RAINFALL AMOUNT IN SAUDI ARABIA AND A TECHNIQUE TO INCREASE THE RAINFALL BY CLOUD SEEDING

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الخلاصـة :

تلخص هذه الورقة قياسات كميات الأمطار في المملكة العربية السعودية، والتي تم جمعها خلال (٢٣) عاماً (١٩٧٠م – ١٩٩٢م) من (٢٦) محطة أرصاد جوية: أظهرت التحقيقات أن المملكة تقع بين الأقاليم الجافة وشبه الجافة. وأن الفرق الوحيد بين هذين الإقليمين هو كمية الأمطار التي تهطل عليهما، وأظهرت التحليلات أن الأمطار في منطقة عسير قد نقصت حيث إنّ هذه المنطقة هطلت عليها (١٥٠) ملم / سنة في عام ١٩٨٧م مقارنة مع معدل هطولها في السنوات السابقة والبالغة (٢٥٠) ملم / سنة.

إن الهدف الرئيس لهذا البحث هو زيادة معدل هطول الأمطار في المملكة وخاصة في منطقة عسير باستخدام تقنية استمطار السحب، وسبب اختيار الدراسة لمنطقة عسير أنها جبلية ولها تضاريس جغرافية فريدة تجعلها الأكثر احتمالاً لإجراء الدراسة عليها.

لقد أظهرت نتائج الدراسة الأولية أنه يمكن زيادة كمية الأمطار من (١٠٪ – ٢٠٪) باستخدام استمطار السحب. لكن يجب إجراء المزيد من الأبحاث على هذا النوع من الدراسات لزيارة الأمطار.

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ABSTRACT

This paper summarizes the rainfall measurements in Saudi Arabia by utilizing the rainfall data covering a 23-year period from 1970 to 1992 collected at 26 Saudi Arabian surface meteorological stations. Investigations showed that Saudi Arabia has two different lands in term of precipitation: semi-arid in the southwest; and arid in the rest. The main difference between these two regions is the amount of rainfall that they receive. The observational analyses also indicated that the amount of annual rainfall measured over the southwestern part of Saudi Arabia, so called Asir region, have substantially decreased in recent years. This mountainous region, known indeed as the rainy region of Saudi Arabia, has received less than 150 mm/year mean annual rainfall since 1987, as compared with a previous value of about 250 mm/year.

Because this study demonstrated the insufficient rainfall across the Kingdom, it is also one of the prime purposes of this paper to briefly discuss the alternative source to increase and enhance the rainfall by cloud seeding techniques in the Kingdom, particularly in the Asir region. This region has a unique geographic setup, so that it has the highest potential to develop orographic and convective clouds throughout the year. The seeding is generally carried out with the intent of adding to the cloud certain particles to start the reaction of raindrop development. It involves many seeding particles and is done with the objective of enhancing the rainfall amount from the cloud. The earlier cloud seeding experiments have indicated that 10 to 20 per cent increase in rainfall may be produced after the seeding. Such a cloud seeding experiment program is needed, and it should be started in the Asir region of Saudi Arabia, in order to meet the demand for water supplies in the near future.

KEY WORDS: meteorology, cloud seeding, cloud and weather modification.

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1. INTRODUCTION

Insufficient rainfall describes the main characteristic of arid climates. The Saudi Arabian (SA) climate includes both arid, in the interior part of SA, and semiarid, along the west coast, Red Sea region, where the prevailing air masses are those that subside in the subtropical highs. The subsidence results in adiabatic warming and low humidity. Even where surface heating produces intense low pressure, the convection layer is shallow because of an upper air inversion whose effects extend the arid conditions well into the latitudes of the trades. This subsidence inversion tends to restrict vertical cloud development especially in the summer months over Saudi Arabia [1]. Thus, the absence of rainfall is a commonly observed feature during summer in Saudi Arabia.

Saudi Arabia is located just above the Inter Tropical Convergence Zone (ITCZ). In this zone pressures are low, winds converge (trade winds), and rising air motion induces cloudiness, and convective rainfall. The weather system of Saudi Arabia is influenced by the extent of two main pressure systems: Siberian High in winter and Tropical Low (Basra Asian Low) in the summer months. The climate is also influenced by Saudi Arabia's unique topography; the mountains in the west bordering the Red Sea and desert land in the interior. An important effect of these western mountains is to induce greater rainfall on their steep slopes. Mountains initiate cumulus convection by causing the moist air to rise. The results are convective cloudiness and precipitation. In this type of cumulus convection in the tropics, the vertical velocity usually attains its maximum at a relatively low level and the value of vertical motion is usually not much higher than 10 m/s, much lower than that in the severe storms in middle latitudes [2].

The main goal of this paper is first, to present the rainfall regime and rainfall measurements for the 26 surface meteorological stations in Saudi Arabia, and, secondly, to discuss and review the cloud seeding technique with a view to enhancing the rainfall amount in Saudi Arabia, particularly over the Asir region. The Saudi Arabian Meteorology and Environmental Protection Administration (MEPA) collects meteorological data routinely. The data used in this research, covering from 1970 till 1992, a total of 23 years, for the 26 meteorological stations were received from MEPA. The data consist of daily values of all the surface meteorological parameters, nevertheless, only the precipitation field was examined in this study.

With the discovery that artificial nuclei could increase ice crystal concentrations in supercooled clouds, cloud seeding experiments began in the late 1940s. Better seeding experiments were conducted in the early 1960s and have continued up until now in various parts of the world [3–7].

2. METHODOLOGY FOR THE DATA ANALYSIS

The precipitation amount at each surface station is examined with respect to its monthly total rainfall amount. Since there is a small amount of precipitation in Saudi Arabia throughout the year, mean monthly total rainfall (MMTR) represents a more useful picture for the precipitation than a daily figure would. From the monthly total rainfall field for the 23 year period, maximum rainfall values for each meteorological station are also analyzed and presented in this study. If the MMTR is less than 20 mm/month, this region is considered as dry during that particular month. However, if the MMTR exceeds more than 20 mm/month, then the region is considered wet for that particular month.

3. RESULTS AND DISCUSSIONS

In general, Saudi Arabian land does not get enough precipitation at any period during the year. Analysis of the 23-year data set in this study revealed that precipitation generally forms during the winter months, especially from November till April. The maximum mean annual rainfall was recorded as 229 mm at the Abha stations during the 23-year period. The second highest value was 209.6 mm at Khamis. The minimum mean annual rainfall values were 20.6, 20.6, and 28.0 mm at Yanbu, Al Wejh, and Sharorah respectively. Comparing these values with some other mean annual rainfall observations around the world illustrates the relative dryness of Saudi Arabia. One of the highest rainfalls in the southwestern part of Saudi Arabia was 382 mm in Khamis in July, 1970. The analysis also showed that the record monthly total rainfall for the station Turaif was about 513 mm in the month of February, 1980. This monthly rainfall amount was recorded in the original raw data set as the summation of daily rainfall values. This value looks somewhat doubtful; therefore, the second highest value of 129.4 mm in April, 1983 may be considered as the record monthly total rainfall value for the station Turaif.

In Figures 1 to 5, the highest monthly total rainfall (HMTR) and mean monthly total rainfall (MMTR) amounts are depicted for the 26 surface stations. Figures 6 and 7 depict the record monthly total and mean annual rainfall amounts and record maximum and minimum temperatures across the Kingdom, respectively. From these figures it can be seen that the southwestern part of Saudi Arabia receives more precipitation than the eastern or central provinces. In the southwest, there is always precipitation throughout the year even though in small amounts, whereas precipitation generally forms during the winter months in the east and central part of Saudi Arabia. For the western stations, the highest mean monthly maximum precipitation is about 67.6 mm/month at station Abha in the month of April. It can be concluded that the stations Taif, Al Baha, Bisha, Sulayel, Khamis, and Gizan define the rainy region of Saudi Arabia, although these stations are still in the tropical zone, but in a mountainous region. The maximum and minimum temperatures in the Asir Region are found to be less than those for desert land, due to its high elevation. The Record Monthly Total Rainfall (RMTR), and the Highest Monthly Mean Total Rainfall (HMMTR), and the mean annual rainfall (ANNUAL) amounts (mm) for the 23-year measurement period are presented in Table 1.

Table 1. Summary of the Rainfall Measurements for the Surface Meteorological Stations in Saudi Arabia. Note that RMTR and HMMTR represent the Record Monthly Total and Highest Mean Monthly Total Rainfall amounts, respectively.

Station ID	Station Name	LAT (°N)	LON (°E)	Annual (mm)	RMTR (mm)	(Occurrence)	HMMTR (mm)	(month)
024	Jeddah	21.5	39.2	40.0	83.0	(Nov-1972)	11.0	(Dec)
030	Makkah	21.5	39.8	85.4	89.2	(Apr-1989)	29.8	(Dec)
036	Taif	21.3	40.4	139.1	159.3	(Nov-1972)	29.5	(Apr)
055	Al Baha	20.1	41.6	120.0	109.6	(Mar-1987)	29.6	(Apr)
062	Sulayel	20.5	45.7	37.8	180.0	(Mar-1974)	17.5	(Mar)
084	Bisha	20.0	42.6	86.3	84.1	(May-1985)	28.2	(Apr)
112	Abha	18.2	42.5	229.8	227.8	(Apr-1990)	67.6	(Apr)
114	Khamis	18.2	42.6	209.6	382.0	(Jul-1970)	39.9	(Jul)
128	Nejran	17.5	44.2	61.7	110.0	(Mar-1974)	23.9	(Mar)
136	Sharorah	17.5	47.1	28.0	46.9	(Apr-1986)	13.7	(Apr)
140	Gizan	16.9	42.5	79.2	107.4	(Mar-1981)	12.6	(Jan)
356	Turaif	31.7	38.7	130.7	513.3	(Feb-1980)	47.7	(Feb)
357	Arar	30.9	41.1	68.2	63.6	(Apr-1988)	12.9	(Mar)
360	Guriat	31.4	37.2	56.5	50.1	(Dec-1985)	14.2	(Dec)
361	Al Jouf	29.9	40.2	41.9	47.9	(Nov-1987)	7.2	(Apr)
362	Rafha	29.6	43.5	97.1	131.1	(Dec-1974)	19.3	(Apr)
373	Gaysumah	28.3	46.1	112.0	164.1	(Dec-1975)	21.8	(Dec)
375	Tabuk	28.3	36.5	43.0	59.3	(Dec-1985)	8.6	(Jan)
394	Hail	27.5	41.7	102.1	104.0	(Nov-1985)	21.5	(Apr)
400	Al Wejh	26.2	36.4	20.6	38.6	(Nov-1986)	7.6	(Dec)
405	Gassim	26.4	43.9	136.7	144.4	(May-1982)	28.9	(Apr)
416	Dhahran	26.3	50.1	81.0	208.5	(Mar-1982)	32.7	(Mar)
420	Al Ahsa	25.2	49.5	65.6	56.3	(Feb-1988)	23.4	(Mar)
430	Medina	24.5	39.6	50.7	79.0	(Apr-1982)	13.6	(Apr)
438	Riyadh	24.6	46.7	79.0	106.6	(Apr-1986)	22.5	(Mar)
439	Yanbu	24.1	38.0	20.6	74.8	(Nov-1991)	11.1	(Nov)

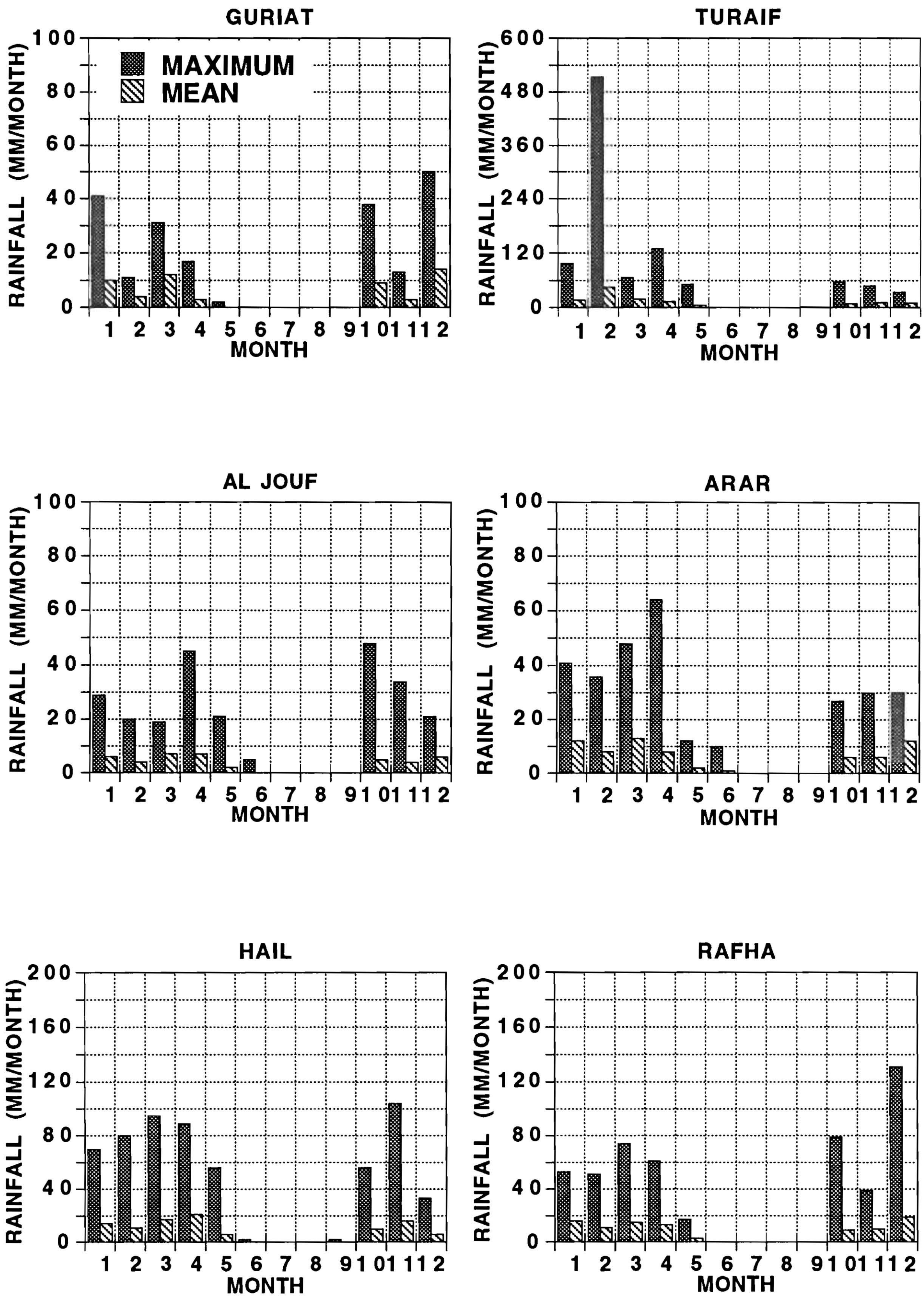

Figure 1. The Highest Monthly Total and Mean Monthly Total Rainfall (mm) for Stations Guriat, Turaif, Al Jouf, Arar, Hail, and Rafha.

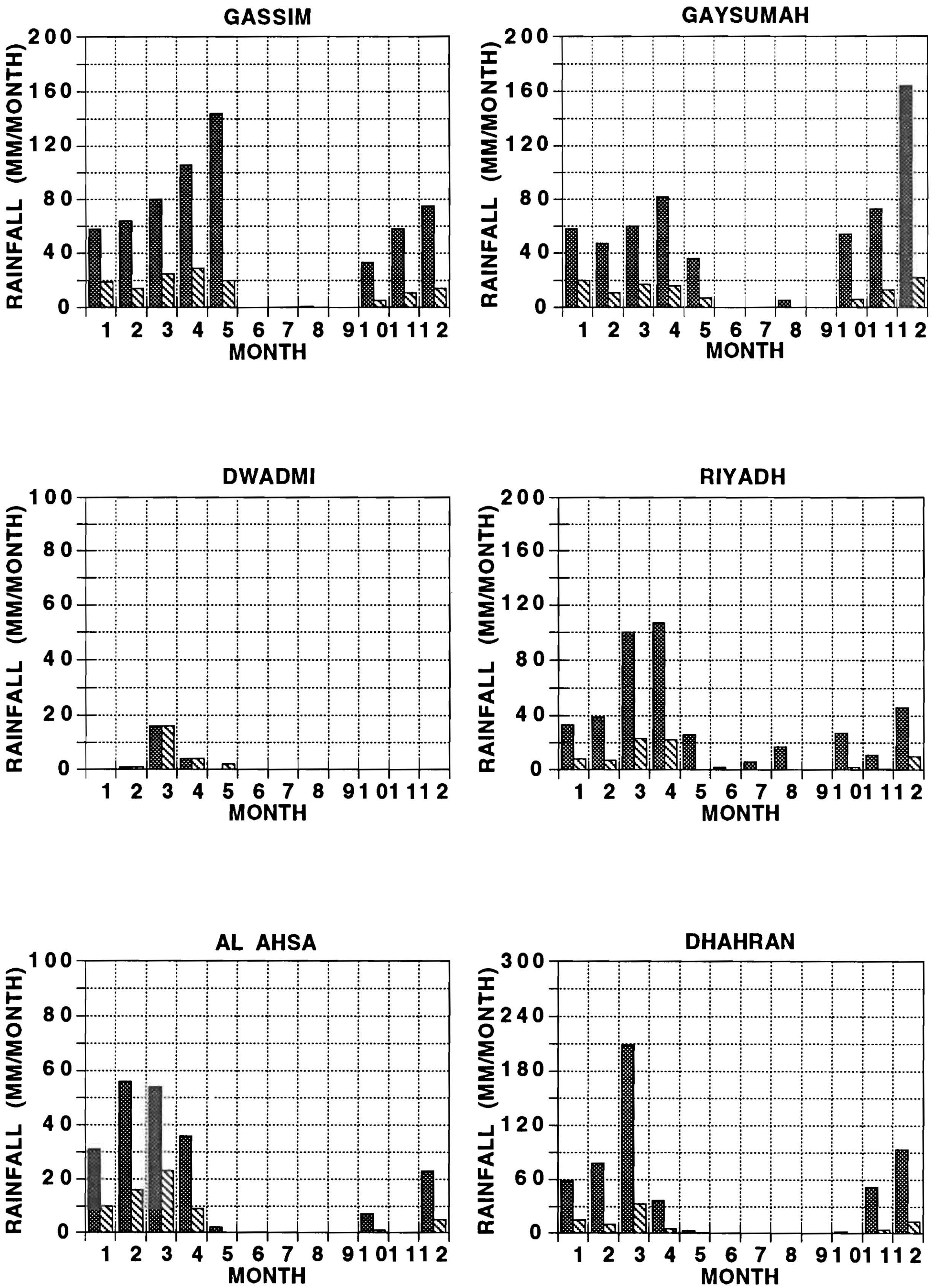

Figure 2. The Highest Monthly Total and Mean Monthly Total Rainfall (mm) for Stations Gassim, Gaysumah, Dwadmi, Riyadh, Al Ahsa, and Dhahran.

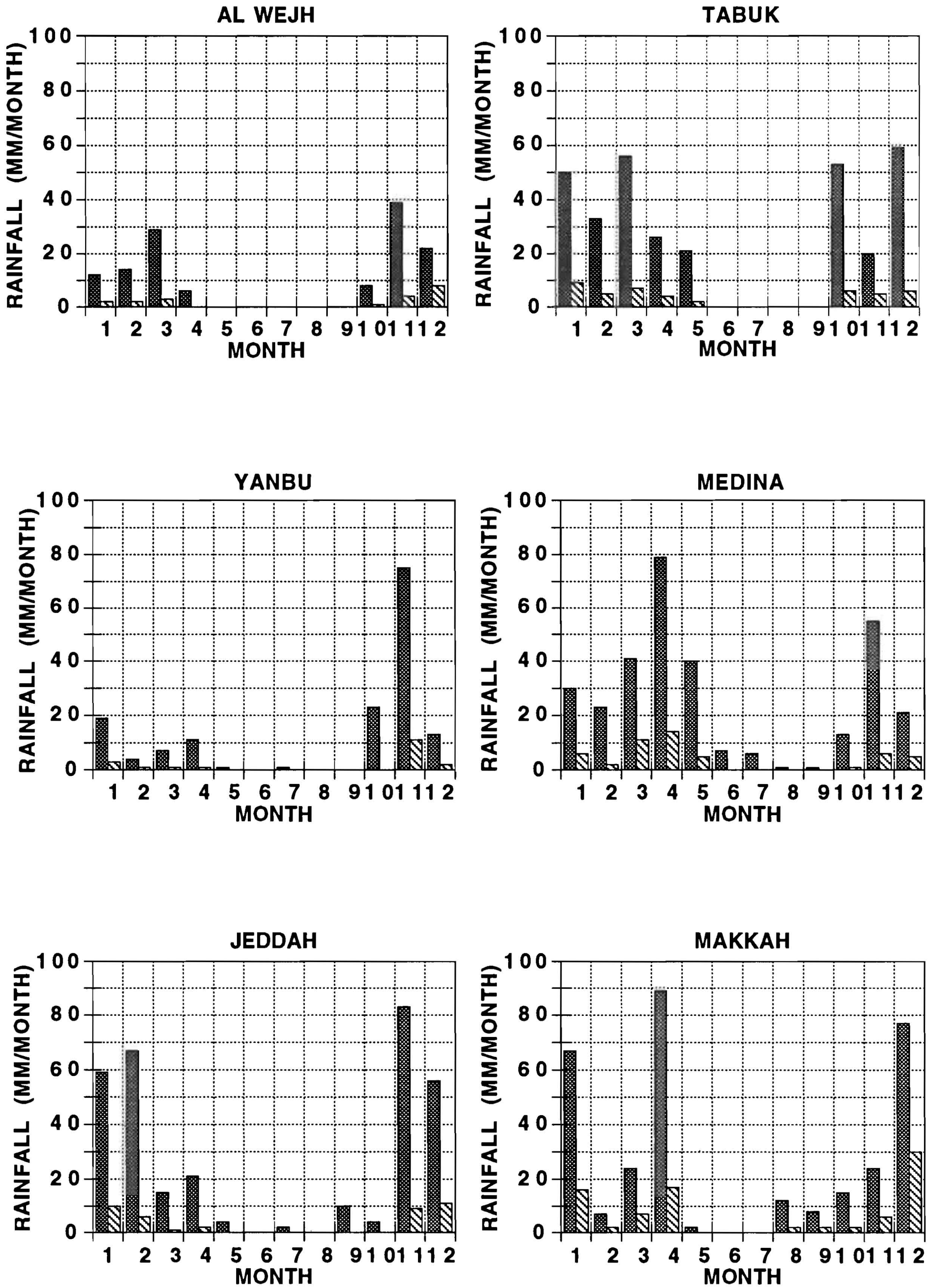

Figure 3. The Highest Monthly Total and Mean Monthly Total Rainfall (mm) for Stations Al Wejh, Tabuk, Yanbu, Medina, Jeddah, and Makkah.

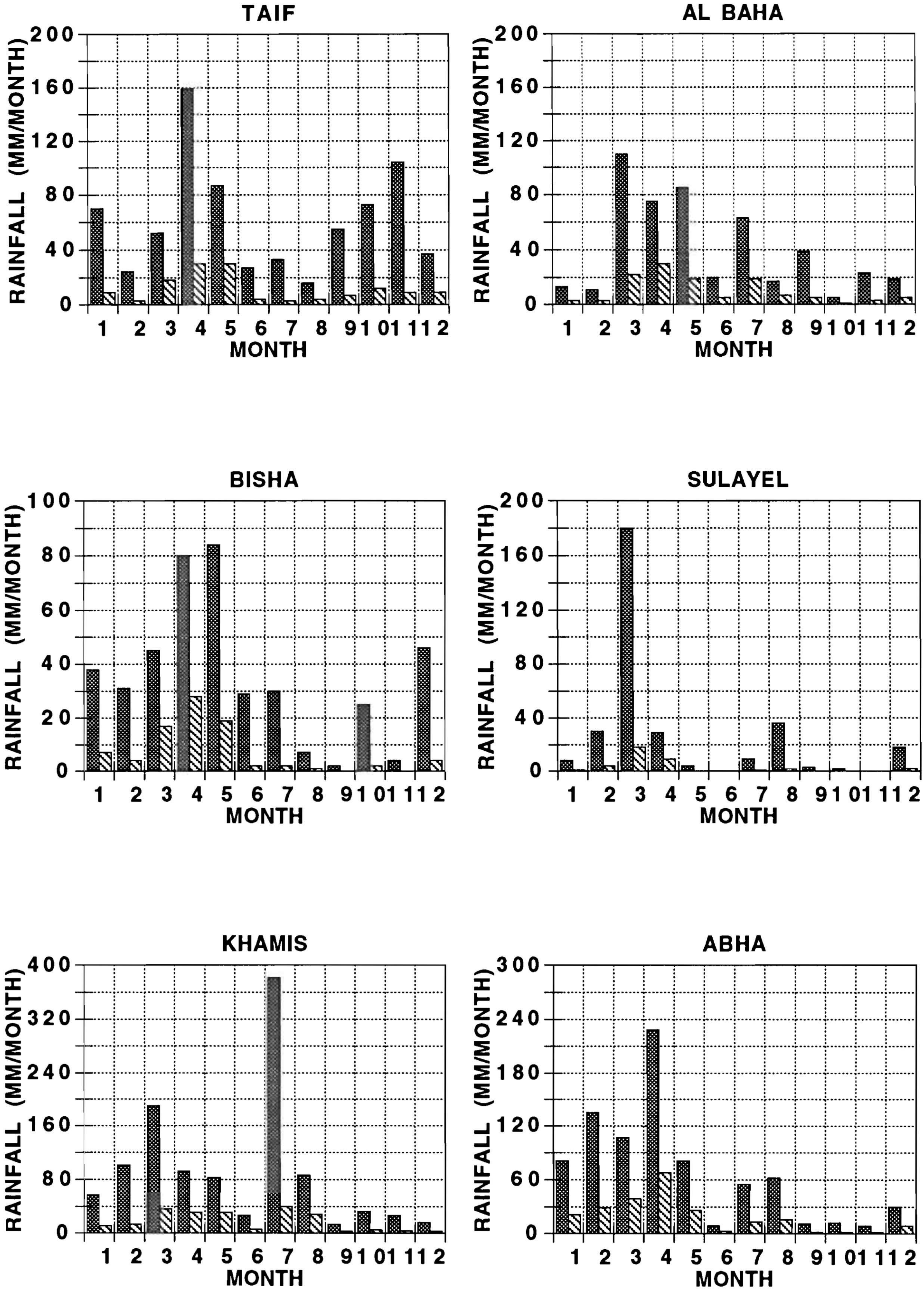

Figure 4. The Highest Monthly Total and Mean Monthly Total Rainfall (mm) for Stations Taif, Al-Baha, Bisha, Sulayel, Khamis, and Abha.

Generally speaking, most of the precipitation of the tropical arid and semiarid regions is of the thunderstorm type associated with strong forced convection which forms due to topography or low level convergence. The precipitation rapidly exceeds the absorptive capacity of the soil and because there is little vegetative cover, the runoff water is great. Thus a relatively small part of the precipitation (rain) is retained as soil moisture. The major flash floods in Saudi Arabia occur in the southwestern mountainous region. The forced convection due to orographic lifting in these mountainous regions triggers heavy rainfall. High intensity storms and steep terrain cause the rapid runoff of rain water. Historical records indicate that several catastrophic floods have happened in Saudi Arabia. Especially noteworthy are the so-called great flood of 1969 in Makkah, and the flood of 1982 in Wadi Al-Dillah, a place which is close to station Abha. Observational studies have also shown that the regions which are close to stations of Abha, Khamis, and Taif may have a high risk of flooding.

In addition, Figures 8 to 11 depict the rainfall amount in recent years over the Asir region, where the precipitation has significantly decreased. Keeping in mind that the stations Taif, Baha, and Abha are in the Asir region, a rainfall amount of almost 250 mm/year decreased to about 100–150 mm/year from 1985 to 1991. Decrease in rainfall may significantly influence the ground and underground water supplies, and agriculture and vegetation as well. With the implementation of rain enhancement, cloud seeding procedures could increase the potential for precipitation over the aforementioned region. Many times in the past, cloud seeding experiments have been successful in the tropical and extra tropical regions. Overall, these studies resulted in about a 10–20 % increase in rainfall under some meteorological and geographical circumstances.

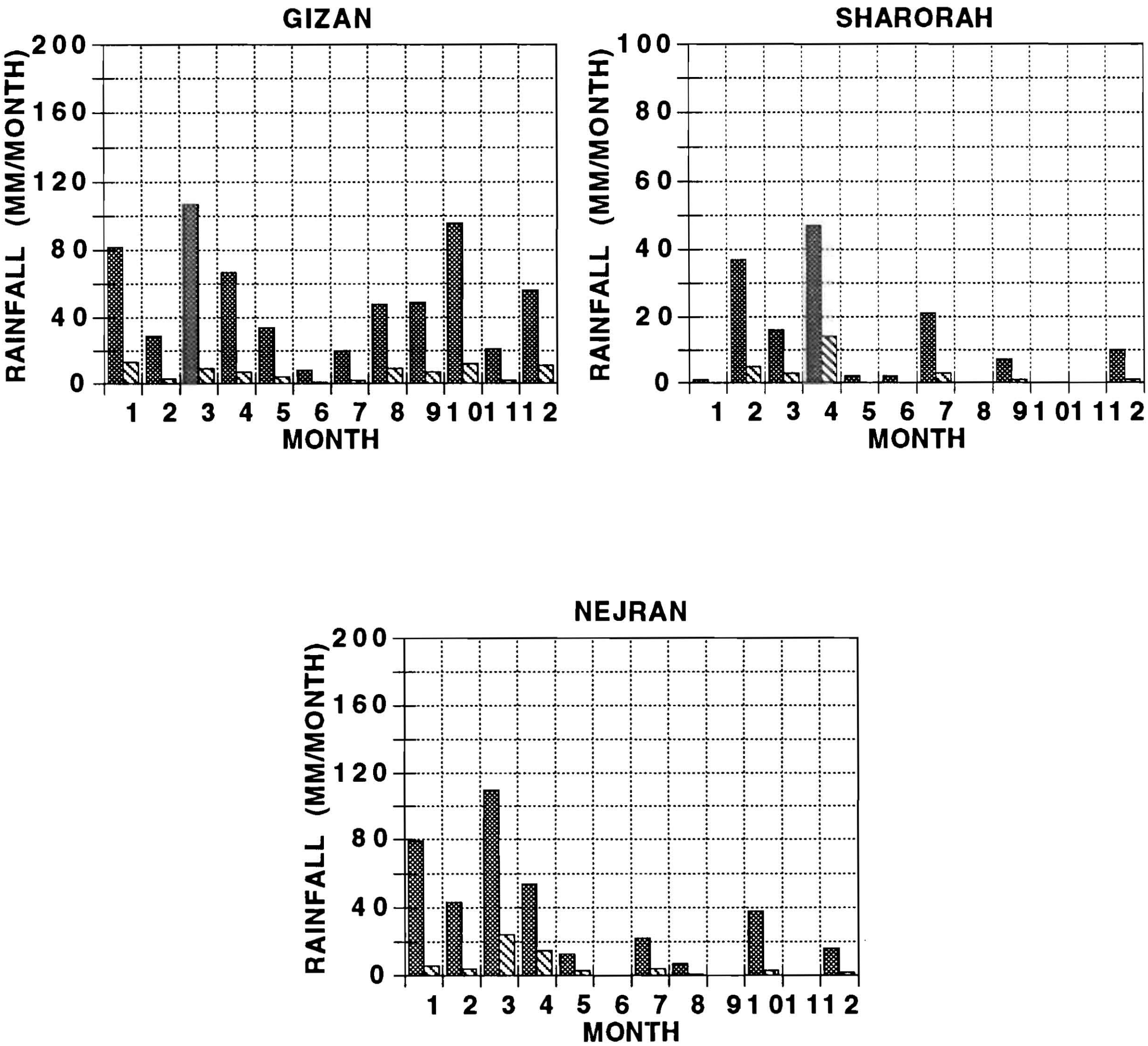

Figure 5. The Highest Monthly Total and Mean Monthly Total Rainfall (mm) for Stations Gizan, Sharorah, and Nejran.

4. CLOUD SEEDING OPERATION

4.1. Theory and Background

Cloud seeding is a conventional technique carried out with the intent of adding to a cloud certain particles that will alter the natural cloud development, in order to start a chain reaction of raindrop development within suitable clouds. Cloud seeding may involve a number of different types of seeding particles, and may be done with the objective of enhancing the rainfall amount from the cloud. The hypothesis behind seeding is based on the observation that some orographic, convective, or stable clouds contain supercooled liquid water, that is inefficiently utilized in the natural precipitation process, can be forced to precipitate.

Cloud seeding is applied from either ground or airborne generators or dispensers, and it can be static or dynamic. The main idea of static seeding is to enhance the precipitation from supercooled clouds by introducing an optimum concentration of ice crystals. The ice crystals can be created by the introduction of ice nuclei (such as AgI) or a coolant (such as dry ice). On the other hand, the main concept of dynamic seeding is to seed a supercooled cloud with large enough quantities of ice nuclei or a coolant to cause rapid glaciation of the cloud. The resultant latent heat release from the vapor deposition growth of ice crystals and freezing of supercooled drops will then increase the buoyancy of a cloud; this will cause the cloud-grow deeper and may increase rainfall on the ground.

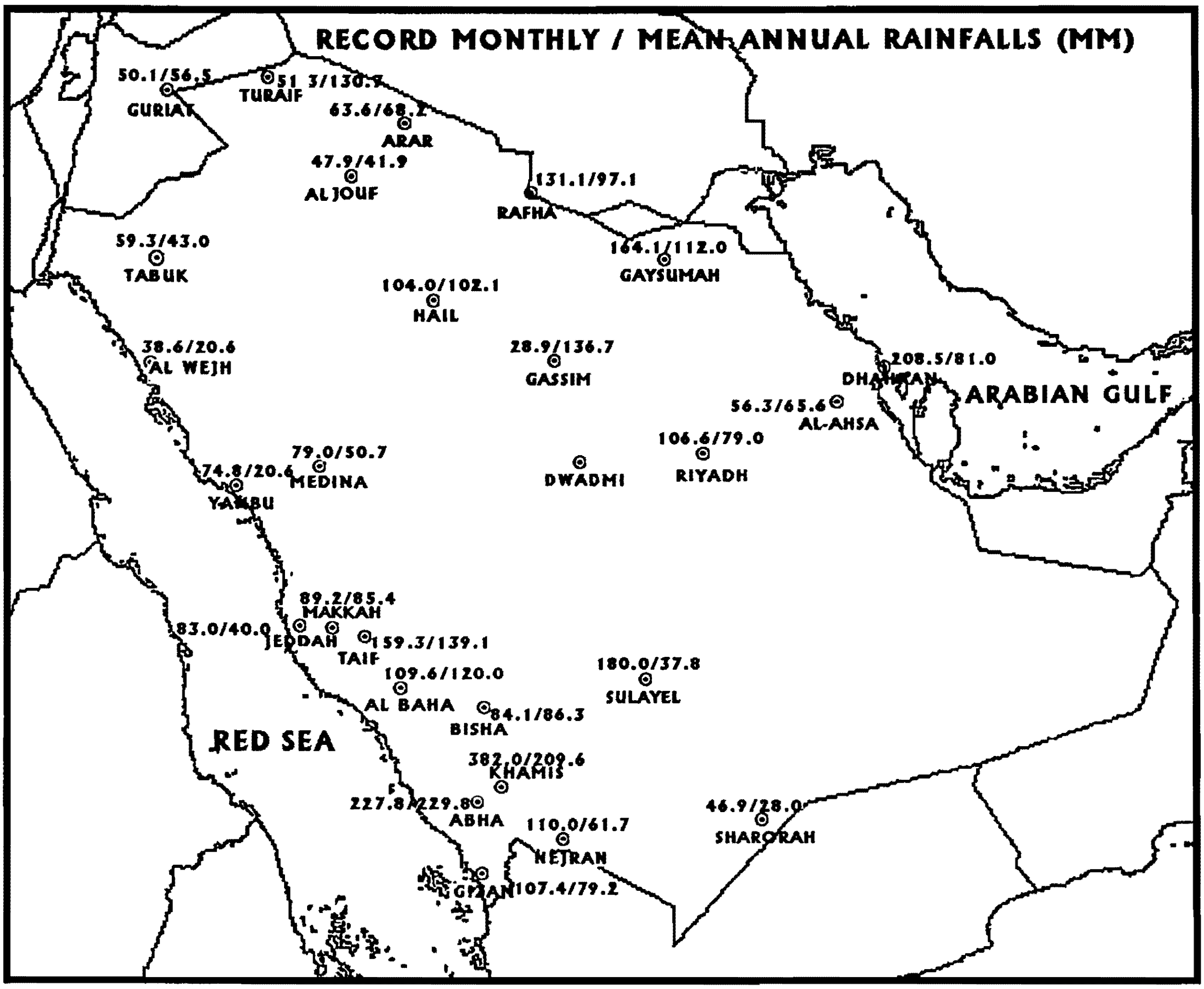

Figure 6. The Record Monthly Rainfall and Climatic Mean Annual Rainfall (mm).

Seeding the cloud with silver iodide (AgI) and sodium iodide (NaI) crystals or solid carbon dioxide (dry ice) from an aircraft initiates the creation of ice crystals, small snowflakes, or rain droplets. Furthermore, the efficiency of seeding strongly depends on the atmospheric wind field, temperature, cloud systems, stability conditions, and storm characteristics, *etc.*

There have been a number of attempts by man to increase the rainfall by lighting of fires, the firing of canons, the production of electric discharge, and water and dust spraying from airplanes. The basic idea here is that suitable clouds may be forced to precipitate by introducing artificial cloud condensation nuclei (CCN) and ice nuclei (IN), also called cloud agents. Cloud droplets form in the atmosphere by condensation on existing particles. The most successful attempts to modify clouds have involved some modification of the population of condensation nuclei on which the droplets form, or of the ice nuclei which are responsible for the appearance of ice. The sources of atmospheric aerosols, which act as condensation nuclei in the atmosphere, includes volcanoes, forest fires, industrial smoke, and other anthropogenic sources. The most natural ice nuclei are insoluble clay particles picked up from the ground by the wind. These nuclei are placed in a supersaturated or supercooled solution to result in precipitation and to overcome the deficiency of condensation nuclei by seeding the clouds with either solid carbon dioxide or silver iodide or water droplets. Cloud and weather modification with these methods not only increases the rainfall but also prevents the formation of excessive rainfall and damaging hailstones when overseeding. In a severe storm environment, seeding conducted just under the inversion layer at the early stage of cloud development, before the convective outbreak, will immediately suppress further cloud and storm development.

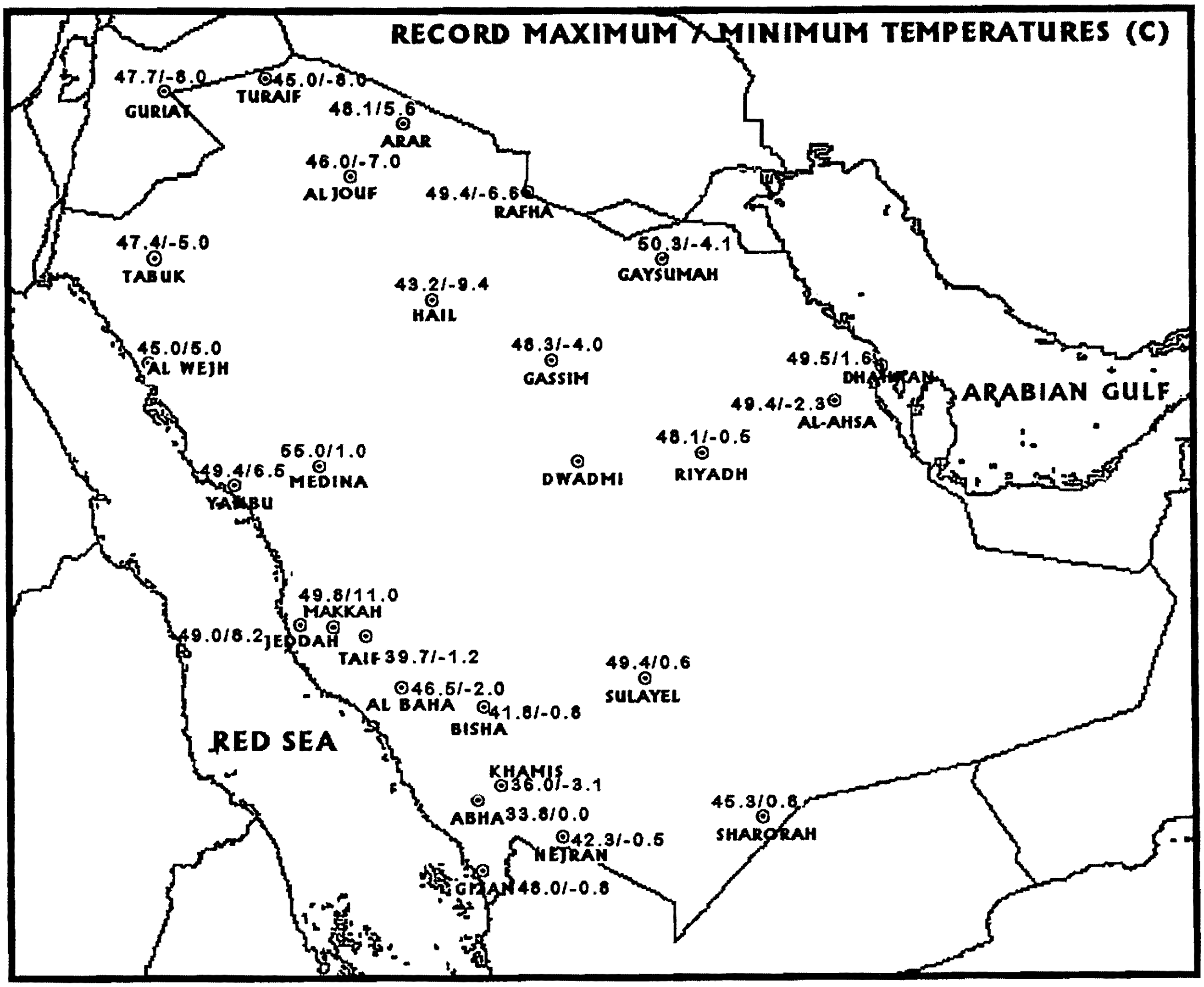

Figure 7. The Record Maximum and Minimum Temperatures in Degree Celcius.

Precipitation enhancement from supercooled clouds and from warm clouds require different methods and applications. Supercooled clouds contain supercooled water and liquid droplets at a temperature colder than 0°C. It has been observed that large amount of supercooled water in such clouds are not converted to precipitation, and can be forced to precipitate by the seeding explained above. On the other hand, warm clouds are those whose cloud tops do not exceed the height of at which freezing tables places. In these clouds, the physical processes involved in the initiation and development of rain are condensation, collision, coalescence, and break-up. Seeding warm clouds is carried out with either a hygroscopic material (*i.e.* artificial CCN) or with small water drops.

4.2. Cloud Seeding Program

Cloud seeding programs generally consist of two main components; rain enhancement experiments, and measurement, modeling, and laboratory investigations. The enhancement experiment includes the actual seeding on a developing convective clouds or orographic clouds like those found in Asir region, and seeding during both day and night. The second component deals with field measurements, meteorological observations, and modeling studies before, during, and after the seeding. Cloud top and base microphysical properties and formation of precipitation are highly dependent on the evalution stage of the cloud. Cloud microphysical properties, such as liquid water content, population of condensation and ice nucleus and their sizes, water droplet size, cloud top and base temperatures, and vertical updraft velocity *etc.*, are measured with a variety of modern instruments such as Doppler radar, liquid water content probe *etc.*, in and around the cloud. This information is useful to establish whether the cloud is growing, or decaying.

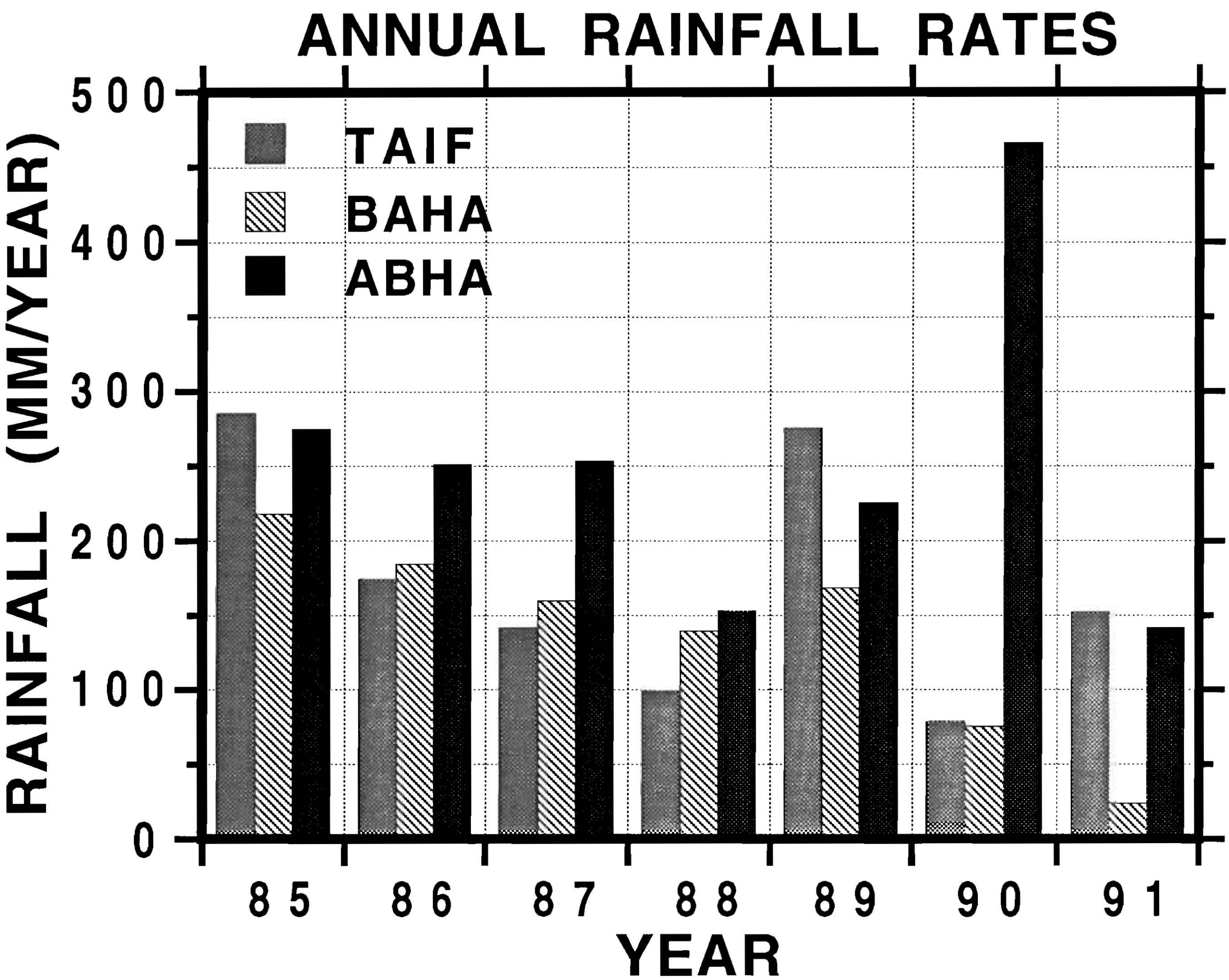

Figure 8. Annual Rainfall Rates for the Stations Taif, Baha, and Abha.

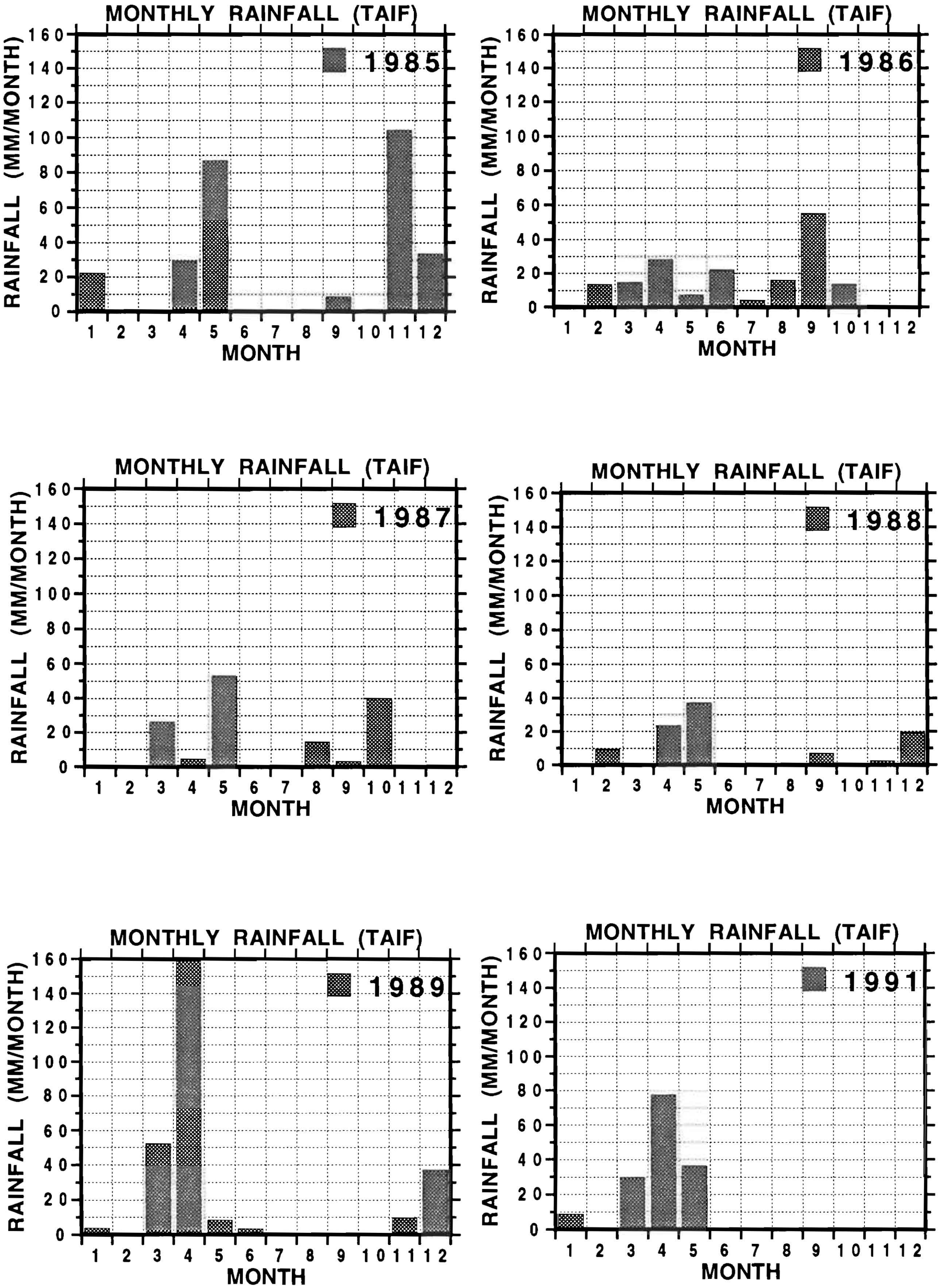

Figure 9. Monthly Rainfall Rates for the Station Taif.

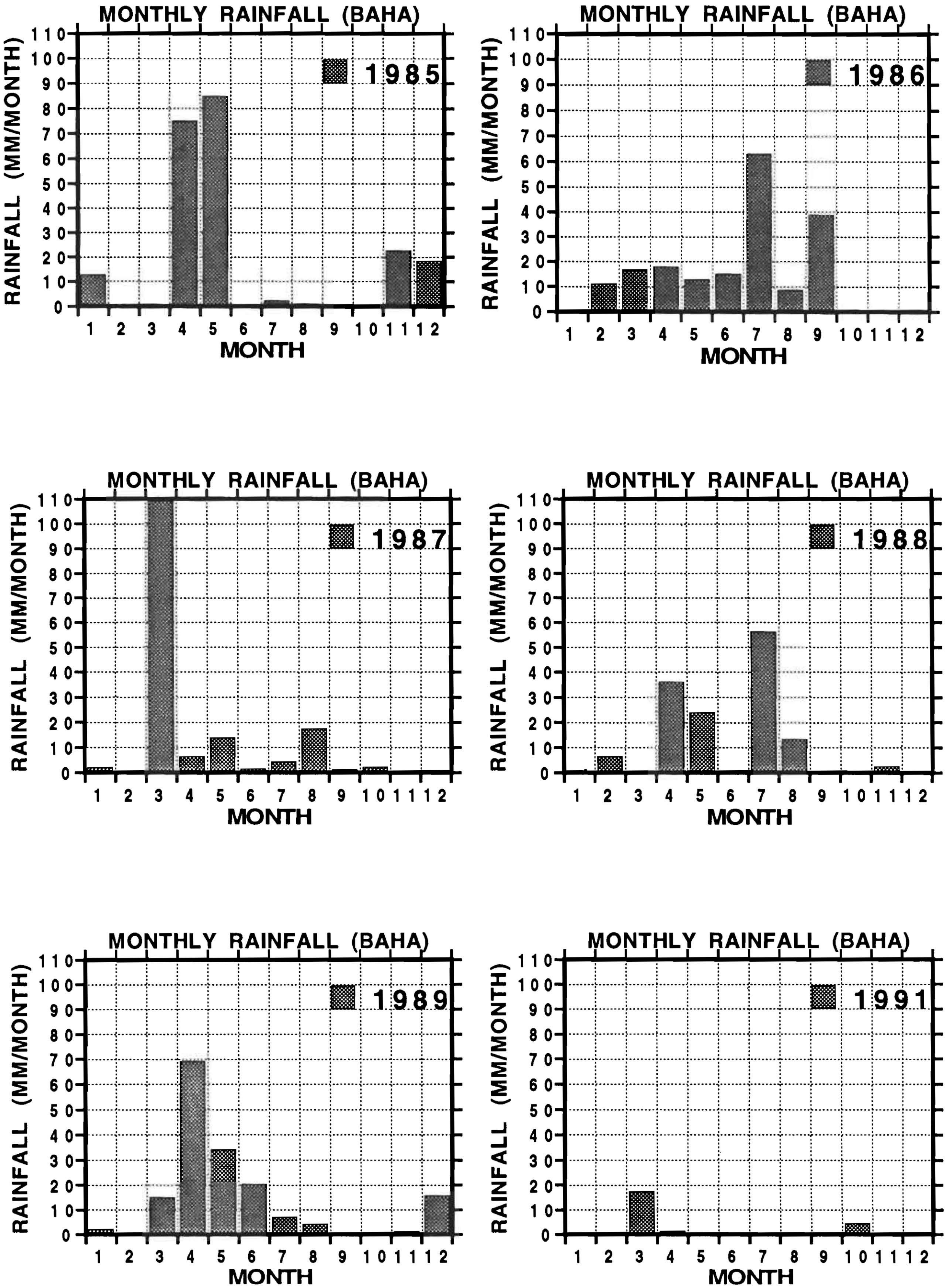

Figure 10. Monthly Rainfall Rates for the Station Baha.

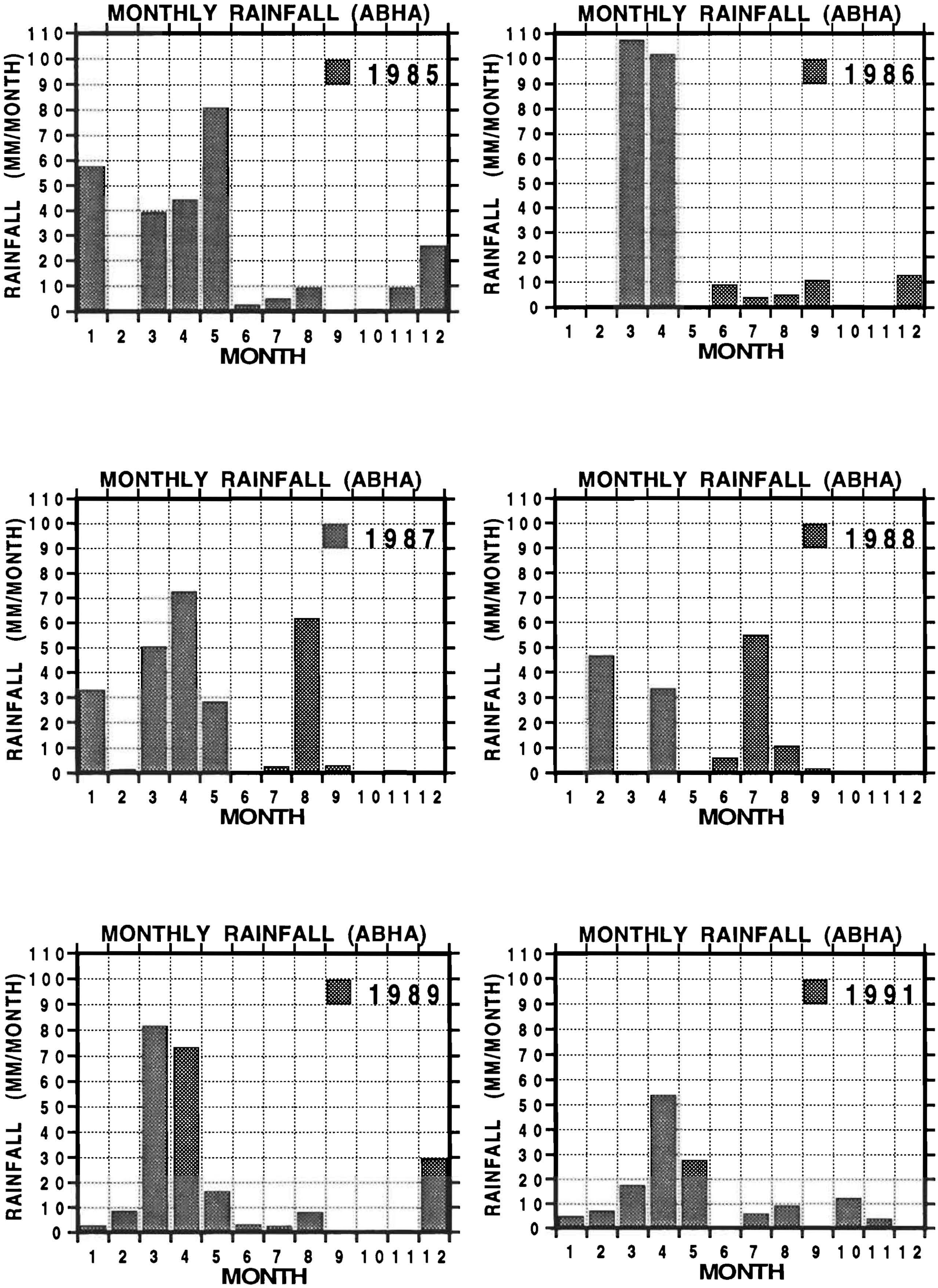

Figure 11. Monthly Rainfall Rates for the Station Abha.

In addition, the cloud top properties that are relevant for determining the precipitation properties are (*a*) cloud top temperature; (*b*) composition of ice or water; and (*c*) effective radius of cloud particles, which could be measured from aircraft or satellite imagery. Rosenfeld and Gutman [8] used Advanced Very High Resolution Radiometer (AVHRR) data to retrieve cloud top properties, and thus to infer whether these clouds were precipitating or not. These inferences were found to be well correlated with actual detection of rainfall using a weather radar. Aircraft and satellite measurements of cloud top properties will help scientists to determine the suitability of clouds.

4.3. Cloud Seeding Programs Around the World

Cloud seeding for rain enhancement has also been sought as a potential way to alleviate the water shortage in the Mediterranean and Middle East region in recent decades. Up until now, three major cloud seeding experiments [9] have indicated that rain enhancement varied strongly with geographical location and meteorological conditions. Rosenfeld and Farbstein [9] also noted that desert dust already seeds the clouds naturally, thus reducing the potential rain enhancement by artificial seeding. Therefore, correct identification of suitable conditions for cloud seeding should be undertaken before seeding.

The cloud seeding on the orographic clouds was also studied by many investigators. Like seeding of convective clouds, seeding of orographic clouds increases the precipitation. Evaluation of orographic cloud seeding projects in the U.S.A. resulted in an increase of rainfall in the target area. Efficiency of orographic cloud seeding depends on liquid water content, the number and size of condensation nuclei, stability of the cloud, cloud top temperature (as low as –30, –40°C), and the seeding rates. Seeding rates of orographic clouds are smaller than those applicable to convective clouds (*i.e.*, up to several hundred grams AgI per hour [10].

The characteristics of clouds, that were included in the High Plains Cooperative Experiment (HIPLEX-1) experiment conducted in Montana, U.S.A. during the summers of 1979 and 1980, are discussed in reference [11]. It was found in this experiment that precipitation development took place 8 minutes after the seeding. F.A. Huff *et al.* [12] analyzed the results of two warm-season seeding projects which took place in Kansas and Oklahoma in 1975–1979. The rainfall enhancement was about 9% in the warm season. The cloud seeding procedure in South Africa in the years 1972 to 1981 was evaluated in reference [13]. In this project, silver iodide was extensively used and 8% to 24% rainfall enhancement were achieved.

The results of seeding experiments conducted in the Central Sierra Nevada of California from 1984 and 1986 are presented in reference [3]. In this experiment, clouds were selected for seeding with either dry ice or silver iodide based on the amount and temporal duration of supercooled liquid water. The precipitation rate increased by 0.1–1.0 mm/hour. Finally, Gagin and Gabriel [14] presented analyses of an experiment conducted in 1969–1975 based on continuous time data from a recording raingage. Cloud seeding by silver iodide was applied in two consecutive experiments. Overall, daily rainfall for all target areas increased by about 15% and 13%, in these two experiments.

4.4. Proposed Seeding Program in the Asir region of Saudi Arabia

During the Spring of 1991, a cloud seeding experiment took place in the Asir region under the joint program between the Department of Atmospheric Science of University of Wyoming, USA and MEPA of Saudi Arabia. The program was short and research flights covered about 12 days. Many of the results were preliminary and initial indications only. During the experiment, the Asir region experienced a period of heavy rainfall in association with large scale disturbances. Two major systems were identified: the mesoscale convective complexes associated with the large scale disturbance and orographic cloudiness (*i.e.*, mountain cumulonimbus, MCb). The cloud base conditions were characterized by temperatures of 15°C and 2°C for the coastal and inland clouds, respectively. The estimate of the enhancement for isolated convective clouds was about 5 mm over the experimental period of February through May.

The long term, rather than short term, cloud seeding program should be conducted under the weather modification research program in the Asir region where the mountain range runs parallel and close to the Red Sea, extending from the southwest corner of the Arabian Peninsula toward over a length of about 800 km. Figure 12 illustrates the topographic view of Saudi Arabia as well as other middle-eastern countries. It is clear in this figure that the mountain in the southwestern part of Saudi Arabia reaches about 3000 km in height. The ultimate objective of this program should be to develop a methodology to identify, in near real time, specific clouds that would produce more rain when seeded in the region. This should open the way to large scale cost effective operations of rain enhancement, that will increase the overall available water resources in the Kingdom. The program should include following features and facilities:

1. Synoptic observations from the standard meteorological network,
2. Raingage network,
3. Rawinsonde upper air observational network,
4. Radar, satellite, and aircraft measurements, and
5. Modeling for numerical simulation.

A mesoscale numerical model as well as a single cloud model with explicit detail microphysics are also to be employed in order to determine the weather pattern, suitable orographic, and convective clouds, timing of the seeding and simulation of processes taking place in and out of the cloud. A large scale application of cloud seeding for augmenting water resources is confounded by the large variability in the suitability of clouds.

Cloud modification has been identified as a potential way to augment rainfall as well as ground water in most of the countries. Similar cloud seeding experiment in order to enhance rainfall with droppable silver iodide (AgI) can be established and carried out for the Asir region and the southwestern part of Saudi Arabia. The main objective of such study should be first to initiate the rain enhancement program at a research level, second to investigate the precipitable and suitable clouds for seeding and their microphysical characteristics and, finally to enhance the rainfall by seeding in the interest region. The specific objectives of carrying out the rain enhancement program in the Asir region can be briefly summarized as follows.

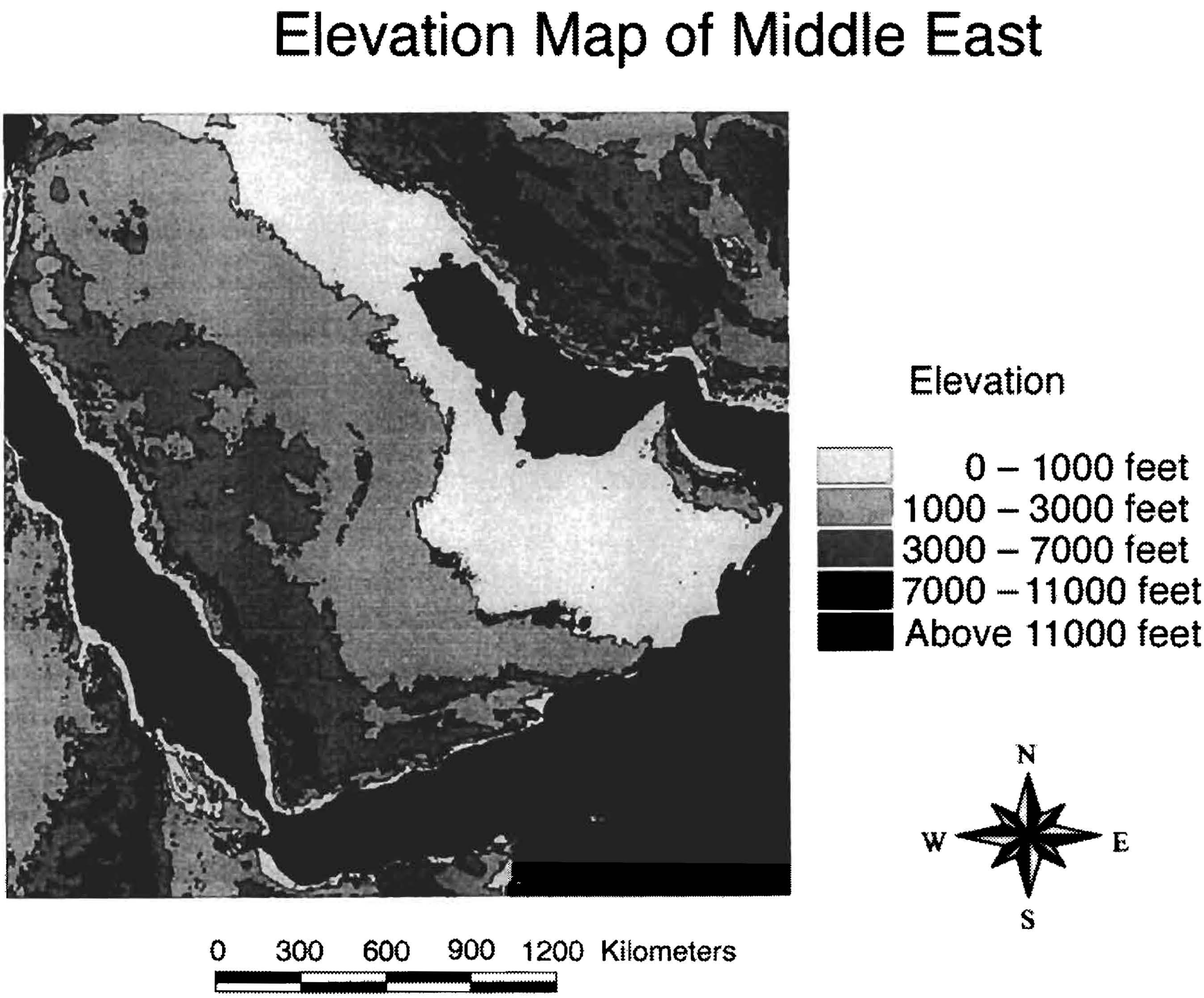

Figure 12. Topographical Map of Saudi Arabia. Note that pure back color shows the boundary of Arabian Gulf and Red Sea regions.

Pre-Analysis and Determination

To identify the conditions under which cloud seeding causes precipitation enhancement in Asir region. This involves determination of cloud types, weather systems, synoptic situations, climatic conditions and setting up the field program.

Actual Seeding and Data Collection

To seed the appropriate clouds with (AgI) from an aircraft, to monitor the cloud and rain as well as ice droplet concentration and their size in the cloud and finally to measure cloud microphysical parameters and rainfall amount at the specific targeted locations.

Post-Analysis and Assessment

To evaluate and verify the cloud seeding procedure, and rainfall amount in the target region and to study its environmental impact. This phase involves mainly processing the collected data, cloud and mesoscale modeling, numerical simulation, and study of cloud dynamics and precipitation formation.

4.5. Cloud Seeding and Its Environmental Impact

Any weather modification cloud seeding program in Saudi Arabia should be launched with the hope of securing environmental, economic, and social benefits. However, the implementation of a cloud seeding program can be a very complex problem if the procedures explained above are not followed precisely and fully. Recent developments in remote and acoustic devices enable scientists make accurate measurements and identify suitable clouds for perfect rain enhancement, now more than ever.

There will be a great positive environmental impact, such as increase in rainwater, and groundwater, even though there might be some slight negative impact, which can only be determined after the seeding experiments in Saudi Arabia. In the past studies and experiments around the world, there was no serious negative impacts reported in literature. However, the effects of the original cloud seeding experiments have been felt in almost every country of the world during the last 50 years or so. Most of the concern about seeding agents has centered about the release of AgI. The other seeding agents have been used less widely. In addition, most of them are soluble compounds like NaCl or biodegradable organic compounds. Dry ice quickly vaporizes into CO_2 gas. The concerns about damage to ecology and to human health come down to a question about the effect of AgI on the environment.

Investigation into possible side effects of AgI have covered such points as the total amounts released per year, the AgI concentrations in rain or snow and in the soil. The concentrations of AgI in rainwater and snow from seeded storms are the order of 10^{-12}, that is well under 1 part per billion (1 ppb) [10]. As AgI is not soluble in water, it is readily washed into the sea, but tends to be deposited in the soil and the bottom of streams. It was also noted that AgI is not toxic in the ordinary sense. A number of laboratory investigations of the effect of AgI on organisms have been made in the USA and Canada. The results up to 1977 agreed that AgI did not interfere with biological processes.

In short, most countries are still continuing to develop their weather modifications simply because of its ultimate and risk-free cloud seeding and weather modification operations. With advanced technology and knowledge, rain enhancement and severe weather suppression by cloud seeding can be successfully achieved in Saudi Arabia and around the world.

5. CONCLUSIONS

The Saudi Arabian rain characteristics have been investigated using the rain gauge data from the 23 year data set. Investigations show that Saudi Arabia has two different lands in terms of precipitation: semiarid in the southwest and arid in the east and center. Very little annual rainfall (as low as 20 mm/year) is the common rainfall for the Saudi Arabian arid land, whereas about 200 mm/year rainfall is measured in the semiarid part, almost ten times larger amount of rain. The reason for such difference in Saudi Arabia is the location of mountains in the southwest. These mountains act as a barrier, so that moist air climbs and adiabatically cools. Convective cloudiness, and precipitation, as a result, is a commonly observed feature.

The following stations receive very little precipitation (*i.e.*, less than 100 mm/year); Jeddah, Makkah, Sulayel, Bisha, Nejran, Arar, Guriat, Sharorah, Al Jouf, Tabuk, Al Wejh, Dhahran, Al Ahsa, Medina, Riyadh, and Yanbu. These are very dry regions. On the other hand, regions nearby stations of Turaif, Gaysumah, Hail, and Gassim receive a rainfall of less than

200 mm/year but more than 100 mm/year. Stations of Abha and Khamis get more rainfall than any other stations in the Kingdom (*i.e.*, more than 200 mm/year). Most of the time, precipitation forms during the winter months.

Observational studies also revealed that the rainfall rate over the most rainy part of Saudi Arabia, Asir region, was decreased by almost half. A rain enhancement program for this region is briefly discussed and recommended in order to meet the future groundwater need. Rain enhancement by cloud seeding was proved to successfully augment rainfall by up to 20% for some meteorological and geographical circumstances. It has been reported that more certain knowledge of cloud seeding procedure and process is now available in the scientific communities. It was estimated that even modest increase of precipitation by seeding the horizontally flowing supercooled liquid water, will pay back more than the cost of seeding. The results of recent studies have already demonstrated that it is highly possible to enhance considerable amount of rainfall by seeding.

The microphysical and precipitation properties of a given cloud are very complex function of many factors. This rain enhancement research program will provide a unique opportunity to investigate such relationships on synoptic scales, with spatial resolutions suitable to treat the individual clouds within the Asir region. This study will also help us to understand natural and augmented precipitation development in Saudi Arabian atmospheric environment. With the help of knowledge gained in this program, it may be feasible to extend rain enhancement to other parts of Saudi Arabia.

ACKNOWLEDGMENT

The author wishes to acknowledge the support of Research Institute of King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia.

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Paper Received 29 September 1997; Accepted 3 July 1998.