## FOREWORD

This discussion of artificial rain stimulation in general and the mechanisms for the production of rainfall in the tropics is being distributed in this Technical Memorandum series not only for the interesting material it contains, but also as a source of ideas and help to other Southern Region field officials who might be called upon to present a non-technical talk on the subject of "rain making".

# ON THE MECHANISMS FOR THE PRODUCTION OF RAINFALL IN PUERTO RICO

by
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## 1. Introduction

It is a pleasure to participate in this seminar and make a contribution to the discussion of this important subject. The problem of water and water resources is of vital interest to the organization with which I am connected, the Environmental Science Services Administration - Weather Bureau, as the study and forecasting of rainfall and its hydrological aspects constitute an important part of our functional responsibilities. The problem of rainfall in Puerto Rico is also of great personal interest to me.

In the limited time available today, I would like to touch briefly on the role of the Environmental Science Services Administration in Puerto Rico, the data we have available, and the services that we may be able to provide toward the study of water problems in Puerto Rico. I shall also discuss some of the technical aspects of the production of rainfall in Puerto Rico and some of the principles and implications of artificial modification of natural rainfall processes.

## 2. Role of Environmental Science Services Administration-Weather Bureau

As you all probably know already, about 8 months ago the Weather Bureau, and the U. S. Coast and Geodetic Survey, in addition to other scientific service groups in the U. S. Department of Commerce, were merged into a new organization known as the Environmental Science Services Administration. Within this new organization, the Weather Bureau has retained its traditional role and responsibilities for observing, measuring, recording, reporting and forecasting the weather for the benefit of the public. It also provides special forecasting services of great benefit to aviation, agriculture, shipping and other commercial and industrial groups, as well as other Government interests. In Puerto Rico, weather, for the most part, means rainfall. Our main problem here is rainfall and, occasionally certain special forms of severe weather.

To carry out its tasks, the Weather Bureau maintains nationally about 300 principal stations and about 12,000 part-time observation facilities. In Puerto Rico we maintain the main office at Isla Verde Airport, where a rather complete survey of atmospheric conditions is recorded on a continuous basis. Measurements of wind, humidity, and pressure to altitudes of about 30 kms are made twice a day at 8 a.m. and 8 p.m. We maintain a station of limited facilities in Ponce (city) where rather complete surface observations are made every 3 hours. The military services maintain stations at Ramey AFB in Aguadilla and Roosevelt Roads in Ceiba, where hourly observations are recorded. In cooperation with Caribair

Airlines we obtain hourly observations during the daylight hours at Mercedita Airport in Ponce and Mayaguez Airport. In addition, and most important for the study of rainfall, we maintain an association of scores of cooperative observers, a network of about 100 stations throughout the islands, which keep records of daily rainfall amounts and in some of them daily temperatures. Evaporation and associated wind records are kept at a few locations in the island. Rather complete records have been kept in Puerto Rico since 1900.

All of these records are collected and summarized and are for the most part available in our Climatology Section in San Juan. Those that are not immediately available there can be obtained in one form or another from the national repository at the National Weather Records Center in Asheville North Carolina. You are no doubt familiar with the various weekly, monthly, annual and other long-term summaries that are routinely prepared and published.

All of this information provides an excellent backbone for the study of water problems in Puerto Rico.

There are other aspects of ESSA's services in Puerto Rico that can be brought into play in studies of rainfall and water problems. The field of atmospheric sciences has advanced considerably in the last 25 years. There has been progress in our understanding of the physical and dynamical processes of atmospheric motions and in particular in the operational application of those advances to the problem of weather forecasting. These advancements have been associated with, and largely aided, by the development of three spectacular engineering and electronic achievements: namely, the electronic computer, the radar and the satellite observatories. Presently the field of weather forecasting in the operational center at the National Meteorological Center in Washington has achieved a high degree of automatization and sophistication. A considerable amount of prognostic charts and materials is distributed to the field by facsimile networks. Here in San Juan we are equipped to receive all this material and apply it to the forecasting problem. We have a satisfactory radar installation and have access also to powerful radars maintained by FAA and the military services. These radars could be organized to assist in various types of rainfall studies. We now have facilities to receive data directly from certain satellites passing overhead. Much of this material that could be utilized effectively in studies pertinent to the water problem in Puerto Rico is available in San Juan, other could be obtained from the records libraries in Asheville and Washington. I personally shall be prepared to assist to the extent feasible in whatever studies are undertaken. There are also other scientists in Washington and in other university centers in the United States that I know have a profound interest in rainfall problems in this area. I feel certain that my superiors in ESSA are in the most cooperative disposition to assist in the solution of water problems here.

3. Previous Studies Conducted in Puerto Rico

We in Puerto Rico have been rather fortunate that a great deal of experimentation has been done right here, using Puerto Rico and its vicinity as an experimental platform. In addition to studies on rain making there have been numerous studies that have contributed greatly to the knowledge of rainfall processes in the tropics. A now classical expeditional study was conducted around 1946 in the vicinity of Puerto Rico by a group of scientists from the Woods Hole Oceanographic Institution. Professor Joanne Simpson, then at the Woods Hole Oceanographic Institution, brought expeditions here several times during the 1950 decade in studies that contributed considerably to our understanding of rainfall processes in this area. The result of these studies are available in the scientific literature. Professor Herbert Riehl, previously at the University of Chicago and now at Colorado State University, has written several papers on the subject and is author of an excellent book on tropical meteorology, where observations from Puerto Rico are used extensively.

The U. S. Army conducted an extensive observational program around 1960, which provides hourly observations of several parameters for a period of one or two years at 6-7 localities in the island. The U. S. Weather Bureau research aircraft have collected data around here numerous times.

In the specific field of rain making in Puerto Rico, some very important experiments have been carried out here. As you know, the modern era in cloud seeding was initiated by experiments by a group under Dr. Irving Langmuir in 1947. This original group of Dr. Langmuir's came to Aguadilla sometime in 1947 or 1948. The actual date and the details and results of their work are now uncertain. Since then several other groups have worked here. There was a large group from the University of Chicago which made important experiments out of Ramey AFB around 1953 and 1954.

Commercial groups, in particular that of Dr. Wallace Howell, have worked in Puerto Rico Several times, the last time was in May-June 1965. The Puerto Rico Water Resources Authority has sponsored some work and actually carried out some.

Recently we have had experiments by Project Stormfury, a project sponsored by the Weather Bureau, assisted by the military services, particularly the U. S. Navy. The experiments have been directed to stimulation of individual cumulus clouds and to hurricanes. Whether we deal with an individual cumulus cloud or with hurricanes the idea is essentially the same, it is an attempt to modify convective processes artificially. Experiments were carried out in 1961, 1963, and in July and September 1965. Some of the results of the earlier experiments have been published; the ones for 1965 have not appeared yet.

My main purpose in mentioning this is to point out that there is a considerable library of previous studies, whcih should provide a starting point or base upon which to plan for the future.

4. Present Status of Artificial Rain Stimulation

While on the subject of artificial rain stimulation, it may be of interest

to this group to mention that this subject is being widely discussed now and the picture looks quite different than it did six months ago. This is due to the appearance of two separate reports on the subject prepared by highly responsible and influential scientific committees, one sponsored by the National Academy of Sciences and National Research Council and the other by the National Science Foundation.

These committees undertook the task of evaluating the present status of the various facets of weather modification and to make recommendations for future action. I would like to quote a few statements from those reports. The committee of the National Academy of Science states the following: "There is increasing but still somewhat ambiguous statistical evidence that precipitation from some types of cloud and storm systems can be modestly increased or redistributed by seeding techniques. The implications are manifold and of immediate national concern." There are several conclusions in other aspects of weather modification, but one that I personally found very significant is this one: "The dissipation of super-cooled ("cold") fogs and low stratus clouds over limited areas is operationally practicable, as demonstrated by the operational cleanings of airport fogs in Greenland by the U. S. Air Force, in the U.S.S.R., and in the western United States by several airline companies". Note that this statement refers only to super-cooled fogs, that is, fogs in which the water droplets are at temperatures below zero. In the case of fogs at temperatures above zero the situation is different. This statement is interesting because it is a flat statement that something positive has been accomplished in at least one facet of weather modification, and coming from such a committee it has added significance. There are also other encouraging conclusions in this report.

The report for the National Science Foundation, after taking note of the conclusion just quoted from the NAS report goes on to say the following, "Present indications, if taken at face value, are that local precipitation can be increased in many situations in the order of 10% by seeding. These positive results are obtained in cases where rain would have fallen anyway without seeding; there is no evidence that seeding can induce rain to fall when normally there would be none. Thus, seeding is of limited value in relieving drought situations".

I would like to emphasize that the question of rain making, as it interests us in Puerto Rico, is just as controversial now as it was in the past and the evidence pro or con is just as inconclusive as it ever was. You have noticed that the statements of these Committees are somewhat guarded and carefully phrased. What I personally consider to be the significant implication of these statements is that responsible scientific groups are now on record as stating that there is something to rain making and that we should be nationally concerned. The most important result is that currently there is considerable thinking and discussion on the subject among govennment agencies. Specific recommendations have been made to the

effect that increased resources should be allocated to pursue this program vigorously in the next decade, that specific national policy be established and that the increased financial support be adequately administered. There are also recommendations of specific lines of research that should be pursued. The subject is now being discussed in Congress, where there are already specific measures under study. I visualize that some national policy will be defined and, most important, that increased funding most probably will be available in the near future.

As I said before, Puerto Rico has been a popular platform for study and experimentation in the past and I think there will be more of it in the future. Unquestionable, this Water Resources Research Center here in Mayaguez is in an excellent position to participate, stimulate, and play a significant role in the future research efforts in all aspects of rainfall processes.

## 5. Fundamental Principles in Rainfall Production

The problem of water in Puerto Rico, its hydrological aspects, distribution, and the possible role of artificial insemination in attempting to solve the existing problems, can be best understood by review of the physical and meteorological processes that determine how and why we get the share of rainfall that we get. In studying why we don't get rainfall when and where we need it, and what we can do about it, it is a good policy to look first at the question of how we normally get the one that we get.

In the approach to this problem, I thought it advisable to discuss the fundamental aspects of rain production, even though the principles may be well known to most of you.

The production of rainfall in the atmosphere, no matter the place, time or circumstances, involves three main processes: ascent of air, condensation of the water vapor, always present in the atmosphere, into liquid water drops to form clouds and growth of the water droplets into bigger drops so that when they are big enough they fall by gravity as rain.

Puerto Rico is located in the tropical belt, a region of prevailing easterly flow. The tropical easterly current, known also as the trade winds, is one of great persistence and high moisture content, since the region is essentially oceanic. The moisture content of air in Puerto Rico is generally as high as found anywhere else on earth, even in winter which is the driest season. The main producing mechanisms are typical of those that prevail in tropical islands of maritime influence. Lack of moisture is not a problem.

As I mentioned before, the three main phases of the rainfall cycle are air ascent, condensation and drop growth. Let me cover first the condensation and drop-growth phases. The study of these two phases falls under the branch of meteorology known as cloud physics. The processes involved are strictly physical and are determined by the physical properties of water. It is also in this phase of condensation and drop-growth that artificial insemination or cloud seeding is supposed to operate.

When air ascends in the atmosphere it decreases its temperature steadily with elevation and a temperature may be reached so that the moisture in the air is then enough for the air to become saturated. Any additional moisture present would then condense into minute droplets of liquid water to form clouds. The elevation at which the ascending air current reaches saturation, or the base of the cloud, is located in Puerto Rico and vicinity around 2500 feet. The elevation to which the top of clouds may reach varies with the strength of the ascending current. Clouds in the tropics are mostly of the cumulus type. The large cumulonimbus reach to as much as 50,000 feet. In order for condensation to occur it is necessary that there be a so called "nucleus" upon which the cloud droplet begins to grow. This nucleus could be any kind of particle, like dust or other substances always present in the atmosphere, like salt particles, which are abundant in maritime regions. Salt, as you all know, has a high affinity for water and is effective as a condensation nucleus and also in the growth process. One technique that has been applied in cloud seeding is to spray the regions near the base of the clouds with pulverized salt.

The temperature of the cloud mass is an important consideration in the rain producing process. In the area of Puerto Rico, cloud masses at altitudes below 15,000 feet, approximately, have temperatures above zero degrees centigrade; above 15,000 feet the temperature is below zero. When a cloud mass penetrates above the freezing level the water droplets, as a rule, do not crystallize immediately into ice, but water drops continue to exist in the liquid phase even though the temperature is below zero. These are referred to as supercooled cloud-drops.

There are several hypotheses proposed to account for drop-growth: coalescence or merging of small drops to form bigger ones; temperature differences between neighboring drops and the presence side by side of ice crystals and water drops. The most accepted hypothesis is the one involving the presence of ice crystals in the cloud. Artificial ways have been developed to accelerate the crystallization of supercooled cloud drops: one is by cooling the cloud mass to temperatures around -40°C, which would cause spontaneous crystallization; the other is by addition of reagents which induce crystallization. Silver iodide is one such substance, which has been found to be the most efficient. Silver iodide would generally induce crystallization at temperatures around -5 to -10°C. Such temperatures are found in Puerto Rico at altitudes around 20-25,000 feet. Also, when the supercooled drops go to the ice phase, there is a release of heat, which gives additional buoyancy to the cloud mass. This is the physical reasoning for use of dry ice and silver iodide for artificial cloud seeding. They are supposed to induce crystallization of supercooled droplets. The presence of ice crystals in the cloud would then induce growth of the drops to accelerate the rainfall stage.

We should also take note of the fact that there are considerable clouds at altitudes below 15,000 feet, at temperatures above zero, in the vicinity of Puerto Rico, and elsewhere, which also precipitate. We refer to these

as "warm clouds". The physical process which leads to drop growth and rain in warm clouds has not been established with certainty. Growth by coalescence is the generally accepted one, but coalescence is supposedly not very effective. One method used to stimulate rain in warm clouds is by spraying the top of the cloud with water itself. It is important to note that silver iodide and dry ice are supposed to operate only in cloud masses at below freezing temperatures; if they stimulate any rain in warm clouds, the physical process is presently unknown.

It is generally accepted that clouds that produce significant rainfall in Puerto Rico and elsewhere in the tropics extend well above the freezing level. Clouds that extend to freezing heights in Puerto Rico probably would produce rain anyway by natural processes. That is essentially why it is claimed that cloud seeding may increase natural rain in situations in which it would probably rain anyway, but would not produce rain in low clouds which would not rain out by natural processes.

## 6. Rain-producing Factors in Puerto Rico

As I mentioned before, the initial, and also most important, phase of the rain producing mechanism is ascent of air. I would like to discuss this question in some detail because it is this one aspect that generally determines the rain characteristics of a given place.

Ascent of air can be produced by several ways; mechanical lifting of air forced by an obstacle, such as a mountain range (this produces what is known as orographic rain); ascent of warm currents or convection; and ascent due to horizontal convergence.

Orography is an important effect in the formation and distribution of rainfall in Puerto Rico. Thermal currents or convection is another important factor, both over the ocean in the vicinity and over land. The land mass introduces a significant heat source due to the rapid heating of the land. In addition to the lifting effect of mountains, there is also the fact that mountains introduce a heat source at their tops, high above the surface. Thus temperature plays a significant role. This is the main factor why in Puerto Rico, and in the tropical regions in general, rainfall is maximum in the summer and is maximum in the afternoons.

Ascent in the atmosphere is produced also by horizontal convergence of air currents. Convergence can be produced by bringing air currents against each other or by differences in wind speed along a current or both. Where we have convergence we get ascent and, as a rule, bad weather. Conversely divergence is associated with descending currents and good weather. One interesting example of local convergence is found here in Mayaguez. In the afternoons a current from water to land is created, the so-called sea breeze, which blows from west to east. This westerly current comes head-on against the prevailing easterly current and produces a line of convergence which contributes to the rainfall here. Mayaguez has 76 inches a year, more than many stations in the interior.

Convergence in the atmosphere is produced also in association with large scale circulation systems, what we refer to as perturbations or synoptic systems. These are organized systems of several 1000 kilometers in size. Some popular names for these are frontal zones, cyclones, hurricanes, easterly waves, troughs, etc. These are the really important agents in producing rain. It can be easily demonstrated that most of the rain, in the order of 70-80% of the rain in Puerto Rico and everywhere else on earth, comes in association with synoptic perturbations. Orography, convection, local convergence like that of the sea breeze in Mayaguez, are additive factors that contribute to rain production, but by themselves do not produce much. One can easily visualize that. For example, in the dry summer of 1964, the temperature was as high as ever, the orographic effects were present, the easterly current was there, the sea breeze circulation developed as usual, but we had practically no rain. Something was lacking, and it was the large scale perturbations.

The annual variations in rainfall in Puerto Rico are essentaally a result of the annual march of the sun, but the important effect is not just the increase in temperature as such. The important effect comes about from the changes in circulation observed over the western hemisphere region. With the coming of summer and the warming of the oceanic and continental masses, there is a retreat of the polar front northward; the equatorial low pressure zone is displaced northward to the north coast of South America and the tropical trade easterly current becomes highly unstable. The warming of the ocean brings an increase in the heat flux from ocean to atmosphere, which increases the convection and thermal instability of the air mass. Perturbations which we called easterly waves are generated and move westward across the Caribbean Sea with a frequency of one every 4-5 days. Extensive weather zones are associated with these systems. In the high troposphere, cyclonic systems develop that are also displaced westward. These are the systems mostly responsible for the precipitation. Occasionally, the perturbations may intensify to tropical cyclones or hurricane strength.

As a rule, weather in Puerto Rico comes from the east in summer and from the northwest in winter. Weather producing systems during summer originate in the tropical easterlies and come from the east. In winter there is a general stabilization of the easterly current and of the air mass. The equatorial systems are displaced southward and perturbations in the easterlies, both in the lower and upper troposphere, are completely suppressed. Practically no rainfall in Puerto Rico in the months from December to April can be attributed to tropical perturbations. Instead, the polar air masses and other circulation systems of middle latitudes are displaced southward toward the tropics. Cold air masses move from the continental U. S. southeastward and often penetrate into the Antilles causing increased cloudiness and weather; a drop in temperature of a few degrees and sometimes quite strong winds from the northeast. Old timers refer to these systems as "nortes". In the high troposphere, at altitudes of 40,000 feet, strong westerly currents prevail that occasionally contribute also to low level convergence and weather. Those are the types of perturbation that produces rainfall in winter, but the rainfall produced is not as plentiful as that of summer.

One interesting aspect of the winter regime is a coastal effect produced by ENE currents along the north coast of Puerto Rico, which produces a line of weather right over the coastal area. This coastal weather is most frequent at night. People living along the north coast are familiar with it. This is reflected in the statistics and the mean rainfall in the north coastal sector shows significant precipitation in winter. About one third of the annual total in the north coastal sector falls from December to April; a proportion higher than for other sectors of the island. On the other hand, the south coastal sector receives very little rain in winter.

7. Distribution of Rainfall in Puerto Rico

For the reasons explained above, Puerto Rico receives the majority of its rainfall in summer. Close to two thirds of the rain falls in the period from May to November. The rainiest months throughout most of the island are May and September, which contribute, between the two, about one fourth of the total annual rainfall. The dry period covers from December to April.

The annual totals vary from about 160 inches per year in El Yunque to about 35 inches in the south coastal sector. The mountainous section in the central and west portions of the island receive from 80 to 100 inches; the north and east coastal sectors receive around 60 inches and the western coastal sector receives close to 80 inches (see attached figures). The differences between different sectors of the island can be explained by the orographic effects and the local circulations mentioned before. One important aspect of the mountain effect is that while it may act to increase the rainfall in the windward slopes, it also produces a decrease in the leeward side. That in part explains the relatively little rain received in the south coastal sector.

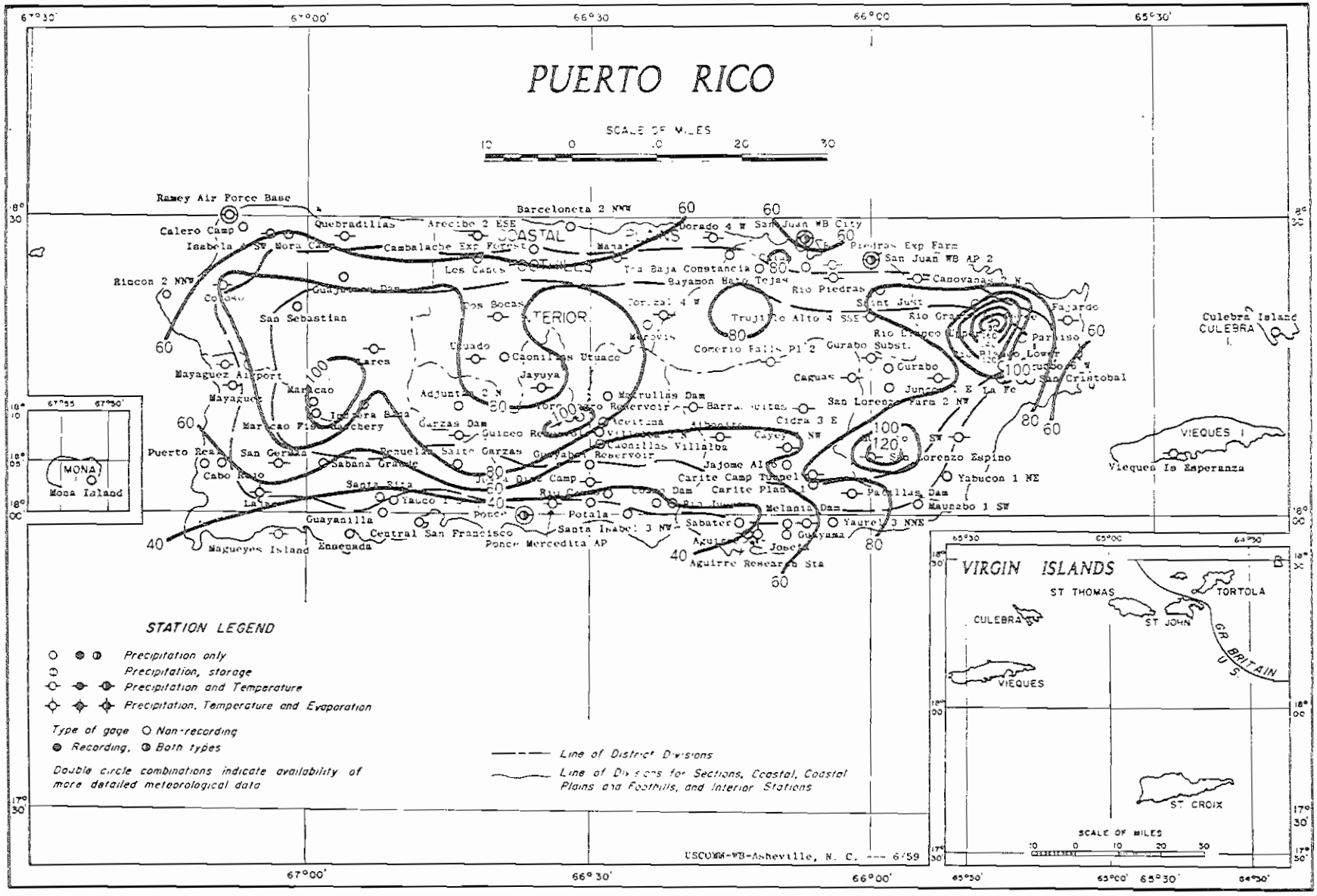
Serious abnormalities in the rainfall in Puerto Rico, like the droughts of 1964, are the result of corresponding abnormaliies in the circulation over extensive areas extending very far from Puerto Rico, which may even be of hemispheric nature. Usually they are manifested in smaller frequencies of synoptic perturbations, or in displacements of the normal track to areas far to the north or to the south of Puerto Rico. As you all know, sometimes we have many hurricanes, sometimes we have few. Sometimes they tend to move close to the Antilles, sometimes they pass far to the north. This is all part of the same story. There is nothing that we can do about it, except study the atmospheric patterns and understand what goes on and why. For that we need to operate over large continental and oceanic areas, with the aid of electronic computers. With adequate study, I visualize that it might be possible to detect trends well before the changes occur and that predictions with some skill could be made a few months in advance That is, we may be able to determine in the spring months the chances that rainfall in the following summer is going to be above or below normal.

A great deal is known already and long-range forecasts a month in advance are already being made over the United States and other sections of the northern hemisphere. But there is still much research work that needs to be done.

The problem can also be attacked by purely statistical methods. With a long period of record, one can apply statistical theory to study and interpret the interannual or seasonal variations and determine the probability of occurrence of particular situations.

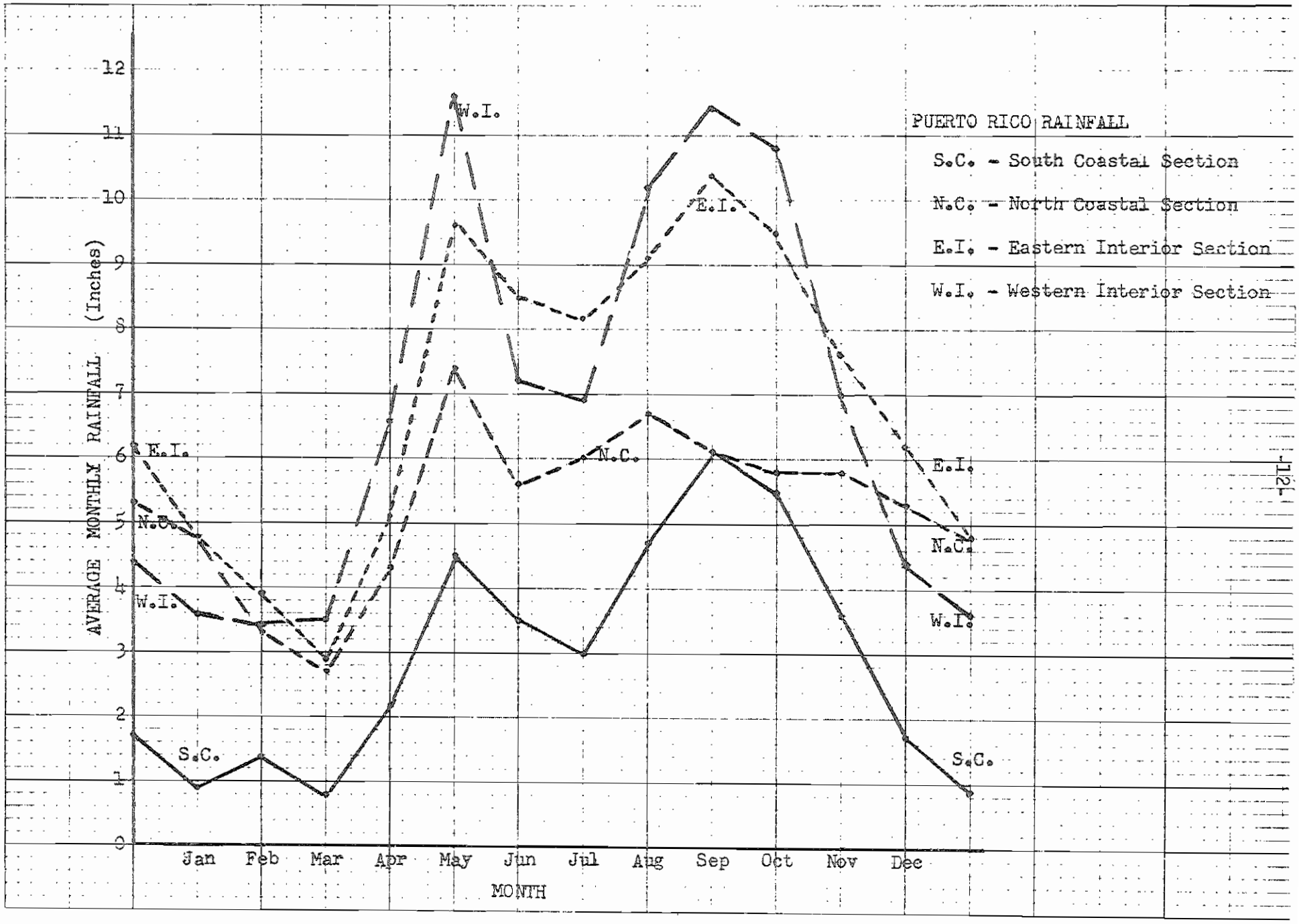
In closing, I would like to mention that there are many peculiarities of the distribution of rainfall in the island, that require further study and understanding. We can study the type and frequency of systems that bring more rainfall to particular localities. We should also continue to follow advances in the field of artificial stimulation. So far, the results are not too encouraging because the methods that seem to operate do so only when mother nature is ready and willing to produce rain anyway. But something may turn up in the future.

# MEAN ANNUAL PRECIPITATION, INCHES




Based on period 1931-55

Isolines are drawn through points of approximately equal value. Caution should be used in interpolating on these maps, particularly in mountainous areas.


PUERTO RICO RAINFALL
S.C. - South Coastal Section
N.C. - North Coastal Section
E.I. - Eastern Interior Section
W.I. - Western Interior Section
AVERAGE MONTHLY RAINFALL (Inches)
0
1
2
3
4
5
6
7
8
9
10
11
12
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
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MONTH
W.I.
E.I.
N.C.
S.C.