever reported. It seems reasonable, therefore, to dismiss iodine in AgI at present levels of use as a source of ecological concern." (Cooper and Jolly, 1969).

9.2 SILVER

Silver is not dismissed as a danger as easily as iodine. Silver is a highly toxic heavy metal, one that is used in industry as a microbial poison. However, it is relatively harmless to higher animals, including man.

9.2a TOXICITY STANDARDS FOR SOLUBLE SILVER COMPOUNDS

The American Industrial Health Association Handbook lists maximum airborne concentration (occupational exposure) of soluble silver compounds as 0.1 milligram per cubic meter.

The Handbook of Industrial toxicology lists maximum permissible airborne concentration (occupational exposure) of soluble silver compounds as 12×10^6 particles per cubic foot, ($\sim 4 \times 10^8$ particles per cubic meter).

The U. S. Public Health Service standard for drinking water is 0.05 ppm of silver compounds to water. Silver in water in excess of this threshold constitutes grounds for rejection of the water for drinking purposes.

9.2b SILVER IODIDE AS A DIRECT HAZARD TO MAN IN FLORIDA

During a typical seeding in Florida, approximately 1 kgm of silver iodide is dropped into a seeded cloud having a tower radius of 1 km and a height of 6 km. Because each flare produces approximately 10^{15} silver iodide particles per gram, about 10^{18} particles are introduced into the seeded cloud. This gives a concentration of about 10^8 silver particles per cubic meter of cloud air before the cloud enters its growth phase. This concentration is instantaneously near the maximum permissible airborne concentration of soluble silver compounds, but upon cloud growth and eventual diffusion of the silver iodide through the target area, the concentration decreases to far below the permissible airborne concentration.

In using mass concentration, the mass of a silver iodide particle produced by a silver iodide flare is of the order of 10^{-13} gm. For 10^8 particles/m^3, the mass of silver iodide is 10^{-5} gms/m^3, about an order of magnitude less than the maximum airborne concentration permissible.

Again, this concentration would only be realized immediately after seeding and it would decrease shortly thereafter.

Of most concern is the effect that silver compounds might have once they reach the ground. This is a many faceted problem of great complexity. No one is certain how, when, where and in what concentration silver iodide reaches the ground. Cooper and Jolly (1969) report that:

> "Silver in precipitation from non-seeded storms has been measured at levels up to 20 x 10^{-12} grams of silver per milliliter of precipitation (0.00002 ppm). Silver concentrations in precipitation from seeded storms range from 0.000001 to 0.00176 ppm. Typical values are 0.0001 to 0.0003 ppm. This is of the same order as the concentration of Ag in normal seawater -- 0.00015 to 0.0003 ppm."

However, recently Summers and Renick (1971) report that up to four parts per billion (.004 ppm) were found in the samples collected downwind of their seeding. Analysis for silver content was done using atomic adsorption spectrophotometry. This value is an order of magnitude less than the U. S. Public Health Service standard for drinking water.

The seeding technique of Summers and Renick is similar to that employed by EML in Florida. However, comparable silver concentrations in rainwater have not been found (Ostlund and Stearns, 1969) in Florida above the natural background using neutron activation analysis. Nevertheless, it is suspected that the silver compounds were present in the water and that they were not detected because of adsorption of the silver to the walls of the plastic collecting system.

It is a relatively simple matter to calculate the maximum possible concentration of silver compounds in rainwater following seeding in Florida. During a typical multiple cloud seeding experiment here a maximum of 15 kgm of silver iodide might be used and between 10^{13} and 10^{14} gm of precipitation might fall from the seeded clouds (Simpson and Woodley, 1971; Woodley et al. 1971). If all the silver iodide were washed out by the precipitation, there would be a silver concentration of 0.001 to 0.0001 ppm in the seeded precipitation, or about an order of magnitude less than the U. S. Public Health standard of 0.05 ppm. When the seeded precipitation is mixed with the precipitation from non-seeded clouds, the concentration would drop by another order of magnitude, and if it were all deposited into Lake Okeechobee, the silver concentration for the one seeding would be 0.00001 ppm (calculation assumes 4×10^6 acre-feet of water in Lake Okeechobee).

These calculations for Florida suggest that immediate concentrations of silver and iodine in the air and rainfall will be exceedingly small, and we agree with Douglas (1968) that there is no direct hazard to humans from the use of silver iodide as a seeding agent, However, Douglas did not consider reconcentration of silver through biological processes and as Cooper and Jolly (1969) point out... "It is this very reconcentration possibility that must be assayed in making predictions about the ecological effects of large-scale, long-term use of AgI."

9.2c LETHALITY OF SILVER COMPOUNDS TO PLANT AND ANIMAL LIFE

Cooper and Jolly (1969) looked into the lethality of silver compounds on plant and animal life and the possibility of environmental concentration of these compounds. With respect to mammals, they report that silver, even in highly soluble form is only moderately harmful to mammals, primarily because it does not act as a cumulative poison in mammalian systems. The effect of silver in birds or reptiles is unknown because no one has yet given this problem extensive treatment.

Silver compounds are apparently more toxic to fish than to terrestrial vertebrates (Cooper and Jolly, 1969). Some of the higher concentrations of silver recorded in precipitation from seeded storms are comparable to the lowest concentrations lethal to fish in the short run. Apparently, the silver interferes with gas exchange by the gills, but the precise mechanism is not known. All of the fish experiments were conducted with $AgNO_3$ and it is not clear that silver from seeded clouds will have the same effect. Even if the effect were the same, the deposition of seeded rainfall into water bodies would result in a much lower silver concentration than in the tests. Further, silver iodide in lakes and streams will reflect average, not maximum, concentration in precipitation from all storms, including non-seeded storms,and adsorption on vegetation and bottom sediments will further reduce concentrations in water.

Silver is apparently not harmful to plants, except in concentrations that far exceed what one might expect in precipitation from seeded clouds, but silver is toxic to microorganisms in lesser concentrations. It is remotely possible that prolonged seeding with silver iodide might have a long-time effect on some bacterial action. The ecological consequences of this possibility are unknown.

9.2d CONCENTRATION OF SILVER COMPOUNDS AND ITS CONSEQUENCES

Once again we draw heavily on the report by Cooper and Jolly (1969). We quote relevant passages:

"Because of the low solubility of most silver salts and because of the tendency for adsorption of silver by soil colloids, most silver in terrestrial systems will presumably be immobilized.

"Because most land plants do not take up silver actively, there is lttle likelihood of silver concentrating through terrestrial food chains, nor of danger to terrestrial plants or animals if silver is used as a nucleating agent. This can be said with respect to both immediate effects and effects over a period of perhaps 20 years. Continuous reassessment during such an intermediate term of application should be made as new information accumulates.

"Aquatic organisms do effectively concentrate silver and other heavy metals relative to their environment... There has never been any indication that marine organisms which concentrate silver suffer in any way as a result.

"The data available in the literature indicate that there is little likelihood that silver from cloud seeding will adversely affect terrestrial plant and animal communities or marine environments, either immediately or after some 20 years of AgI application. Such a statement is clearly risky; a similar survey of pesticide effects 20 years ago would almost certainly not have anticipated the relatively recent discovery that DDT reduces the thickness of bird egg shells, and thereby lowers the reproductive rate of many bird species. Similar unforeseen metabolic effects of silver may appear, but we believe that they are unlikely.

"Direct lethal effects on fresh water fish are also unlikely, either as a result of detrimental levels of silver in the water or of ingestion of harmful silver compounds concentrated through the aquatic food chain. There is a possibility, however, that there may be sufficient silver in some fresh waters, especially at the headwaters of streams, to slow the growth of susceptible fish or of the aquatic invertebrates upon which they feed. Laboratory experiments, under simulated field conditions, should be undertaken to determine the effects of very low levels of silver compounds on growth rates of fish and of representative classes of insect larvae. Consideration should be given in designing such experiments to the chemical nature of the Ag compounds used, and to the likelihood that much of the silver will be removed from solution by adsorption on vegetation surfaces and bottom sediments.

"Perhaps the most likely possibility is that adsorbed silver will inhibit the growth of freshwater microorganisms -- algae, fungi, and bacteria. If such an effect does occur, it is more likely to be a selective reduction in growth of certain organisms than a dramatic lethal response. This would be detrimental if the affected microorganisms serve as food for larger animals. More serious would be interference with biological decomposition of bottom sediments, particularly in lakes and ponds. This decompostion process is a vital link in the cycle that returns essential nutrients to the water. Similar inhibition might affect sewage treatment processes, but this is less likely because of the rapid turnover and close control in such systems."

In summary, Cooper and Jolly (1969) state that:

"Silver is a potentially toxic heavy metal that will be introduced into the environment. Preliminary indicators are that it will not concentrate to harmful levels through either terrestrial or aquatic food chains. The threat of environmental contamination from silver iodide does not seem great enough to preclude its use at this time. Close attention should be given to the problem, however."

EML plans further analysis for silver contents of the rainwater from seeded clouds and from other clouds in the near and more distant vicinity to aid in further understanding of both the meteorological and ecological effects of silver iodide seeding.

10. SUMMARY

A cloud seeding program for drought mitigation was conducted by the Experimental Meteorology Laboratory over south Florida during April and May 1971. The program was supported jointly by NOAA and the Central and Southern Florida Flood Control District. There were 14 days of seeding operation in this period, during which a total of 105 hours were flown, 2066 flares were used and 196 clouds or cloud complexes were seeded. Seeded clouds produced nearly 200,000 acre-feet of precipitation, most of it over the area south of Lake Okeechobee. Approximately 70 percent of the total seeded precipitation fell on only four days of seeding operation

(25-26 April, 9 and 22 May, see Table 6). At least half of the precipitation from seeded clouds, or about 100,000 acre-feet can be reasonably attributed to seeding.

Seeding during April and May 1971 did not break the drought ravaging the south Florida area, nor was it expected that it would do so. However, precipitation from seeded clouds did provide temporary relief, especially in Everglades National Park and in the coastal areas from Palm Beach south to Homestead. Seeded precipitation also extinguished many grass and muck fires and decreased the fire hazard in areas where it fell. Because very few suitable clouds were found north of Lake Okeechobee, only a fraction of the precipitation from the seeded clouds actually reached the lake.

11. CONCLUSIONS

This study suggests the following conclusions:

1) As expected, dynamic cloud seeding is not a short-term solution to severe drought because suitable conditions for rain enhancement procedures are infrequent in periods of drought stress. Rather, dynamic seeding will be effective over the long term to build up water storage for use during periods of rainfall deficiency. Nevertheless, 14 seeding days were obtained during the 61 day operational period, which was better than the ten days originially expected. About 20 seeding days could have been obtained, had a back-up seeder aircraft been available.

2) As a short term tool, dynamic cloud seeding is effective in

providing temporary, highly localized drought relief, such as extinguishing glades fires and decreasing water demand in metropolitan areas by watering lawns.

3) Results of seeding on days with high shear (e.g. 26 April 1971) suggest that dynamic seeding may be effective in increasing rainfall from clouds in some of the weak frontal zones that traverse south Florida during the dry season. However, it is likely that the severe weather potential is increased when seeding under such conditions.

4) The crossover design for randomized cloud seeding experiments is impractical in Florida because of the great spatial and temporal inhomogeneity of suitable clouds. The disparity of suitable clouds in targets P and S during April and May 1971 support this statement.

5) Only the most dense of raingage arrays is adequate for the evaluation of seeding experiments. Radar calibrated with a few recording raingages is preferred, especially when the seeding is conducted over large geographical areas.

6) It is nearly impossible to forecast severe weather potential in Florida. Whenever clouds reach massive cumulonimbus stature, severe weather is a possibility. Because of this, severe weather may occasionally be associated with dynamic cloud seeding.

7) A two aircraft seeding operation is more efficient than a one aircraft operation. The efficiency of a single aircraft can be

increased by using a faster aircraft than the DC-6. The RFF C-130 would appear to be better in this regard.

8) Seeding may accelerate the growth and precipitation of small cumulonimbus systems.

9) The optimum amount of silver iodide for dynamic growth remains undetermined.

10) Meso-scale cloud interaction must be better understood before dynamic cloud seeding for drought mitigation to become an operational reality.

11) The ecological impact of dynamic multiple cloud seeding should be a matter of increased study in future experiments.

12) If the C&SFFCD requires detailed rainfall measurements for their water management procedures, this study suggests that the current network is not adequate to do the job. Radar calibrated with a few raingages might be a more viable alternative for making these measurements.

13) Randomization was not feasible in this program and it is unlikely to be feasible in future programs undertaken either in the dry season or in severe droughts. This is due to too few seedable clouds in any specified target area, coupled with the rapid movement of frontal cloud systems. Even if it were feasible to randomize in a drought mitigation program, it may be operationally unwise to do so. As we have seen, most of the rainfall in a drought mitigation program falls on only a few days of seeding operation. Randomization is, therefore, unde-

sirable because it elminates some of the favorable seeding opportunities that are so necessary for a successful drought mitigation program.

12, ACKNOWLEDGMENTS

This program was a joint effort of EML, NOAA and the Central and Southern Florida Flood Control District. EML would like to thank the C&SFFCD for their beautiful cooperation on all phases of the program, which we hope will pave the way for further Federal-State cooperation on water management and cloud modification programs. Mr. Robert W. Padrick Chairman, and Mr. G. E. Dail, Jr., Executive Director of the C&SFFCD, are to be highly commended for foreseeing the drought in ample time to design an optimum seeding program. Their public information officer, Mr. Thomas E. Huser, was helpful at all times. Mr. Robert Taylor and his staff deserve special credit for installing and maintaining the entire raingage network at a high level of efficiency.

The NOAA Research Flight Facility contributed with imagination and dedication to their pioneering effort in practical modification. Our special gratitude goes to the Chief Meteorologist Dr. James McFadden, who provided creative leadership and outstanding competence thoughout the program. We appreciate the balance between courage and caution on the competent flying of the Chief Pilots, Fred Werley, John McCann, Don George, Dave Turner and Merle Henderson. The engineering crew went far beyond routine duty in keeping the aircraft flying in fine repair the maximum amount of time. The excellent pyrotechnic delivery system and wing pods designed by Brad Patten functioned perfectly.

The Radar Laboratory of the University of Miami provided one of the primary tools of rainfall evaluation. Their staff, under the leadership of Professor Harry V. Senn, are to be commended for putting the radar in operation on two days notice.

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Victor Wiggert and Jane Eden shared the seven-day-per-week job of running the EML model in real time. Ronald L. Holle helped with all phases of the EML photographic program and his initiative provided invaluable time-lapse pictures of the May 7 seeded merger, made from the Computer Building on the University of Miami campus. He was also responsible for systematic cataloging and storing of the mass of data collected. Mr. Robert Powell provided great help with the raingage network, made ice nucleus counts aboard the seeder aircraft and prepared all the illustrations. Alan Herndon helped very significantly in the rainfall analyses and calculations. Peggy Lewis and Briseida Sancho coordinated the project participants on a seven-day basis, and Constance Arnhols ably typed, referenced and edited the manuscript.

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APPENDIX

Restrictions on Florida Cumulus to Reduce Potential for Severe Weather

We report here the results of a coordinated NOAA effort to establish objective criteria to restrict Florida cumulus seeding in such a way as to minimize the risk of severe weather in association with seeded clouds.

Firstly, it has been shown that roughly half of severe weather occurrences in south Florida occur when a "Severe Weather Watch" or "Box" has been issued by the National Hurricane Center, under a well-recognized synoptic pattern. No cumulus seeding operation will be scheduled at any time when a severe weather watch has been issued for any portion of Florida south of the northern boundary of the primary seeding target. This precaution is considered adequate by the Florida Flood Control District officials.

In view of NOAA management's request to apply a within-NOAA restriction one step more conservative than requested by the state officials, we shall (until a later mutually derived re-evaluation) apply further restrictions as follows:

Conditions A: Stability index[1] 0 or greater or vertical wind shear (850-200 mb) less than 50 knots. Seeding permitted anywhere in predetermined target areas.

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[1] The Showalter stability index is defined as the temperature deficiency relative to the sounding when an air parcel from 850 mb is lifted dry adiabatically to its lifting condensation level and moist adiabatically above that to 500 mb.

Condition B: Stability index 0 to -2 and shear 50-70 knots. Seeding will be restricted to clouds one-half hour advection time away from the densely populated areas, defined by a line drawn 10 miles inland of the Florida East Coast.

Condition C: Stability index in range -2 to -4 and shear 70-90 knots. Seeding will be restricted to clouds one-hour advection time away from the densely populated areas as defined above.

Condition D: Stability index less than -4 and shear greater than 90 knots. No seeding will be undertaken.

These criteria were derived by consultation with Drs. R. H. Simpson, N. H. Frank and Mr. G. B. Clark of the National Hurricane Center, with Mr. Allen Pearson of the Severe Storms Forecast Center and with the existing literature[2] on severe weather in south Florida. Available research shows that the probability of severe weather increases with instability and strong shear, which apparently operate in conjunction with each other to produce the conducive environment. Studies also show that the most severe manifestations, particularly funnels and tornadoes, occur in the vertical growth stages of the cumulonimbus, which occupy about the first 15 minutes following seeding in a seeded cloud. Hence, seeding 30 minutes upwind of a populated boundary should provide a clear safety margin.

All the experts agree that the above criteria are probably both overly conservative with regard to risk and overly restrictive to the

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2 See bibliography

seeding operation. The most productive seeding day (waterwise and scientifically) of the 1971 program so far was April 26, which classified as Condition C. Applying the above restriction would have eliminated one of the two seeded clouds and a loss of about 5-10,000 acre-feet of desparately needed water. Weighted against this, the trivial damage reported due to small hail[3] seems inconsequential. Furthermore, the alleged report of a hook echo on radar on that day has been discredited by the more mature radar experts present.

It should be noted that 26 Everglades fires were put out by seeding on April 26, 1971, as documented in an official survey and press release by the Flood Control District. Further, our cloud population surveys have shown that situations like these provide virtually the only seedable clouds during dry seasons and periods in Florida.

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[3] One automobile windshield alleged broken - cost roughly $60

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