ON THE POSSIBILITIES OF RAIN AUGMENTATION BY CLOUD SEEDING IN THE PERSIAN GULF AREA (QATAR AND OMAN)

Consultant's Report
for
Food and Agriculture Organization of the United States

Joanne Simpson
Simpson Weather Associates and
University of Virginia
Charlottesville, Virginia

PREFACE

Cloud seeding is a developing science within the broader fields of cloud physics and meteorology. It began in 1946 with the discovery that dry ice would cause a supercooled (below $0^{\circ}C$) liquid cloud to convert to a cloud made of ice particles. Shortly thereafter it was discovered that silver iodide would also cause a supercooled water cloud to glaciate. Silver iodide becomes active as an ice nucleant at $-4^{\circ}C$. It works because the crystal lattice structure is very close to that of ice, although it is not yet fully understood how the introduction of silver iodide particles actually causes the cloud to glaciate. There are two physical bases for rain augmentation by silver iodide seeding, not necessarily exclusive, namely:

1) Increased precipitation efficiency when natural ice nuclei are scarce. At below freezing temperatures, the saturation vapor pressure over ice is lower than that over water. Hence when ice and water co-exist in a supercooled cloud, the tendency is for the ice particles to grow at the expense of the water drops. Thus it is possible to make larger particles which are able to fall out as rain or snow. In general, it requires about 1 million tiny cloud drops to make one rain drop. Hence many clouds do not precipitate efficiently -- the cloud drops evaporate without being able to grow -- often at supercooled temperatures when natural ice nuclei are scarce.

   Seeding for increased precipitation efficiency has been demonstrated to increase precipitation by about 15% - 20% in several carefully controlled experiments, in Colorado snow packs and in the winter Mediterranean-type storms in the near East.

2) Silver iodide seeding for dynamic invigoration of cumulus clouds-dynamic seeding. Computer models suggested that if cumulus clouds were massively seeded with silver iodide (20 - 100 or more grams per cloud) the latent heat of fusion so released could under suitable conditions cause the cloud to grow taller, fatter, process more water, last longer and make more rain. A series of statistically controlled experiments has been conducted in Florida on dynamic seeding. These began with pairs of individual isolated clouds, in which induced rain increases by seeding were shown to be a factor of 2 - 3. Application of this concept to a

large area (1.4×10^4 km^2) in the so-called FACE experiment has shown after six years that significant rain increases can be obtained under certain specifiable cloud and weather conditions. The percentage increase possible by dynamic seeding over an area is not yet specified, although it is unlikely to exceed 30% for seeded versus unseeded conditions on those days suitable for experimentation. In Florida summers about one-third to one-half of the days are suitable, that is a computer model shows "dynamic seedability" and seedable clouds appear in the target.

The question of whether the rain from warm (non-supercooled) clouds can be enhanced is not yet resolved. Experiments are underway with hygroscopic materials such as salt and the fertilizer urea to determine whether drop growth by coalescence and collection can be increased in this manner. If successful, this would "wring" more water out of a cloud, but would not cause it to process more water or grow larger. Hygroscopic seeding has also been used in attempts to increase precipitation in supercooled clouds, either alone or jointly with silver iodide seeding. Results are not yet conclusive.

This Consultant's report is, therefore, presently focused on the potential for silver iodide seeding although experiments elsewhere on hygroscopic seeding should be carefully monitored as a possible future option for the Gulf area.

It should be emphasized that under adverse conditions, seeding may decrease precipitation, particularly when natural ice nucleus counts are high and/or clouds are glaciating naturally. Hence, it is unwise to undertake seeding without the prequisite research program described herein. Furthermore, a properly designed field experiment to evaluate soundly the effects of seeding virtually always require 5 - 10 years of carefully planned work.

SUMMARY

This report is a preliminary description of the measurement steps which must be taken to assess rain augmentation potential in the Gulf area, particularly in Qatar (Part I) and in Oman (Part II).

Both Qatar and Oman are arid areas with average annual rainfalls of 100 mm or less (except in the mountainous areas of Oman where it may be 2 - 3 times greater). Rainfall distributions are highly skewed, with about 1/3 of the years above normal and 2/3 below.

Rain cannot be relied on to support agriculture, which must be irrigated from ground water or other storage. Hence, seeding potential assessment must be an integral part of the overall water resources programs which are underway in both countries.

Fortunately, the rain and cloud documentation studies already required by the water resources projects are the necessary Phase 1 to determine seeding potential. These involve rain measurements with gages, weather radar and satellite imagery.

If these indicate that supercooled clouds exist in the rainy and cloudy

weather conditions, then Phase 2 of an investigation is warranted, involving internal cloud measurements by aircraft and model runs to determine seedability.

At that juncture, if conditions look favorable, a careful decision analysis can be undertaken to weigh the relative merit of a seeding program against other options to increase available water supplies (this would be Phase 3). A seeding experiment or operation would be Phase 4.

After this first brief survey, my conclusion is that investigative Phase 1 is clearly justified, cannot fail to benefit the water resources projects in both countries, and should be implemented. The possibility of rain augmentation by seeding is hopeful enough to warrant the preliminary measurements which, in themselves, will pay for the cost of making them.

In the report, I have explicitly outlined the necessary measurements in the context of the water resources problem and water project of each country. I have also outlined various options for achieving the measurement goals.

To achieve these goals, continuity in senior personnel is essential. The senior expert involved in the early phases of the program should remain to assist the governments in the follow-through to subsequent phases.

Cost figures in this report are approximate. A supplement with more accurate itemized figures will be supplied to FAO Headquarters and project managers by mid-March 1976.

I. ON POSSIBLE RAIN AUGMENTATION IN QATAR

1. Introduction

Qatar is an elliptical peninsula, with the long axis (190 km) nearly north-south and the minor axis (85 km) nearly east-west. The peninsula is flat and sandy, with a maximum elevation of 100 m and a total area of about 12,000 km^2. It is centered at about 25° 20' N. lat. and 51° 10' E. long. Qatar lies wholly within the Northern Hemisphere desert belt. Virtually all rainfall occurs in the period December through April (1). Annual rainfall is lognormally distributed with a mean value of about 60 mm (2.36 in.) a median of 44 (1.73 in.) and a mode of 20 mm (0.79 in.) per year. Most of the rain falls in Mediterranean type cyclonic storms, with a lesser amount from "boundary fronts" related to land-sea contrast (1) and in local thundershowers in April and occasionally in May. The probability of one major storm per year is 90%, of two 50%, and of three only 10%. Frequently 75% of the annual precipitation may fall in one storm.

I was called upon to estimate the possibilities of rain enhancement by cloud seeding. In brief, I believe these are sufficiently hopeful to undertake the necessary meteorological measurements to assess the seeding potentialities, particularly since all of these measurements will contribute to a better ability to document and even predict the atmospheric water resources, whether or not a seeding program appears to be worth trying after measurements have been made.

The hydro-geology of Qatar has been well documented, as has the existing knowledge about rainfall and water budgets in a fine report by Pike et al (1) which is drawn upon heavily here.

2. The Water Budget Problem

All water for agriculture in Qatar comes from ground water while about two-thirds of domestic consumption is provided by a desalination plant. The desalination plant produces 12×10^6 m^3 per year at a cost of \$0.25 per m^3.

Precipitation is said to be of no direct benefit to agriculture. Present estimates are that about 10% of the precipitation charges the ground water, while the rest is lost by evaporation; only a very small fraction runs off to the sea. Latest studies (2) show that groundwater recharge by precipitation occurs only in the northern half of Qatar. In the southern half it filters into a gravelly layer which supports desert vegetation and is thus mainly lost by evapotranspiration. At present, rates of water use there is a net annual deficit of 17×10^6 m^3 which is reducing the supply of ground water. Estimates are that ground water will be exhausted or contaminated by salt water intrusion by the year 2000 unless something is done shortly either to restrict use and/or to provide new sources. Desalination is one option, feasible in view of the large supply of natural gas. What could be expected of cloud seeding should the clouds appear suitable?

3. A Rough Estimate of Optimum Seeding Potential

If we take 50 mm/yr and multiply by the area of Qatar (12,000 km^2) we have annually 600×10^6 m^3 over the peninsula or perhaps 300×10^6 m^3 on the northern half. Suppose, as has been demonstrated over a much smaller[1/] target in another mid-eastern country (3) that rainfall over the northern half of Qatar could be increased by about 17% and that 300×10^6 m^3 would fall naturally on the northern half. Then an additional 50×10^6 m^3 per year would ensue. If only 10% of this additional rain went to ground water recharge, 5×10^6 m^3 per year would be added to recharge, or 29% of the present rate of overdraft. In amount, this is less than half supplied by the present desalination plant; however, the water, if thus obtainable, would be less expensive. A rough estimate of the cost of an operational airborne seeding program would be \$500,000 per year, or a cost of \$0.10 per m^3. An added benefit would be that the measurements made in connection with operating and evaluating the seeding program would be necessary and beneficial to the rainfall studies which are an integral part of the overall water resources program.

The question, therefore, becomes one of outlining the necessary steps to determine whether or not a cloud seeding program is worthwhile undertaking and if so, whether it should or can begin as a statistically controlled and evaluated experiment, or as a state-of-the-art operation based on extrapolation of positive results elsewhere.

[1/] Each of the two targets in the randomized crossover design is about 2-3 x 10^3 km^2.

4. Preliminary Prerequisites for a Seeding Program

Cloud seeding techniques have only been demonstrated to produce increased rain, in my opinion, in some few experiments, where silver iodide or dry ice have been used to nucleate supercooled (temperatures below $0^{o}C$; silver iodide becomes active at about $-4^{o}C$) clouds. Attempts to increase rain from "warm" clouds is in an experimental stage and I do not expect firm results for a few years[2/]. Hence, my report focuses entirely upon supercooled cloud seeding.

The scientific bases for my recommendations are to be found in the book entitled "Weather Modification" edited by W. N. Hess. Primarily, I based my recommendation upon Chapter 13 (3) which reports an experiment in a near Eastern country with perhaps similar Mediterranean type winter rain and secondarily upon my own experience with a cumulus seeding experiment described in Chapter 6 (4) in Florida. The latter appears to have reached positive significant results for an area of 1.3×10^{4} km^{2} after five summers of randomized experimentation; however, this statement is preliminary. Confirmation and release of these analyses is planned by the summer of 1976.

Just prior to coming to this region, Mr. Vincent J. Oliver, of NOAA's National Environment Satellite Service, was kind enough to make for me a brief study using high resolution infra-red digitized products from the polar-orbiting NOAA 2 satellite, which crosses the Arabian area between 9-10 a.m. and 9-10 p.m. local time. Looking through January and February of 1973, he found that those storms which crossed the area did indeed have clouds with sub-freezing tops as reported more fully in my report on Oman. This finding supports the belief that the possibilities of man-made rain enhancement in the Gulf area are worthy of a careful investigation. The recommended steps toward this determination are outlined here, in a preliminary fashion.

A. Requirements:

1) Cloud population statistics, namely:

a) Base and top temperatures and heights
b) Nature, size and spacing of clouds
c) Cloud liquid water contents
d) Ice particle concentrations in supercooled portions
e) Ice nucleus and condensation nucleus counts
f) Frequencies of the above and their relationship.

2) Ambient atmospheric structure and circulation.

a) Vertical soundings of pressure, temperature and humidity, for stability and "dynamic seedability" calculations (4).
b) Synoptic charts, showing the nature of the weather systems producing the clouds.

B. Implementation in sequence:

1) Satellite study of rain and cloud characteristics:

2/ A properly controlled hygroscopic seeding experiment is just beginning in Brazil. With good luck, some reliable results may be available from it by 1979-1980.

a) Implementation of Barrett proposal (5).
b) Access to and study of high resolution visible and infra-red data from NOAA satellites. HRPT equipment costs about $250,000. Can be used, together with gages to obtain areal and time variations of rain (6,7). Infra-red (IR) can be used to obtain cloud top temperatures and hence supercooled populations. Options:

    i) A receiver can be installed on the Arabian peninsular for use of all regional scientists.
    ii) A receiver can be installed by any user nation.
    iii) Data can be obtained from the U.S. after the fact.

Recommendation: In view of the anticipated geosynchronous satellite over the region in 1978 (by the European Space Research Organization) I would advise one HRPT in this area, with properly trained maintenance personnel and data analysts, who can be aided in their work if necessary by consultants such as Dr. Barrett.

2) A good weather radar installed and calibrated against gage clusters in Qatar. Calibration of the radar with rain gauges for quantitative rain measurements will be more difficult in Qatar than in Florida, owing to greater and variable evaporation of the rain between cloud base and the ground. Hence, a "flying rain gage" is recommended in the next section as part of the aircraft program. It could be a Knollenberg probe (using lasers and electronic light detectors) or the NRL cloud evaporator instrument. Both are expensive and require an expert technician to operate and ensure good data. For description of these and other instruments, see Hess Chap. 4(8). The radar should have PPI and RHI capability, be coupled to a mini-computer and produce hard copies which are contoured in dBZ. A Pacer III or Enterprise 5 cm radar would be fine; software can be included which corrects for a range, attentuation and possibly also for anomalous propagation. Such a radar would cost $100,000 - $200,000 (rough estimate) depending on the accessories desired.

Recommendation: A weather radar is necessary for the water resource project on Qatar anyway. I suggest its purchase as soon as possible, and calibration following the method of Woodley (4,9). If a proper contractor is hired for the aircraft work his people will be capable of aid in the choice, installation, calibration and beginning operation of the radar.

3) Instrumented aircraft measurements in actual clouds. This can be undertaken, if the satellite study looks promising, shortly after the radar is functioning properly. The radar operator must be in voice communication with the aircraft meteorologist (or pilot if he is properly trained). If VOR and DME navaids are not excellent, the aircraft should be equipped with a transponder and the radar with a transponder receiver.

The aircraft should be equipped to measure in-cloud temperature, dew point, liquid water (in cloud and rain sizes) ice particles and ice nuclei. It should have, if possible, a time-lapse cloud cine camera and a condensation nucleus counter. It will take approximately three versatile persons (pilots-cum meteorologists-cum instrument technicians) to run the aircraft program.

Recommendation: An aircraft measurement program be undertaken in December - April of the first year in which a radar can be properly operating by December. It would appear best to engage a reliable U.S. contractor for this work: I know at least two with the necessary capability and experience. This would presumably be the same firm to undertake the seeding, if it were decided to proceed with it the following season. If the people were chosen properly, they would not waste time before and between rainstorms, in that they could from earlier data perform satellite analyses, aid in radar and gage evaluations, run soundings with the cloud model, etc. I can only roughly estimate that the cost of this part of the program would be between \$250,000 - \$400,000 with the contractor supplying the fully equipped aircraft and personnel.

5. <u>The Next Decision: Whether and how a Seeding Program?</u>

If the cloudy situations show a reasonable population of supercooled tops, without high ice particle and ice nucleus counts, I would recommend design and serious consideration of a seeding program, particularly if the clouds show dynamic seedability on occasions and/or continental characteristics.

Recommendation: If indications are positive, I would recommend calling in at this stage a statistical consultant, highly experienced in weather modification, such as G. W. Brier of the Colorado State University or Dr. Ronald Biondini of the University of Virginia, to determine whether and how a statistically randomized modification experiment could be undertaken. A proper experiment is highly desirable in view of the excellent opportunity for a complete water budget calculation in Qatar.

A dual target randomized experiment might be possible in Qatar, with the northern area seeded (with perhaps 2 random seed cases for each random control), a buffer zone crossing the peninsula near Doha, and the southern area a control target. Rainfall correlations between these targets can be calculated; the reports of Pike et al (1) suggests they would be fairly high for the main rain-bearing storms. A randomized crossover design as in (3) could also be considered. The disadvantage of having more unseeded control cases in the northern area where rain is most beneficial might be overweighed by the increased efficiency of the design. In any case, the experiment would probably take at least a decade to reach significant results, and perhaps two. This estimate is based on the fact that there would probably be only 5 - 10 GO days per year, in contrast to the existing Near Eastern experiment which has about 60 annually and still required 6½ years to reach significance.

Another option exists, namely to go directly to a non-randomized seeding operation. In my opinion, this is not desirable unless a randomized experiment is underway elsewhere on the Arabian peninsula, such as in Oman or Saudi Arabia. Even so, results from Oman, since it is mountainous could not be extrapolated to Qatar with certainty.

If time and funds permit, I believe that the best option would be to conduct more than one randomized experiment on the peninsula and somehow use extremely clever statistics to combine their results into an inference pattern. This would require careful coordination, at least a decade of effort and expenditures of over ten million dollars. For comparison, the budget of the National Hail Research Experiment in the U.S. is about 4 million dollars per year; that experiment will run about 8 years. The budget of the FACE (Florida Area Cumulus Experiment) has been about one million (including aircraft) per year; the project will probably run 6 - 8 years.

6. My visit to Qatar

I visited FAO, Doha, Qatar, January 30 - February 1, 1976 and consulted with Drs. John Pike, David Parker, Brian Gemmel and Mr. Michael Farah, co-manager of the Project from the Qatar Ministry of Agriculture. Fortunately, my visit coincided with the first major rainstorm of the season. Light rain began on a southeast wind on 31 January. Many cumulus towers with high bases were observed and photographed through breaks in the overcast. Repeated lightning was seen at nightfall and heavy rain occurred during the night. In the morning of 1 February many of the Doha streets were flooded up to the hubcaps of cars. The wind had shifted to the north and the sky was still a broken overcast with many cumuli visible throughout the morning.

Dr. Pike and his staff were busy organzing rain gauge readings, together with evaporation calculations and examinations of several depressions in the northern area where ground water recharge occurs. He informed me that the country has begun a meteorological service which is at present mainly concerned with avaiation forecasts. He plans to obtain from them synoptic charts relevant to this disturbance and also the rawinsondes from Bahrain. The island of Bahrain is separated by a 40 km wide channel from the Qatar peninsula and is 125 km northwest of Doha. If these soundings reach me and look promising, I will try my cumulus model on them to estimate the heights, temperatures and water contents of the natural clouds and to calculate dynamic seedability.

7. Conclusion and Recommendation on Qatar

I am impressed with the water budget studies on Qatar, from both the viewpoint of the hydro-geological situation permitting fairly confident budget calculations and the viewpoint of the competent personnel and good beginning on instrumentation with rain gauges (21 at present, 3 recording). I highly recommend a cloud and rainfall satellite study and the installation, calibration and similar coordinated study with a good weather radar. In the interim, an effort might be made to obtain systematic pilot reports on cloud bases, tops and the existence and location of aircraft icing.

It appears to me that the FAO program here needs a meteorologist, not from lack of ability of present staff but because of the lack of time and the nature of commitment that any proper rainfall study requires, even without a seeding program. It might be possible to share a meteorologist with Dhofar on that portion of Saudi Arabia whose rain occurs in the summer monsoon.

In conclusion, I recommend a satellite, radar and aircraft cloud/rain study in that time sequence. Then a complete joint evaluation of data to determine whether an experimental or operational seeding program would be worth the added investment. In the 1-2 years required to complete this Phase 1, cloud modification science will also advance in other nations and thus permit a sounder decision. At present, I would estimate the probability of a worthwhile seeding program, given the completion of Phases 1 - 3, as 60 - 70%, the higher the more the scientific knowledge gained would be esteemed, and the more effort put into the proper design and evaluation of the project.

REFERENCES (QATAR)

1. Pike, J. G., J. Harhash, and B. A. P. Gemmell, 1975: Rainfall and ground water recharge Qatar. Tech. note 24, State of Qatar, Integrated Water and Land Use Project, United Nations Development Program, FAO, 17 pp.

2. Pike, J. G. et a., 1975: Memorandum: Ground Water Resources and their development for agriculture. Unpublished note on file at FAO, Doha, Qatar.

3. Gagin A. and J. Neumann, 1974: Rain stimulation and cloud physics in Israel. Chap. 13, in "Weather and Climate Modification", Ed. W. N. Hess, Wiley-Interscience, New York, 454-494.

4. Simpson, J. and A. S. Dennis, 1974: Cumulus Clouds and their modification. Chap. 6 in "Weather and Climate Modification". Ed. W. N. Hess, Wiley-Interscience, New York, 229-281.

5. Barrett, E. C. 1975: The scope for remote sensing in the search for solutions to water supply problems in countries bordering the Gulf. Consultant's Report for Food and Agriculture Organization of the United Nations. October 27, 1975. On file at FAO, Rome.

6. Barrett, E. C. 1975: Rainfall in Northern Sumatra. Analyses of conventional and satellite data for the planning and implementation of the Krueng Jreue/Kruerg Baro irrigation scheme. Final Report under contract to Binnie and Partners (Consulting Engineers), October 1975. On file at FAO, Rome.

7. Griffith, C. G. and W. L. Woodley, 1974: Rainfall estimation from geosynchronous satellite imagery. Proc. 11th Space Congress, 2, Cocoa Beach, Florida, April 1974, pp. 5-16 to 5-24.

8. Ruskin, R. E. and W. D. Scott, 1974: Weather Modification instruments and their use. Chap. 4 in "Weather and Climate Modification", W. N. Hess, Ed. Wiley-Interscience, New York, 136-205.

9. Woodley, W. L., A. R. Olsen and V. Wiggert, 1975. Comparison of gage and radar methods of convective rain measurement. J. Appl. Meteor., 14, 909-928.

II. REPORT ON OMAN: RAIN RESOURCES AND POSSIBLE INDUCED AUGMENTATION

1. Introduction

The Sultanate of Oman lies between the latitudes of 16^{o}N and 26^{o} N, 55^{o} and 60^{o} E longitude. It is shaped like a north-south oriented crescent with the convex side facing east on the Arabian Sea. The country thus occupies the south-eastern corner of the Arabian peninsula. Its extreme northern province, Musandam, is a sharp promontory controlling the entrance from the Gulf of Oman into the Persian Gulf.

Only in the extreme north of Oman, with rainfall mainly in winter Mediterranean-type rain storms, and in the extreme south (Province of Dhofar) with monsoon type rain mainly in July-August, do the climate, soils and water supply support agriculture. Between these two extremes is largely desert.

The primary area covered by this Consultant's report lies in the northern part of Oman, straddling the tropic of Cancer which passes just south of Muscat, the capitol city. The region considered (shown in Fig. 1) extends roughly along the coast from Muscat to the northern extreme of the Batinah (at Khatmat al Malaha) to Sur on the South, and inland from Qaba to Ibri, Adam and Kamil Wafi. The terrain is characterized by high mountains (up to 3000 m) separating the coastal strip from the interior.

A main part of this area, a square of about 17,000 km^2, with corners at Khabura, Ibri, then Adam and Muscat, has been studied by Gibb and Partner (1). Their report concerns mainly ground water and its quality. They attempted to establish rain gauges and several meteorological stations, which experienced vandalism and other difficulties.

With the sparse data available up to 1975, a superb job of summarizing the rain-bearing situations in Oman has been conducted by Renardet Sauti Ice (2). In 1973, this firm set out 20 rain gauges, including 4 chart-recording gages at high elevations. They conclude that this density and distribution is inadequate for specification of temporal, spatial and particularly altitudanal variations. The strength of their report lies in their careful classification and presentation of those synoptic situations which bring rain (by season) to the several parts of Oman. These relationships should be of great aid to forthcoming satellite studies (13).

A brief recapitulation of their findings for the Primary area follows, namely:

a) Rain falls primarily in the winter months.

b) Rain may fall in any month.

c) Any month may experience no rain.

The latter is rare in winter (14% frequency in existing record for January) and common in summer (96% frequency in existing records for August).

Concerning the circulation features associated with the rain-bearing disturbances, it seems that cold fronts cause the heaviest rain. There are two types of air circulation and cold fronts over Oman, namely:

1) The Siberian anticyclone stretches as far as Arabia, a depression which is probably thermal deepens over the Arabian Gulf, sending cold air from Irban over Oman.

2) A depression of dynamic origin deepens at altitude over Arabia as the jet stream describes a large loop to the south. On the surface, the Siberian anti-cyclone withdraws from the region leaving a col between itself and the Siberian anticyclone. Cold air associated with a Mediterranean depression then migrates to the southeast across Arabia. In these situations, the Saharan anticyclone lies far to the north, covering the Mediterranean and southern Europe.

There is another small rain maximum in summer in the Primary area as a result of disturbances on the Intertropical Convergence Zone during the Monsoon.

Winter disturbances specifically for 1976 are briefly discussed further in Appendix 1 entitled, "Preliminary Satellite Study".

Despite their excellent work with the small amount of data available Renardet Sauti Ice were not able to document altitude variations of rainfall in Oman in the various weather conditions, nor were they able to relate the latter to cloud configurations as shown on satellite imagery.

A very brief discussion of the southern monsoon regime area (Dhofar) called the "Secondary Area" is given in Appendix 2. The hatched area in Fig. 1 is hereinafter referred to as the "Primary Area".

This Consultant was retained for about three weeks in January - February 1974, jointly by the Government of Oman and the FAO/UNDP:

1) To study available material on the atmospheric water resources, and

2) To outline preliminary steps in the determination of whether, when and how a cloud modification program might be undertaken to augment rainfall.

My main recommendations are: 1) The atmospheric water resources, their fate and role in a fairly accurate water budget must first be calculated as planned in the present program and 2) the natural clouds and rainfall must be examined carefully to determine whether they might be amenable to rain increase by artificial ice nucleation (silver iodide, dry ice, or seeding by some other form of artificial freezing nucleant). As stated in my concomitant report on Qatar (Part I), I do not believe that as yet hygroscopic seeding of warm clouds has been adequately demonstrated to increase rainfall in Oman, although by the end of the proposed 2 - 3 year study of the natural clouds and rainfall in Oman, projects elsewhere[1/] may have shown that hygroscopic seeding is also a viable option.

This report emphasizes that rain augmentation must be a long-range, strongly data-based and carefully evaluated program" requiring 2 - 3 years preliminary study and 5 - 10 years experimentation (3). Omitting these preliminary steps has contributed to the counter-productive controversies surrounding weather modification in other countries. An excellent survey book on all aspects of the subject entitled "Weather Modification"(4) is frequently referenced herein. A copy has been left with The Water Resources Project in Oman.

2. The Primary Area

The area is abruptly divided into two distinct regions by a range of high mountains, the Jebel Akdar, which rises to a maximum height of 3000 m. To the north of the Jebel, from the foothills to the sea, stretches from Batinah plain. The coastal plain varies in width from about 25 km at Sib to only about 10 km at Al Kaburah. This plain has a fringe of cultivated land along the sea coast for 1-2 km inland; the remainder is largely stony desert with some scrub vegetation. To the south of the Jebel lies an arid desert with rocky outcrops leading eventually to the "Empty Quarter" close to the foot of the Jebel. Both in the north and south are small towns and villages sited in more or less fertile areas fed directly or indirectly by water from the Jebel. The cultivated areas along the coast and around the interior towns and villages footing the Jebel are the only areas as of 1974 (1) supporting agriculture, although there are several types of evidence that the water resources for agriculture are fully or efficiently exploited even in these areas and that land, apparently cultivated and irrigated in the past is no longer worked. Primary sources of water for irrigation have been the "falaj", natural outcroppings of ground water protected by man-made structures and originally pumped by animal-power. These have been falling in disrepair in recent years. Irrigation is now conducted mainly from bored wells from which water is pumped by machinery.

The report of Gibb and Partner (1) indicates lowering of the water table and deterioration of water quality in many of the pumped areas. The deterioration was attributed either to intrusion of sea water, to the presence of more saline water below a fresh surface layer and/or to recycling

---

1/ e.g. Brazil

of irrigation water after use. However, the data for the Gibb study were taken in a dry year. More extensive and precise data are desperately needed. Fortunately, they are presently being gathered by the Water Resources Project.

3. Water Resources and Their Use

An assessment of the country's water resources and their present use has been summarized in a Draft Development Plan for Oman by UNDP-FAO Project Director Samuelsson (5). From the consulting firm reports it is estimated that the total water resources retained for exploitation are 630 x 10^6 m^3 per year for the whole country. The present consumption is about 430 x 10^6 m^3 per year for the whole country. The present consumption is about 430 x 10^6 m^3, leaving a supposed excess of above 200 x 10^6 m^3. The present low efficiency of water use leaves room for further development by applying modern irrigation, high class conveyance systems, controlled water use and crop-yield increasing irrigation schedules. With these improvements, 15% savings is believed possible, or about 60 x 10^6 m^3. Then the total area presently under irrigation should manage with (430 - 60) x 10^6 m^3 or 370 x 10^6 per year. Furthermore, it may be possible to catch some part of the flood water which at present is lost to the sea and desert; this is estimated as a potential additional saving of 100 x 10^6 m^3 for resources available for development. Consequently, there is an annual amount of (200 + 60 + 100) x 10^6 m^3 or 360 x 10^6 m^3 to be exploited for extension and development schemes, which is an increase of 80% of present water use.

In addition, a desalination plant is soon to be in usage in Oman for domestic and industrial water. Its capacity is 6.6 x 10^6 m^3 per year, at an expensive rate estimated as high as $6.00 per m^3!

The point of the foregoing discussion is that in contrast to Qatar, there appears still to be a surplus of available water rather than a serious deficiency, so that the immediate objective is to quantify the budget and improve the efficiency of water use, rather than an immediate desperate search for additional water resources.

4. Rainfall in Oman

Rainfall information in Oman is sparse and difficult to obtain, with a reasonable length of record at only two or three stations. The best data I could find so far were in the Renardet Report (2) and in an FAO/UNDP report by Burdon dated 1972 (6). The main features of Oman rainfall is that it is sparse, highly variable and increases with elevation in the Jebel. At present the Water Project has 70 raingauges fairly well distributed around the primary area. My main recommendation is that accurate space and time rainfall distributions, in their weather system contexts, must be properly documented for several years, a difficult and expensive task. There is little use in even planning a seeding program until the natural rain distribution and its dependence is documented. Furthermore, the time required for evaluation of a seeding program cannot be specified without this information. (4.7). It appears to me that rain information on Oman is presently less well known than in Qatar (8,9).

Presently the following rough qualitative information is available to me:

The northern area is dominated by winter rain associated with Mediterranean type storms, perhaps also frontal and subtropical cold low activity. Although the bulk of the precipitation falls in December through March, there is rain, particularly in the mountains, in all months. The southern province of Dhofar experiences the opposite, namely a monsoon regime with a summer maximum, although there is also a finite probability of rain in all months. The edge of the monsoon occasionally penetrates far into the interior, leading to heavily showering isolated cumulonimbi in summer.

At Muscat on the coast the average annual rainfall is about 100 mm. It is estimated (2.6) that in high areas it may increase to 250300 mm; this estimate needs veritification. Behind the Jebel at Nizwa, from 1965-1971, the average rain was 171.9 mm per year, with 609 mm falling in 1972. The average at Salalah in Dhofar (1943-1971) is 114.9 mm. However, in arid areas such as Oman, average rainfall figures mean quite little. The distributions are highly skewed; the data are usually well fitted by gamma or log-normal distribution (8.9). Thus the median and modal values are always much less than the mean. Many dry years are interspersed with occasional very wet ones. In the northern area, a winter can pass with no storms at all, leading to severe drought as in 1973-1974 (1), or 6 or more storms can effect the area.

When a heavy rainstorm (20-100 mm can accrue in one storm) does occur it is frequently accompanied by flash flooding owing to the rocky geological structure of the mountains. Moreover, it is estimated that about 30% (10) of the rain runs off to the sea, an unfortunate perhaps partially preventable loss if documented by ongoing studies. Furthermore, if Qatar is an example applicable in part to Oman, probably as much as 50 - 60% of the rainfall evaporates, a figure which must be determined, leaving perhaps 10% to recharge the ground water. The water budget, particularly the recharge method and fraction is now being intensively studied (8).

5. On the accurate measurement of rainfall and cloud structure

A first necessity for a water budget, and also for assessment of seeding potential is accurate determination of the temporal and spatial distribution of rain, and then the rain and cloud characteristics. Those additional characteristics which must be determined to assess seeding potential are described in Section 7.

It is particularly important to learn the effect of the mountains on rainfall and the variation of precipitation with elevation under the different weather regimes. For example, it is known that cumulus showers occur over the mountains probably on a local, terrain dependent basis during the "dry" summer months. These local showers may or may not be important for agriculture; they could also conceivably be enhanced by seeding. The mountains will also have different effects on preferred cloud developments in the winter storms depending on the associated air structure and circulation patterns.

An adequately dense raingage network to document rainfall in Oman is patently out of the question. Even if funds permitted telemetering gauges in remote mountain locations they could not be adequately dense for an accurate treatment of space variations, which may be above 10 mm in a few km. The gages are furthermore subject to vandalism. Remote sensing by satellite and weather radar is clearly mandatory, in combination with properly distributed gage clusters (11,12).

It should be emphasized that all three of these tools must be used together and that no one alone will suffice. Vast progress in satellite estimates of rainfall has been made in the past three years (13, 14) but gages, radar, cloud type and weather information are necessary to translate the imagery, by empirical curves to "rain on the ground". The confidence which can be placed in these empirical curves is less in the mountainous regions than in flat regions. Weather radar, together with gage clusters, on the other hand, has advanced to the point where sampling errors have been reduced to about 10% for an area of 5 km^2 for intervals of 5 minutes, a fantastic achievement (15). This demonstration has been made for the Dee Valley in the United Kingdom. Accuracy could be less in Oman owing to more rugged terrain and to more variable evaporation of rainfall between cloud base and the ground. Nevertheless, this Consultant is convinced that for Oman, weather radar is an absolute must and should be given high priority. A satellite study is a relatively inexpensive adjunct which can commence immediately by implementing the proposal of Barrett (13). Later, Oman may wish to purchase an HRPT (high resolution picture taking) system on its own, which costs about $250,000. A regional purchase of such equipment with supply of data to all regional users would appear preferable, whereas radars must be installed <u>in situ</u> by each user since their calibrated range is limited to 80-200 km depending on power, wave length, etc. For precipitation studies C-band or S-band radars (5.6 cm or 10 cm wave length) are customary, with narrow beam width in the vertical, not to exceed 1^o. For C-band, this requires a 3.7 m diameter antenna dish, which has been used in many developing countries without difficulty. PPI (flat) and RHI (vertical slice) presentations on the scope are necessary. The radar signals must be digitized and tape recorded in a computer-compatible fashion. A device presenting contoured hard copies of the scope picture on request is highly desirable; this feature is virtually mandatory with a seeding program, but could be added later if necessary. Software is necessary (and readily available at no cost) to convert the output to rainfall either for areas or individual clouds or cloud systems (17) depending on the empirical establishment of the relationship between power return (Z) and rainfall (R), the so-called Z-R relation, which is written $Z = AR^B$ (1), where Z is customarily in units of mm per m^2 and R is in mm per hr.

Raingage clusters and raindrop distrometers (15) are mandatory to determine A and B, without which the whole project falls on its face. The most sophisticated and accurate use of this method, and the <u>only</u> one in a mountainous area is the Dee Valley Project in U.K. (15,16). It is noteworthy that different Z-R relations had to be developed and used in different rain situations to obtain the 15-20% accuracy reported. In the Dee Project, the exponent B was kept constant at 1.6 while the constant A was varied. From the writer's experience in the GATE project[27], she is virtually certain that the exponent should vary also, at least between regions and quite likely within one region, such as Oman, which experiences different rain regimes with season, terrain and possibly with time in a single storm.

It should be clear from the foregoing that a radar meteorologist with specific experience in rainfall determination would be essential, at least as a consultant to guide this proposed undertaking, as well as at least one skilled radar technician.

Concerning costs, the Plessey system used in the Dee Project has been quoted [3] at 700,000 sterling for the system. This wants detailed itemization, since the figure seems to me excessive. The Pacer III and Enterprise radars should also be investigated and costed out. It is my impression that these systems can be purchased for around $100,000, but this figure may not include digitizer, software, or tape drive. However, a digitizer can be constructed by a clever electronics technician for a few tens of thousands of dollars following blueprints available at no cost in the U.S. Software is also available there at no cost, and tape drive costs in the ball park of $20,000. If the £700,000 includes rain gages and the calibration effort (a 1-2 year undertaking at best in an arid area) it may make more sense; however, good advice and careful study is warranted in this crucial investment.

There are two other options available at the project for rainfall determination by radar. These are:

1) Cooperation, if feasible, with the Omani military radar. I consulted at some length with Mr. Ray Seifert on this subject. The planned military radar system is intended for aircraft tracking and location. One unit will be installed at Seeb Airport within a year or two. The radars are L-band with one-half degree vertical beam width and a range of 250 km. The signal will be half degree vertical beam width and a range of 250 km. The signal will be digitized in such a way that only the outlines of the shower echoes will appear on the operational scope. The possibility was raised that the new data could be supplied to the water project, who would then have their own digitizer to convert the cloud echoes into rainfall values. However, I am not aware than an L-band radar has ever been calibrated for rainfall measurement and what might be the catches involved, if any. It is possible that the long wave length would not respond to the smaller raindrops reaching the ground, which might be an insurmountable obstacle. Advice of a weather radar expert is clearly needed.

2) Rental of an entire system (with option to buy) from a U.S. firm on contract basis, who would also supply the personnel, conduct the calibration, provide the instrumented aircraft for in-cloud

---

[2] The radar aspect of the GATE (GARP Atlantic Tropical Experiment) was conducted from shipboard radar about 600 mi SW of Dakar, West Africa with the Z-R relation determined by shipboard distrometers and airborne drop impactors.

[3] In a letter to Mr. Morvan from the Plessey Company in U.K.

measurements and the rawinsonde system. This would presumably be the same group to undertake a seeding program if one were decided upon. The data analysis could be done by this group jointly with a university contractor, if desired.

I know from experience that several U.S. firms are capable of setting up such a system within 6-8 months notice; they probably would require some initial capital investment on the radar, which might be partially refundable if the radar were not kept, or payable on long-term installments if it were. I will take steps to get itemized quotations by 1 March 1976 on the cost of a two-season program of this sort to commence in December 1976, to run through February 1977, and again the following winter season.

I expect this would be much cheaper, faster and less onerous than the development from scratch of an in-house capability, which would require at least two positions (radar meteorologist and technician). In other countries (17) programs have been started in this manner, being gradually turned over to the local agencies as these acquire the trained personnel; the training program has been a part of the contract. Whether or not any seeding were even undertaken, this study would contribute invaluable information on the atmospheric water resources which is surely a must for effective use of water in any country, particularly an arid one. Another advantage of this option is that it can be conducted jointly with a satellite study to the enormous benefit of both studies.

In conclusion of this section, it must be emphasized that remote sensing efforts by satellite and/or radar are not magic solutions to the rain measurement problem, particularly in a mountainous region.

In the case of radar, remoting an antenna on the mountains is out of the question. Two radars would be needed if both sides of the Jebel Akdar were to be covered by radar. I suggest one radar at Seeb Airport, with the across - Jebel coverage provided by high-resolution calibrated satellite imagery at the outset.

Two points, however, cannot be over-emphasized:

1) Of the three tools, gage, radar and satellite, gages must still be regarded as indispensable "ground truth". Next in terms of layers of empiricism and assumptions are radars and, finally, satellite deductions, which are the most fragile, particularly in mountains. All methods are immeasurably aided by surface distrometers (15) and aircraft measurements of cloud hydrometeors, their nature, size spectra and water content.

2) A reasonable network of rain gage clusters must be operated to calibrate the remote sensors under any circumstances. This includes gage(s) on the Jebel Akdar. If this requires a few armored gages surrounded by electricified fences, evil eyes, or with full-time caretakers, so be it. Another possibility is to declare military "firing ranges" or some such, at the

gage locations. It would be a false economy to jeopardize what must be a multi-million dollar program (the water resource program overall) for want of whatever extra ingenuity and/or expense is required to see that these gages stay there and function.

Since the Jebel is likely to be a major source of the country's rainfall, and since radar rainfall satellite image - rainfall relations may be different on a mountain top near or within cloud base than on the plain, this recommendation must be implemented for some time period. It may prove later, once the relations are established, that these gage sites can be abandoned. Our experience in Florida (18) and that in the Dee Valley in U.K., unfortunately, suggests that a variable gage correction factor must always be applied to remotely sensed rainfall. Further research may enable prediction or calculation of this correction factor, but I do not forsee it very soon.

6. What might eventually be expected of a Seeding Program

The rain resources and distribution in Oman are not well enough known to me to make any quantitative estimate at this time concerning how much water, if any, might be added to the country's resources by cloud seeding.

As emphasized earlier, the rain distribution and internal cloud structure must be documented. However, rough percentage estimates can be made from the results of projects in other countries. A statistically-controlled project on Mediterranean type storms in another near-eastern country have shown increases in seeded versus unseeded situations of 15-25%. This location, however, has about 60 suitable rainy days per winter season, which may exceed that in Oman by a factor of 2-3. If so, a 15-25% increase on a rainy day in Oman would be a comparatively smaller total amount of water addition, which may prove to be economic anyway if scientifically feasible. The latter estimate is based on the apparent relative cheapness of water obtained from a seeding program than, for example, from desalination. In my report on Qatar the desalination cost was estimated as about \$0.25 per m^3, while the cost from seeding, after the initial research and capital investment, might be about \$0.10 per m^3.

Two other modification potentialities exist for Oman:

1) Dynamic seeding of cumulus, both in the "rain bands" of the winter storms and in the isolated cumulus congestus of spring and summer (4, Chap. 6). Experience in Florida shows that under the right conditions rain from an isolated cumulus can be increased by a factor of 2-3. Very recent results of a 5-year experiment over an area of 1.3×10^4 km^2 finally appear to show positive results from dynamic seeding. However, these are preliminary. The magnitude of the increase cannot yet be specified. My present guess is that on suitable occasion the seeded/unseeded increase area-wide may be as much as 40%. However, even in the Florida rainy season, only one day in three has been found suitable for this type of seeding experiment.

Briefly, dynamic seeding involves massive seeding of cumulus towers with airborne (dropped) silver iodide pyrotechnic flares. The heat of fusion released causes the cloud to grow larger, to last longer, and to process and release more water. A simplified computer simulation of a cloud predicts from a radiosonde observation and cloud base conditions the existence and magnitude of dynamic seedability. For a clearly understandable reference on dynamic seeding, the radar is referred to chapter 6 in the book entitled "Weather Modification" edited by Hess (4).

2) Seeding with hygroscopic materials to promote coalescence of drops until they may become large enough to fall out as rain. This method thus does <u>not</u> cause a cloud to process more water and can "wring out" only that which is already there. In arid conditions these amounts may be pathetically small.

Materials used have been common salts and organic compounds such as urea which has the added advantage of being a fertilizer. My recommendation on this method is to await the outcome of the project in Brazil.

In summary of this section, seeding is not a panacea, in that it can be hoped at best only to initiate or increase rain when suitable clouds are present. Expectations of increases on cloudy and/or rainy days of above 20% appear unrealistic at this time. The amount gained thus is not likely to be more than a fraction of the water consumption. Moreover, storage of a significant fraction of the added water must be provided, either via ground water recharge or via reservoirs. Clouds do not appear where and when they are most desired. This leads to the important caveat that seeding will rarely, if ever, help as a "fire fighting" technique in times of severe drought. Droughts are produced by large-scale atmospheric conditions causing sinking air over wide areas, and the suppression of rain-bearing clouds. Thus, a seeding program, if undertaken, must be an integral part of the overall water resources program in Oman.

It is important to emphasize, however, that the steps which must be taken to determine the feasibility (and economics) of a seeding program are initially the identical steps which must be taken as part of the water resources program. They involve quantitative assessment of the atmospheric water resources. Therefore, the determination of seeding potential is guaranteed to produce scientific results of direct practical benefit to the overall water problem. Results of "Phase 1" therefore, will lead to more economic water use, prediction of flash floods, and understanding and strategies to cope with droughts, for a few examples.

The steps necessary to assess potential benefits from a seeding program are outlined in the next section, divided into phases.

7. Steps to assess cloud seeding potential

A. Phase 1 - Documentation of natural rain distributions

Steps 1 and 2 are essential in the planned water resources program, even if seeding were not contemplated.

Step 1 - Satellite study of clouds and rainfall in Oman - in conjunction with rain gage records.

Barrett (13) has described the satellite imagery available and proposed an excellent pilot study which I recommend be expedited. I believe the steps to do this are already underway. Barrett has proposed a satellite study of Oman rainfall for 1974; I only hope the necessary rain gage records are available. In any case, I recommend he do the Winter Season of 1975-1976 also since the winter has had many disturbances and also probably better rain gage records.

Until 1978, satellite studies will have to be done with polar-orbiting satellites which cross the Arabian peninsula only twice daily. In 1978 a geosynchronous satellite will be available (European Space Research Organization) which will provide continuous coverage in both visible and infrared.

Without repeating Barrett's comprehensive discussions, I will summarize what is needed and can be done from the modification viewpoint:

1) Estimates of rainfall and relationships to synoptic conditions and topography.

2) Determination of cloud top temperatures to determine whether, how often and under what conditions supercooled (colder than $0^{o}C$) clouds are found over Oman.

3) Determination of storm tracks and approximate speeds in relation to circulation characteristics.

Item 3 can be conducted with the relatively low-quality APT system (visible only) which will be set up by the Pan-American group at Seeb Airport within 6-8 months.

I urge that an HRPT (high resolution picture taking)system be installed as a regional effort somewhere on the Arabian peninsula with data access in real time if possible, to all local countries who wish to evaluate and possibly augment their rainfall. This system would be of immense benefit in water resource allocation, drought combating strategies and flash flood forecasts. In the U.S., hurricane rainfall over the oceans as they approach land is being done with these systems sufficiently rapidly to provide flood warnings if necessary [2/].

An HRPT system costs approximately $250,000 [3/].

2/ For further information contact either Dr. W.L. Woodley ERL, NOAA, Miami, Fla. or Dr. Neil Frank, Cir. National Hurricane Center, NWS, NOAA, Fla.

3/ For further information contact Robert Topham, Deputy Dir. National Environment Satellite Center, NOAA, Washington, D.C.

Appendix 1 contains a brief summary of a very preliminary cloud top temperature study I conducted of the Oman area with the cooperation of V.J. Oliver of the U.S. National Environment Satellite Center. Results were encouraging.

Step 2 - Weather radar study, calibrated by gages. This can be optimally undertaken together with both the satellite and aircraft study, if the latter is decided (Step 3, below).

The weather radar options and procedures have already been discussed in Section 5. I would recommend the experienced contractor, at least to begin with.

In the pre-seeding evaluation, radar is needed to determine both rainfall distribution, cloud patterns and the distribution of cloud tops and sizes. This is necessary but not sufficient information for deciding whether or not to undertake seeding.

B. Phase 2 - Aircraft and Rawinsonde study

To increase rainfall, the clouds must be seedable. For silver iodide seeding, there must therefore be supercooled water (below -4°C) and a deficiency of natural ice nuclei. If the clouds are freezing all by themselves, seeding may do more harm than good. It is also better if the clouds are continental (small drops) so that the natural efficiency of the rain process is not high.

Determination of supercooled water contents, ice nucleus and ice particle concentrations and drop size spectra must therefore be determined. These determinations can only be made by instrumented aircraft. My report on Qatar in Part I specifies the instrumentation necessary. For further information, see Hess (4) Chapter 4.

If the clouds over Oman are found to contain supercooled water, small ice particles and ice nucleus counts, then they may be hopeful candidates for seeding to increase precipitation efficiency.

To determine "dynamic seedability" (Hess, Chapter 6), rainsonde observations in the vicinity of the clouds is required. Then the Simpson one-dimensional model (19) can be readily run with the soundings to determine dynamic seedability.

A rawinsonde station should be established at Seeb airport as a part of the growing weather service in Oman[4/]. This would be a start. However, the mountains will modify the vertical air structure, and thus ideally rawinsondes should be sent up so that the balloons ascend over the ridge and also on the inland side. Mobile and readily transportable rainsonde facilities are now available. These could be provided by the same contractor who supplies the radar and aircraft. I will obtain itemized cost figures as soon as possible.

4/ At present there are no plans for rawinsonde facilities in Oman. The only station operating is that at Masirah Island, which would be unlikely to be representative for either the Primary (northern) or Secondary (Dhofar) areas.

C. Phase 3 - Analysis and Decision Phase

If analysis of satellite, radar, aircraft and rawinsonde data indicate a potentially favorable frequency of seeding opportunities, then a decision analysis on the various water increasing options is in order.

If a seeding program is decided upon, then the further decision must be made as to whether it will begin as a controlled evaluated experiment (expensive) or directly as an operation without statistical controls (inexpensive). In my opinion, present knowledge strongly favors the statistical, physical experiment if it can be supported and manned. The topography of Oman and the infrequency of rainfall will make a properly designed experiment very challenging. At this point, one or more expert meteorological statisticians must be called in, such as G. W. Brier of the Colorado State University and/or Dr. Ronald Biondini of the University of Virginia and Simpson Weather Associates.

D. Phase 4 - Seeding Experiment and/or Operation

It is premature to be explicit at this time. In the 2 - 3 years of Phases 1 and 2 in Oman, seeding concepts and technology will hopefully have advanced rapidly in other countries. Thus, a much better experiment design will be possible then than now.

Ease of evaluation will depend to a considerable extent on the space and time correlations of precipitation within and between potential "target areas", which should be kept in mind during Phase 1.

8. Conclusion and Main Recommendations

Cloud seeding is one of the possible options to increase water resources in Oman, hence its feasibility can and should be investigated. While it is premature to undertake seeding at this time, assessment of its feasibility is an integral part of the assessment of the atmospheric water resources in Oman. Hence, I have divided the program into Phases 1 - 4. Phases 1 and 2, satellite and radar studies, are essential parts of the ongoing water resources program in Oman, and of essential benefit to the country, regardless of whether seeding is ever undertaken. If results of Phases 1 and 2 are promising Phase 3 can be implemented, namely a careful decision analysis considering a seeding experiment or an operation. By that time, information should be available for an acceptable estimation of cost-benefits.

Oman is a hopeful area for seeding because of:

1) The integrated approach to the water problem now in progress.

2) The presence of the mountains.

3) Preliminary evidence of supercooled clouds in the winter storms.

4) Success elsewhere of seeding programs on both Mediterranean storms and cumulus clouds (dynamic seeding).

Unfavorable factors are:

1) Low and highly variable precipitation.

2) Present uncertainty regarding the fate of the precipitation.

Thus, the most important conclusion is that seeding assessment and implementation, if undertaken, must be an integral part of the overall water resources program. If so, the facilities developed can be put to multi-purpose use and the extra rain, if such there is, can be at least partially stored in ground water or man-made reservoirs.

Water can only be increased from seeding when clouds are available, and hence must be stored for dry periods. The "firefighting" approach to seeding for rain during a drought period or dry season is quite likely to be useless, while an overall "water resources" approach appears quite promising.

REFERENCES (OMAN)

1. Gibb, Sir Alexander and Partner, 1974: Hydrological and Geological studies. Vol. 1, Interim Report, Water Resources Survey of Northern Oman, The Sultanate of Oman, Ministry of Development, on file at FAO, Muscat, Oman.

2. Renardet Sauti Ice, 1975: Water Resources Survey in North-East Oman. Interim Report, Annex A. Climatology. On file at FAO, Oman.

3. Brier, G. W., 1975: Feasibility of rain stimulation in Algeria. Report prepared for the Government of Algeria, World Meteorological Organization, Geneva. Copies on file at FAO, Qatar and FAO, Oman.

4. Hess, W. N., Ed., 1974: Weather and Climate Modification, Wiley-Interscience, New York. Copy available at FAO, Oman.

5. Samuelsson, B., 1976: Draft Water development plan for Oman. UNDP/FAO Water Resources Center Project. On file at FAO/UNDP Oman.

6. Burdon, D. J., 1973: Current problems and prospects for agricultural development in the Sultanate of Oman. Report of the Joint FAO/UNDP Preparatory Assistance Mission. Vol. 6, Water Resources, FAO, Rome.

7. Simpson, J., J. C. Eden and A. R. Olsen, 1975: On the design and evaluation of cumulus modification experiments. J. Appl. Meteor., 14, 946-958. Copy at FAO, Oman.

8. Pike, J. G., J. Harhash and B.A.P. Gemmell, 1975: Rainfall and ground water recharge Qatar. Techn. Note 24, State of Qatar, Integrated Water and Land Use Project, UNDP/FAO 17 pp.

9. Pike, J. G. et al., 1975: Memorandum: Ground water resources and their development for agriculture. Unpublished note on file at FAO, Doha, Qatar.

10. Applegren, B., 1976: A summary of water resources and agricultural development reports in the Sultanate of Oman. Report of FAO/UNDP Collating Mission, Oct. 1975 - Jan. 1976, Chapter on Water Resources Development. Draft on file at FAO, Rome.

11. Harrold, T. W., E. J. English and C. A. Nicholass, 1974: The accuracy of radar-derived rainfall measurements in hilly terrain. Quart. Jour. Roy. Met. Soc., 100, 331-350. On file at FAO, Oman.

12. Barrett, E. C., 1975: Rainfall in Northern Sumatra. Analyses of conventional and satellite data for the planning and implementation of the Krueng Jreue/Kruerg Bar Irrigation Scheme Final Report under Contract to Binnie and Partners. On file at FAO, Rome.

13. Barrett, E. C., 1975: The scope for remote sensing in the search for solutions to water supply problems in the countries bordering the Gulf. Consultant's Report for FAO, UNDP. On file at FAO, Rome, Qatar and Oman.

14. Griffith, C. G. and W. L. Woodley, 1974: Rainfall estimation from geosynchronous satellite imagery. Proc. 11th Space Congress, 2, Cocoa Beach, Florida, April 1974, pp. 5-16 to 5-24.

15. Plessey Co., 1976: The Dee Water Radar Project, 1975. The Plessey Co., Ltd. Addlestone, Weybridge, Surrey, England. Copy on file FAO, Oman.

16. Woodley, W. L., A. R. Olsen and V. Wiggert, 1975. Comparison of gage and radar methods of convective rain measurement. J. Appl. Meteor., 14, 909-928.

17. Simpson, J., 1976: Report on the CIC-LTK hail suppression programme in Nelspriut, S. Africa. Draft copy on file with NHRE, NCAR, Boulder, Colorado International Corporation, Boulder, Colo. 80302, USA.

18. Woodley, W. L. and A. Herndon, 1970: A rain gage evaluation of the Miami reflectivity rainfall rate relation. J. Appl. Meteor, 9, 258-274. Copy on file at FAO, Oman.

19. Simpson, J. and V. Wiggert, 1969: Models of precipitating cumulus towers. Monthly Wey. Rev., 97-489. Copy on file at FAO, Oman.

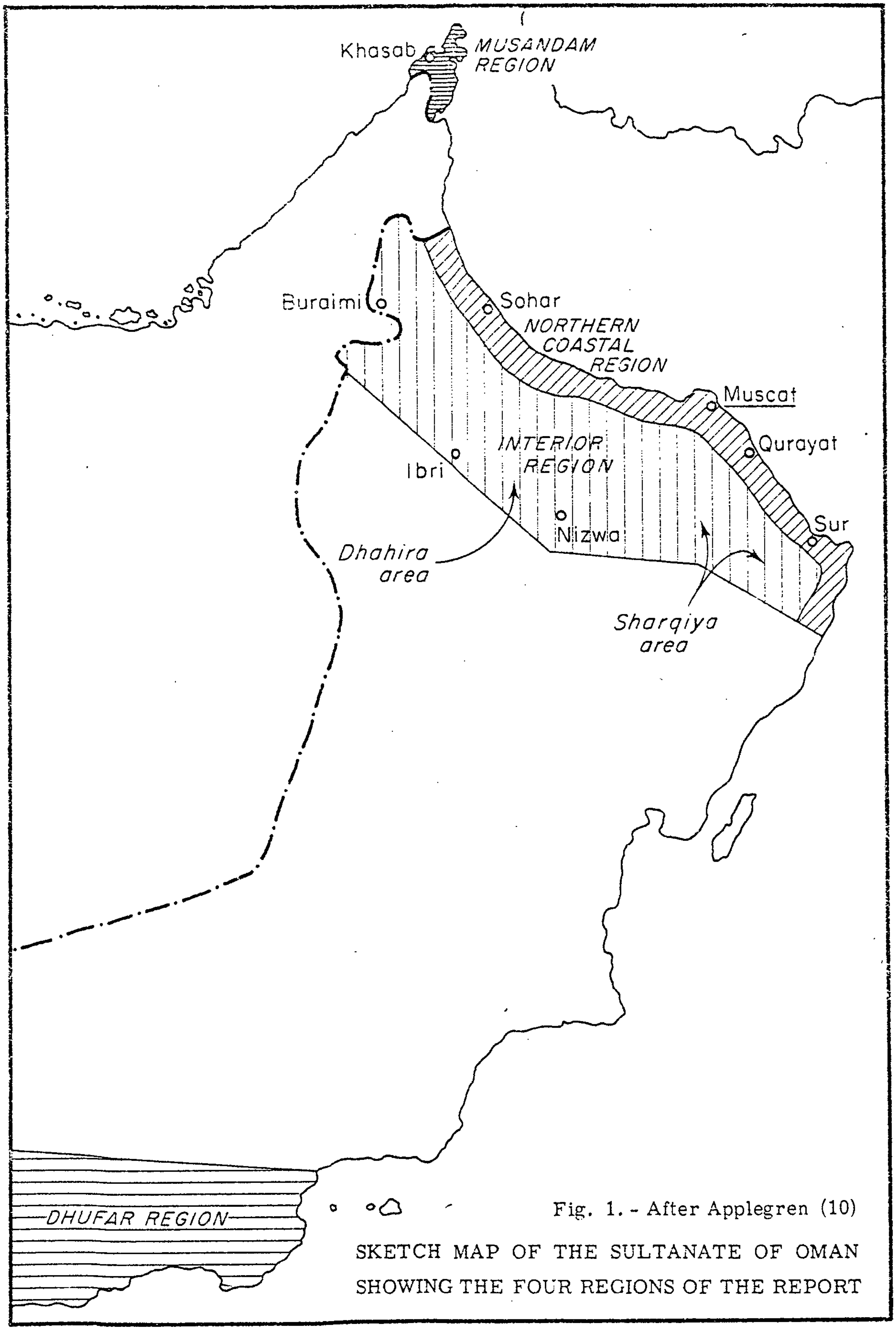

Fig. 1. - After Applegren (10)

SKETCH MAP OF THE SULTANATE OF OMAN
SHOWING THE FOUR REGIONS OF THE REPORT

APPENDIX I

Preliminary Satellite Studies and Further Rainfall Statistics

A. Preliminary HRIR Study, January 1976

HRIR stands for "high resolution infra red". The resolution is about 1 km. The importance of this tool is that it gives cloud top temperatures. Poorer resolution will average over too large an area and give too warm cloud top temperatures.

Mr. Vincent J. Oliver of NOAA's National Environment Satellite Service kindly worked with me during January 1976 to examine cloud top temperatures over Oman using this tool. We examined the pictures and digitized products for January and February 1973. Two or three storm centers passed north of the area which produced middle and low clouds over Oman. The clouds occurring in January clearly reached freezing temperatures. In the first two days of 1973, a cold front went across, bringing in clouds from the Indian Ocean with sub-freezing tops. Later in the month, there were also fronts from the north, with subfreezing clouds. It was not possible to say from the imagery whether or not these clouds were precipitating, although Barrett's study would enable an estimate.

There is a man from Iran at NESS who is studying satellite imagery in the Gulf area. He said there were several days of thunderstorms in the area without rain over the mountains. I am unaware of the basis for his conclusions.

The satellite used here is polar-orbiting NOAA 2, which goes over the Gulf between 9 - 10 a.m. and 9 - 10 p.m. local time, so that afternoon regimes are not seen.

In my report, I have recommended an HRPT system in the Gulf area for further satellite studies of this type. These will become particularly powerful when a geosynchronous (full time) satellite begins viewing the area in 1978.

For further information, write to Prof. E.C. Barrett or Mr. Robert Topham, NESS, NOAA, Washington, D.C., U.S.A.

B. 1976 Rainstorms

This information was kindly provided by Tom Hoopes, of Pan American at Seeb airport. It was received by him in a letter from Keith Grant at the Meteorological Office at Masirah Island.

Satellite pictures (NOAA satellite) for 28 January, 1, 2 and 6 February, 1976, accompanied the letter. They cannot be reproduced here but, if desired, prints could be obtained from the NOAA National Climatic Center, Asheville, North Carolina, U.S.A.

In early 1976, three marked troughs in the upper westerlies passed across Oman, on 28 January, and 2 and 7 February. The subtropical jet stream is at its strongest and furthest south at this time of year. Ahead of such a trough, ascent in the west-southwest winds gives thick medium cloud, high cloud and rain. It may reactivate an old cold front. The trough brings with it cold air which sets off thunderstorms on or ahead of the front; sometimes there is a double band of cloud at first. The topography in the area tends to obstruct the cold air. When this happens, the line or band of cloud may change into a large circular area of thick cloud, perhaps with a cynclonic circulation at mid-levels, producing heavy thunderstorms for quite a while before moving eastwards into the Arabian Sea. This happened on 27 - 28 January 1976 and is beautifully illustrated on the NASA satellite photograph. The picture showed a near-circular area of thick cloud 4 degrees latitude (450 km) in diameter between Seeb and Masirah. Lightning and squalls were experienced widely. Nearly 20 mm of rain fell at Ruwi, more than 15.5 mm at Muscat, 11.5 mm at Saiq, 18.0 mm at Rostaq and 3.1 mm at Nizwa.

The second trough (2 February) exhibited strong instability, with thunder, lightning and reported hail on the north coast. The low moving eastward over Iran split to give a slow-moving low in the Gulf of Oman on the first. The main low moved toward Kashmir but a trough remained over the Gulf of Oman until late on the second. The satellite photograph for the first shows an extensive cloud shield oriented north-south, with the southern portion approaching Oman. The cloud mass is clearly banded, with band orientation NNE-SSW.

At Ruwi, 7.0 mm of rain were recorded, 18 mm fell at Muscat. At Seeb airport, 8.9 mm were recorded, with a report of hail from Sib village. The police reported localized flash floods on the inland side of the Jebel. Rostaq had 6.1 mm of rain; Saiq a trace. Either no rain or no reports occurred at Rumais and Nizwa.

On 6 February, a third trough (fifth of the winter season) gave the usual sequence of weather over the Persian Gulf, with a period of rain at the cold front. There was a line of cumulonimbus clouds on the front; there was also a prefrontal squall line early on 6 February, giving an 8 mb pressure drop in 3 hours at Seeb Airport. The satellite picture shows this double structure beautifully, with the two main cloud bands oriented northeast - southwest. Rainfalls were 12.0 mm at Ruwi, 6.0 at Muscat and 7.5 mm at Muttrah. Seeb airport reported 15.0 mm. Observations for Nizwa, Saiq, etc. were not available; nevertheless rain occurred as far south as Butabul. Local flooding was reported.

C. Additional rainfall statistics

Grant's letter to Hoopes further reports [5/] that the average rainfall at Muscat in January is 25 mm and 18 mm in February (about 43% of the total). The average number of days with 1 mm or more is 2 and 1. The maximum rainfall in 24 hours (during 38 years) 79 mm in January and 56 mm in February. There has been 1 day in ten years with thunder in January; 3 days with thunder in 10 years in February (12 year record). It is also asserted by this source that there is more rain and thunder over the Oman mountains in these situations than on the coast.

5/ According to IDCR No. 108 - Persian Gulf States on file at Masirah Met Office

APPENDIX 2

On Seeding Possibilities in the Dhofar Region

Since the Dhofar rain regime is monsoonal with a summer maximum, my limited time in Oman this visit did not permit a visit to Dhofar. However, I was able to obtain considerably more data on rainfall in Dhofar than I was for the primary Northern area. This was owing to the reports of Sir William Halcrow and Partners, in particular (1).

Their report shows rain distributions in all months which appear lognormal, with about half the total falling in July and August. They present 30 years of record at Salalah (1943-1972), which I suspect will also be well fitted by a lognormal or gamma distribution.

The average rainfall for the period was 106.5 mm. Eight of the 30 years were average (one) or above average (seven) while 22 years were below average. The record high was 500 mm in 1963, while the record low was about 35 mm in 1962 and 1968.

The clouds in monsoon regimes are cumulus and cumulonimbus in tropical air. Usually the coalescence process is active, the clouds would surely have maritime or partially maritime character (wants testing). Hence, my estimate is that only dynamic or hygroscopic seeding would be productive.

This is based on Florida experience which shows usually fairly high natural ice particle counts except in young, active updrafts. Hence, supercooled seeding for increase of precipitation efficiency only is likely to be ineffective or counterproductive.

Since hygroscopic seeding is still not proven effective, I would recommend postponement of its consideration. I would recommend, if data and funds permit, the first steps in investigation of dynamic seeding potential, namely running the one-dimensional cumulus model on soundings made in the area. The soundings from Masirah Island in summer might be representative, although that wants investigation.

If the soundings in the Dhofar area show good dynamic seedability, then the cloud population studies by satellite can estimate how often seedable clouds are present. If may be possible at that point to use Florida results to make a ball park estimate of seeding potential in terms of rain augmentation.

Whether or not a weather radar should be installed in the Dhofar area to pursue these possibilities further depends on the allotment of priorities in the joint water resource effort of the Omani government with the UNDP/FAO.

A serious reservation in extrapolating Florida results to the Dhofar area is found in the Report by Renardet Sauti Ice (2). That report emphasizes the meteorological effects of the upwelling of very cold water off the Dhofar coast in summer, leading to frequent fog and stratus clouds. A strong inversion is suspected in this region of colder sea surface than overlying air. The Renardet report hypothesizes that the inversion rises inland owing to the surface heating and roughness. If the inversion rises high enough so that cloud tops are restrained from growing above the -8^{o}C to -10^{o}C level (perhaps 6 - 7 km), then conditions for dynamic seeding might be ideal, in that the extra heat released could cause lowers to break through a weak remaining inversion. However, if the inversion is at a lower altitude than where the -8^{o}C to -10^{o}C temperature level occurs. This could be fatal for dynamic seedability. The need for radiosonde observations and model runs for the Dhofar area is clearly first priority there, prior to any further considerations of seeding.

REFERENCES (APPENDIX 2)

1. Halcrow, Sir William and Partners, 1976: Memo on Agriculture in Oman and Section 2 of Report entitled "Hydrometeorology". Copy kindly provided to me by J. Anderson of Halcrow and Partners. Presumably there is a copy on file at FAO/UNDP, Oman.

2. Renardet Sauti Ice, 1975. Water Resources Survey in North-East Oman. Interim Report. Annex A. Climatology, on file at FAO, Oman.

APPENDIX 3

My Visit to Oman

I visited Oman from 2 - 13 February 1976, inclusive. I consulted extensively with Dr. Bengt Samuelsson, Director of FAO/UNDP Water Resources Project, with his colleagues, and with members of the Omani Government concerned with water resources. I also studied rainfall and related data from the Consultants reports, coordinated my recommendation with those of Dr. E. C. Barrett, and made several field trips. Upon leaving, I left a book and numerous reprints with the project, and a draft of my reports on both Qatar and Oman. I was fortunate to observe two very good rainstorms, one with thunder and lightning.

Calendar of Visit

Monday 2 February - Coordination of schedule and preliminary discussion with Dr. Samuelsson.

Tuesday 3 February - Lenghty meeting with Mr. Morvan, Head of the UNDP Project in Oman. Detailed briefing on all aspects of project, history, agencies and persons involved.

Met with Mr. Al Bushi, Sudanese Advisor on Water and Petroleum. He is employed by the Omani government. He is a geologist with American training. We discussed weather modification, and specifically the Florida project.

Mr. Samuelsson and I then went to the airport where we were given a detailed briefing on the growing weather service by Mr. Tom Hoopes, head meteorologist of the Pan-American contractor. We also discussed communications and navigation aids with an FAA expert. These of course are essential if an aircraft research or seeding project is undertaken. It appears that weather facilities and communications would be adequate for a seeding project in 1 - 2 years, except for the needed rawinsonde facility.

The cloud bases were well below the mountain tops on this day. There were good buildings offshore; hail had occurred on the coast in the afternoon.

Remainder of day: Discussed weather data with Samuellsson, met his Omani counterpart, Mr. Macki, and studied Consultants reports.

Wednesday 4 February - Met Mr. Morshidy, FAO Project Coordinator, discussed need for more water in Salalah area.

Met Dr. Hesse, Project Manager for Soils and Water Management, FAO.

Met with Dr. Peter Horn, FAO hydrologist.

Studied Samuelsson's and other reports on water resources in Oman.

Thursday 5 February - Went to see Mr. Ali Shanfari, deputy to the Deputy Minister for Agriculture, Petroleum Affairs and Fisheries. Discussed weather modification potential and the possibility of a helicopter survey.

Lunch at Dr. Jaeckli's of the Petroleum Development Organization (PDO). He reported observed occasional snow on the Jebel. Met several persons at PDO who will put me in contact with their pilots and aviation people.

Evening gathering at Samuelssons.

Friday 6 February - Morning went with Peter Horn and Bob Thomas up a Wadi to observe the rain, its run-off and for Thomas to measure the water conductivity. Went as far as Bid'bid.

Went to a large luncheon at El Morshidys. Returned to hotel 5 p.m. for further study, sky still overcast.

Saturday 7 February - Clear. The fifth storm of the season has passed.

Worked at Samuelsson's office on data and Consultant's reports. Went again to visit Mr. Hoopes at airport to discuss storm. Met with Mr. Ray Seifert of FAA to discuss military radar. Further discussion with Samuelsson regarding how to implement rain measurement project.

Dinner and discussion with P.D.O. pilots on Oman clouds and weather.

Sunday 9 February - Met with American Ambassador, Mr. Woolly and his economic advisor. Discussed whole water project and role possibly played by seeding. Discussed how to evaluate seeding potential, also training in environmental sciences in US, and how trainees might participate in Oman water resources project.

Meeting with Minister of Agriculture, Petroleum Affairs and Fisheries, Mr. Shanfair. Present were:

Samuelsson
Thomas
Simpson
El Morshidy
Morvan
Macki
Contiadis
Salim
Shaban (Dir-Gen, Agriculture and Water Resources).

Morvan gave general introduction on program. Minister quizzed me in detail on seeding possibilities. We emphasized overall water resources approach and necessary assessment steps as parts thereof.

He said helicopter would be arranged and also a showing of the FACE (Florida) cloud seeding film.

Worked on reports.

Monday 9 February - Met with Shaban, Director General of Agriculture and Water Resources.

Discussed regional cooperation in matters such as satellite equipment. He said Omani group would consider my report and deliberate what position to take. Then visited Statistics Department, Staff 10 persons. Director Ms. Abdulaimir, Omani trained in Baghdad; UN Expert Mr. Gasin Mousa from Sudan. They do not yet have computer or calculator facilities. Have put out a detailed report on growth of population, students, roads, etc. with a small section on rainfall. Discussed cooperation with FAO project, participation of some FAO staff in statistics course.

Afternoon worked on reports.

Tuesday 10 February - Field trip with Omani Construction Co. (Mr. Magnusson, Engineer) up several wadis to Quriyat, examined falajs, wells groundwater, wadi flows etc. The falaj irrigation system was particularly interesting.

Wednesday 11 February - Worked all day in Samuelsson's office on report.

5 P.M. showed FACE film in Office of Director-General Shaban. Discussion and questions followed.

Thursday 12 February - Helicopter field trip to observe mountainous area to Saiq and Sur.

Friday 13 February - Final discussion with Samuelsson on draft report, plans etc. Collected weather data from January - February 1976 storms from Tom Hoopes (Pan American) and Peter Horn, FAO hydrologist.

Saturday 14 February - Depart for Rome 8 a.m.