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THE EARTH'S GASEOUS HYDROSPHERE AS A NATURAL RESOURCE

VICTOR P. STARR & DAVID A. ANATI

Massachusetts Institute of Technology, Cambridge, Massachusetts

Consideration is given to the desirability of regarding the water vapor of the atmosphere as a resource for the extraction of fresh liquid water by artificial means. One method for doing this, previously proposed by the writers, is analyzed from the standpoint of simple dynamic calculations, using actual meteorological data taken in the Middle East and the Gulf of Mexico. Various problems and design features of the scheme are discussed in the light of climatological factors and of meteorological physics. The necessity of much preliminary study is stressed, in order to increase the probability of success of an initial experimental unit. Due to the importance of cost considerations, ways of decreasing the minimum necessary size of the device proposed are considered for incorporation as design features. In effect the method may be looked upon as the generation by artificial means of a captive and controlled miniature rainstorm. In certain special arrangements it may also be regarded as a means for the desalinization of sea water.

During the past two decades the first author of the present discussion and his collaborators, especially Professor José Pinto Peixoto, have studied the atmospheric branch of the hydrological cycle with the aid of detailed instantaneous and averaged meteorological data from all available observations over the northern hemisphere for a period of several years. Southern hemisphere observations were also employed for the IGY year 1958 (see, e. g. Peixoto 1970). During this period we have kept a watchful eye for the possible utility for practical problems of the various kinds of scientific information gained in these studies. The particularly forceful impression that came to us, which is of consequence for the present discussion, is that the portion of the hydrosphere represented by the water vapor in the atmosphere as a whole constitutes a natural resource which has not as yet been tapped artificially to any extent for the purpose of filling practical needs, and that new methods for doing this should be devised and investigated.

Perhaps the prime objective for such developments is the artificial and controlled extraction of fresh liquid water from the vapor content. Viewed thus, the atmosphere is a huge reservoir of one of man's most basic necessities. In varying concentrations, water vapor is present in the atmosphere in all localities, even where other fresh water sources are practically absent. What is needed especially here are effective means for its utilization. Some methods for doing this have been proposed, and are or may be of actual usefulness. The purpose of this brief paper is to try to reinforce interest in the subject by a further discussion of the relatively novel approach expounded elsewhere by the present writers (Starr & Anati 1971). There may of course be better ways of accomplishing the result desired, and we wish to encourage discussion of them.

In nature practically the entire supply of fresh water of the globe is derived from the precipitation process with all its complexities, known and unknown. During the past three decades or so extensive experimentation has been done in attempts to modify the large-scale natural precipitation process by artificial means, so to speak *in situ,* through the introduction of chemical condensation stimulators and the like. It is encouraging in some respects for our present purpose that these efforts have resulted in a certain degree of success. Our aim is again to retain particular essentials of the natural liquid water production mechanism, but to have it operate on a much smaller scale and, by contrast, within the confines of an engineered piece of experimental equipment – so to speak, partially at least, *in vitro* – where it can be controlled, protected from disruptive environmental factors, and possibly enhanced by various artificial measures. In their previous discussion, the writers used the term *aerological accelerator* to designate the device envisioned here to fulfil this purpose.

SCIENTIFIC BASIS FOR CONTROLLED PROCESS

Although much of what is now to be said is standard information for most meteorologists, others may find it easier to grasp the essence of the present subject if certain much simplified pertinent concepts are explicitly described. (Readers familiar with the concept of parcel instability for a moist atmosphere may skip most of this section.) In any case, it reflects a certain amount of logic to approach the various problems involved from the beginning.

In Fig. 1 we have plotted the aerological sounding taken at Aden on the southern coast of the Arabian peninsula (about 100 miles east of the entrance to the Red Sea) on 5 June 1958 at 1200 GMT (about 3:00 P.M. local time). The light dashed curve traces the temperature structure of the atmosphere (slanted T scale) as a function of approximate height (more nearly the log of the pressure on the vertical scale). The numbers to the left of this curve give the value of the mass mixing ratio of water vapor to dry air in grams per kilogram at various levels. The background isolines for temperature, T, mixing ratio X_m, potential temperature Θ, equivalent potential temperature Θ_e, and pressure p comprise a form of thermodynamic chart known to meteorologists as a *tephigram* (see, e. g., Brunt (1941) for details on this general subject). As suggested in our previous paper, we have chosen a moderately favorable condition in the atmosphere for illustrating the actions to be described, leaving problems which arise under less clear-cut circumstances for possible consideration below and also elsewhere at a later time.

We select a parcel of air from the base of the sounding curve, the station elevation in our case being about 4 meters above sea level. We next assume, as is usual in procedures now being described, that the parcel is lifted through the environment (light dashed curve) without external addition of heat, but so as to be in equilibrium with the ambient pressure. Thus at first the sample will expand dry adiabatically, and the point representing its physical condition will move (light full curve) along a potential temperature line, retaining its initial mixing ratio. After reaching a pressure low enough so that the expansion has caused it to cool to its condensation level, the point will move, according to the simple theory now envisioned, along a moist adiabatic curve or equivalent potential temperature line – with vapor condensing out of it progressively, so that the mixing ratio decreases. We note that in our example the parcel being lifted is at practically all levels warmer than its environment at the same pressure. This is in large part due to the release of latent heat of condensation within it – any liquid water falling out of it being of minor consequence here, although such liquid removal will be of prime importance later for the practical effects desired in our scheme.

The density of air is determined, at a given pressure, jointly by the temperature T and its composition. In many cases the dependence upon variable composition can be neglected, but in our case, since the water vapor content is high and also variable, account of it must be taken. This can be achieved by considering a correction to the temperatures shown as light dashed and solid curves of our diagram. The so-called virtual temperature T' (see Brunt 1941) allows for

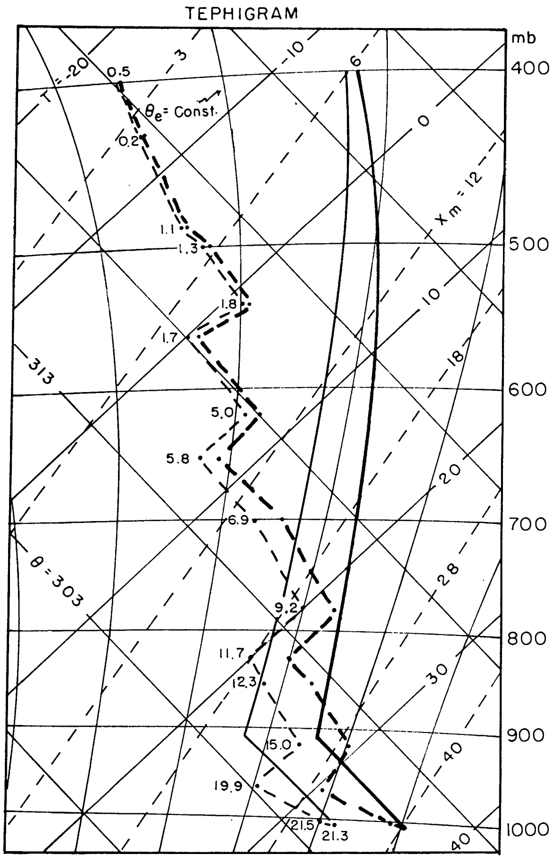

Fig. 1.

Plot of meteorological sounding taken at Aden on 5 June 1958 at 1200 GMT. The light dashed curve represents temperature in °C and the numbers to the left of each data point give the mixing ratio of water vapor to air in g kg^{-1}. The heavy dashed curve represents the corresponding virtual temperature. The light full curve gives the locus of a surface air parcel lifted first dry, then moist, adiabatically to the top of the sounding. The heavy full curve gives the corresponding virtual temperature of the lifted parcel.

the lesser density of water vapor by fictitiously defining a higher, vapor-free air temperature having the density of the mixture. The heavy dashed curve gives the environmental, while the heavy full curve gives the parcel virtual temperature in our case.

The upward buoyancy force a on the parcel, per unit mass, is

$$a = \frac{\varrho - \varrho^*}{\varrho^*} G \qquad (1)$$

where ϱ is the environment density, while ϱ^* is that of the parcel at the same level, and G is the acceleration of gravity. Since in our sounding the virtual temperature of the parcel is higher than that of the environment at practically all levels, the equation of state

$$\varrho \equiv \frac{P}{RT'} \qquad (2)$$

applied to the two cases tells us that the buoyancy force on the parcel is positive, i. e., upward. The gas constant is denoted by R.

What has been described is the simplest form of the theory of hydrostatic instability using the so-called parcel method as applied to moist convection such as is found in thunderstorms and other large convective units involving condensation of water vapor. According to this theory, if the parcel finds itself subject to an upward buoyancy force, it (and others like it) should continue to rise, creating an organized local updraft and associated precipitation if the action is of sufficient vigour.

Usually a chance vertical impulse for the parcel is required initially in order to set off the instability.

As was indicated in the paper by Starr and Anati already cited, what we propose is to enclose a moist convective updraft in the actual atmosphere within an essentially vertical tube of large dimensions. The tube, in the first instance at least, is here supposed to be of circular cylindrical shape with uniform diameter and both ends open. The lower end is considered to be close to the earth's surface so as to serve as an intake for moist air. By this means the process of convection could be localized, controlled, and protected from disruptive influences, as is to be explained later. In what follows, some very gross effects are estimated for such an engineered structure, using the simple theory outlined and the meteorological conditions shown in the sounding discussed above.

ESTIMATED MAGNITUDES OF SOME DYNAMICAL QUANTITIES

To gain certain advantages of concreteness we assume, somewhat arbitrarily, that the diameter of the tube is 100 meters and that its height is 3 kilometers (let us say, extending from about 1000 to 700 millibars). From Fig. 1 we estimate that the rising air inside the tube would have a vertically averaged virtual temperature T' about 3°C higher than that of the environment similarly averaged. Since the mean virtual temperature of the sounding is close to 300°A, and since the pressure on the inside must be but slightly different from that outside, it follows that the mean density of the air inside is about 1 % lower than that of a similar column in the environment. Under these circumstances the weight of the interior column is less than that of the exterior, and will therefore tend to be displaced by the heavier air entering the open bottom end of the tube, thus creating an upward current in the latter.

According to Eq. (1) the upward buoyancy force, a, per unit mass is about 10 dynes g^{-1}; still considering vertical averages only. This mean force on the air within the tube must accomplish two major effects, apart from some possible secondary actions.

1. It must impart to the originally resting air at the intake an upward momentum which is then continually lost at the upper end of the tube.
2. It must overcome frictional retarding effects mainly at the walls of the tube. The larger the diameter of the tube, the smaller relatively speaking will be this retarding effect, leaving a larger fraction of a available for the accelerative action.

Customary engineering formulae give the following expression for for the frictional stress τ at the wall, exerted by a turbulent fluid

$$\tau \equiv \varrho \, C_D w^2 \qquad (3)$$

where ϱ is the mean density, C_D the drag coefficient, and w the vertical velocity. We take ϱ approximately as 10^{-3} g cm^{-3}, C_D as 1.3×10^{-3} (see, e. g. Schlichting 1968), and w tentatively as 15×10^2 cm sec^{-1}. This gives τ to be nearly 3 dynes cm^{-2}. With this value of τ the frictional retarding force for the mass of air in the tube turns out to be about 1.2 dynes g^{-1} on the average, or about an order of magnitude smaller than a. We thus obtain a residual mean vertical acceleration of 8.8 cm sec^{-2}.

The actual distribution of the acceleration making up this mean value is probably not uniform in the vertical. Due to more detailed dynamic effects it no doubt has high values at and near the intake and lesser values higher up. Nevertheless it is reasonable to estimate that were the mean value to operate uniformly on a particle during its residence time within the tube, it should be capable of generating the vertical velocity of 15×10^2 cm sec^{-1} which we have assumed, and which corresponds to a residence time of 200 sec. We see that according to our approximations this is the case, the velocity generated being 17.6×10^2 cm sec^{-1}, which is close enough for our present rough purposes.

From what has been said thus far, using the assumptions made, especially that of pseudoadiabatic flow, it appears that some of the gross necessary dynamic conditions for the successful operation of our accelerator are met for the actual structure of the atmosphere given by the sounding used. As a point of departure, and for formal purposes only, let us compute the ideal rate of water production, retaining the identical assumptions made thus far. Using Fig. 1 we see that the intake air has a mixing ratio of 21 g kg^{-1}, while that leaving the top at 700 mb contains 15.5 g kg^{-1}. The *maximum* water production corresponds therefore to a difference of 5.5 g kg^{-1}. For a mean flow of 15×10^2 cm sec^{-1} over the cross-section of the tube and a mean density of 10^{-3} g cm^{-3}, the total mass transport is 1.2×10^8 g sec^{-1}. Multiplying by 0.0055 we get 6.4×10^5 g sec^{-1} for the water production, or about 2300 m^3 per hour. One half of this rate would probably be a more realistic expectation, because of water losses at the upper end of the tube.

COMMENTS AND DISCUSSION

As compared with natural thunderstorm convection the flow in the tube has some attributes which contribute toward greater efficiency. In the first place, in the natural system the source of moist air is not at the lowest levels (let us say over a warm ocean surface where the humidity is highest) but at a somewhat higher elevation. In the case of the tube, however, the intake can be located so as to suck up air from the surface layer in contact with the water. Furthermore, natural updrafts are subject to derangement by the general wind shear and are weakened through the mixing of drier air from the environment into the rising air. Both of these adverse actions can be eliminated by the presence of the tube.

On the other hand, the natural updrafts are not subject to wall friction and can be of much larger horizontal diameter. Also, as seen from Fig. 1, large differences between the virtual temperature of the rising column and the environment may exist at elevations above 700 mb. These would normally be utilized in natural convection, but their utilization can hardly be contemplated for tube processes because of engineering difficulties. However, as mentioned by us in the prior paper, it is possible that the moist air with vertical momentum exhausted from a device extending to 700 mb or so might initiate natural convection at higher levels. Individual cells of this free convection conceivably could then drift off as autonomous thunderstorms. If the aim is not only to collect water from the interior of the tube, but also to influence the climatic regime in the vicinity, then such breeding action might be of considerable significance.

Within the limitations of the assumptions made, the rough estimates of dynamic quantities given above are probably satisfactory in so far as they go. However, endeavors should be entered upon seeking much more detailed information. One avenue of approach is to make a mathematical model of the flow in the tube including at least the bottom end effect if not also the top, assuming let us say a plane sheet of warm water in close proximity below. (Problems of this general type, but dealing with dry convection, have recently been entered upon theoretically by Hart (1970).) The flow might be thought of as steady and symmetrical about the axis of the tube. Because of the difficulty of solving such a complex problem, no doubt numerical simulation would be desirable. Nevertheless, even were a solution to be obtained, with all the detail that it would no doubt make available, much would still depend upon various categories of assumptions incorporated into it. For this and other reasons we must continue the discussion of further aspects of the physical conditions of the entire subject. Some additional points which are of importance are the following.

1. In selecting Aden as a sample location the writers were partly influenced by the scarcity of fresh water in the Middle East in general. Aden itself hardly ever records rainfall during the warm season. Thus in spite of the high humidity prevailing at this time of the year, no rainfall was measured during June in the 10-year period 1951–1960 inclusive, according to the publication *World Weather Records.* The mean annual precipitation is about 4 cm, occurring mostly during the winter months. A similar climatic regime seems to characterize the Indian Ocean and Red Sea littorals of the southern portion of the Arabian peninsula.

For the sake of interest there is reproduced in Fig. 2 the plot of the sounding for Aden taken on 4 June 1958 at 1200 GMT – i. e. twenty-four hours earlier than that shown in Fig. 1. In other respects the two figures are identically constructed. It is to be seen that in general the conditions for vigorous operation of our device were better on 4 June, if the same assumptions are retained.

The question is to be asked why natural thunderstorm activity did not arise in view of the conditions present as shown in Figs. 1 and 2. Perhaps a partial answer is that an apparent lack of sufficiently strong perturbations enables the series of small stable layers or inversions to prevent the release of the moist instability evident in the soundings. Accordingly, it could follow that the perforation of these damping layers by a tube device might furnish a sufficient derangement of the natural inert state to induce free thunderstorm formation, as already stated.

2. There are, no doubt, various other regions over the globe where favorable

conditions for confined convection exist. A climatological study of the kind needed for this purpose would be of interest. We did note, however, that aerological soundings along the coast of the Gulf of Mexico indicate good possibilities for experimentation, even though fresh water is not in such short supply here as it is in the Middle East. As an example we reproduce in Fig. 3 the plot of the sounding taken at Brownsville, Texas, on 20 August 1958 for 0000 GMT. The plan of the figure is again that of Fig. 1. The indications are quite favorable for our type of confined convection – perhaps even more so than for Figs. 1 and 2. (Water demand exceeds the supply in the Texas region.)

3. A feature of much importance illustrated in Fig. 1 is the great sensitivy of the convective action on the degree of saturation of the intake air. Were it possible to increase the intake mixing ratio by about 5 g kg^{-1}, without altering the potential temperature, so as to lower the condensation level to about 950 mb, the vigor of the convection would be about doubled. Alternatively, it might then be feasible to reduce the height of the tube from 3 to, let us say, 1.5 km. Possibly with still further saturation it might even be reduced to 1 km. As a third consideration, through the added moisture from evaporation, locations otherwise unfavorable for our scheme might still be amenable to successful operation of it. To achieve results of this kind, some efficient means would have to be found for causing evaporation from the warm sea surface to take place in such a manner that the latent heat needed would be supplied by the sea water and not at the expense of the intake air itself. Could this be achieved, the action of the whole scheme would comprise a desalinization process for converting sea water into fresh.

The sounding plotted in Fig. 1 was actually taken at Khormaksar a suburb several miles north (inland) of Aden. The high surface temperature is then probably due to a strong solar heating of the land surface during the afternoon. A local industry in the vicinity is the production of salt through the evaporation of sea water in open salt pans by heat from the sun. This suggests that further evaporation from salt water into the warm air is possible. A large diameter flare at the lower end of the tube, similar in some respects to certain versions of the Borda mouthpiece (see, e. g., Lamb (1932) and references there given) might be useful to enhance further evaporation. The outer edge could then be placed close to the salt water surface while still providing sufficient intake space. Before proceeding further along lines such as these, it is better to examine some of the assumptions we have thus far made.

4. From the scientific point of view the most important physical question relates to the pseudoadiabatic process within the tube. Will the condensation take place

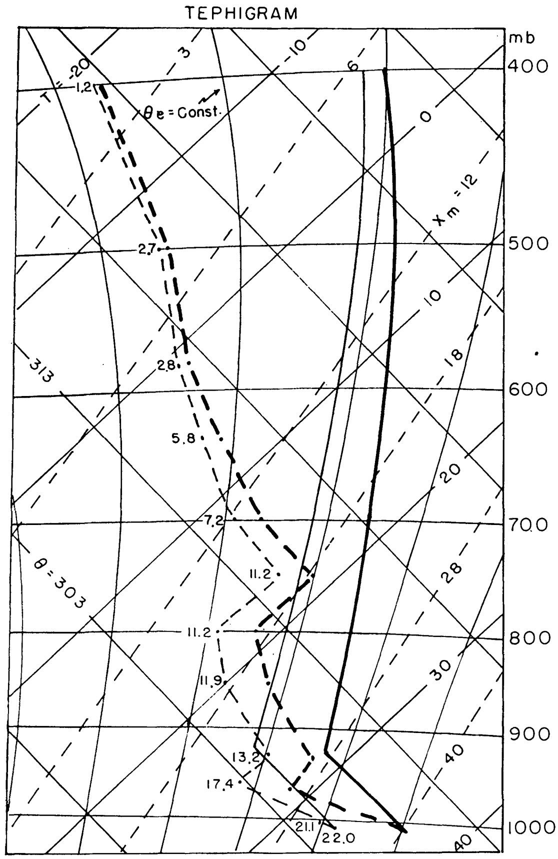

Fig. 2.

Plot of meteorological sounding taken at Aden on 4 June 1958 at 1200 GMT. The light dashed curve represents temperature in °C and the numbers to the left of each data point give the mixing ratio of water to air in g kg^{-1}. The heavy dashed curve represents the corresponding virtual temperature. The light full curve gives the locus of a surface air parcel lifted first dry, then moist, adiabatically to the top of the sounding. The heavy full curve gives the corresponding virtual temperature of the lifted parcel.

as expected, and will the water collect into drops to form a runoff on the sides of the tube or as otherwise arranged? All that can be done here is to list questions, since generally speaking their correct answers will no doubt be slow in coming, and in the case of some will have to await full-scale experiment.

The air passing through the tube will experience exchanges of heat through radiation and conduction with the walls. These exchanges could either increase or decrease the temperature difference between the interior and the environment. Thus if sunshine is present, the tube and its contents would no doubt be warmed by the so-called greenhouse effect and hence the buoyancy action would be increased. The effect on the condensation rate might be adverse, however. Without sunshine the long-wave radiation influence might be to reduce the temperature difference between inside and outside. These possible radiative actions presumably would be less the larger the diameter of the tube and the higher the vertical velocity (i. e., the shorter the residence time). Unless other means were to be provided, the greenhouse effect could likely be depended upon to operate as a starting mechanism to initiate the convection from rest.

In the actual atmosphere the formation of cloud material and, finally, raindrops involves the presence of condensation nuclei and of mechanisms for the accumulation of cloud moisture into drops – processes which still are but imperfectly understood. In the tube conditions would be somewhat altered. For one thing it would be unlikely that cirrus ice crystals could form. However, much experimentation could be done with dry ice, silver iodide, etc., especially in a full-scale device. In fact, as a cloud physics laboratory the apparatus might offer unparalleled advantages in certain directions.

Assuming that droplets of appreciable size are formed, there is the problem of collecting them into a runoff, otherwise the convection might proceed as outlined but all the water be blown out of the exhaust end of the tube. From this consideration it probably would not be to advantage to achieve abnormally high vertical velocities. However, design features could be incorporated to help the situation. For example, baffles could be installed in such fashion as to give the updraft a rotation about the vertical. This action might then fling droplets against the walls where the water could trickle into a system of gutters and conduits for its disposal. On the other hand, it might help to incorporate varicosities or bulges in the diameter of the tube at proper places where the updraft speed might diminish to facilitate the fallout of droplets.

5. An essential feature of the process of water production in our device is that a rapid transfer of air particles to lower pressure takes place due to the convective motions. Since the hydrostatic drop-off with height of the pressure is, in a sense, rather slow, a large vertical dimension of the apparatus is required. This pressure drop-off in a small-scale model would have to be more rapid if a laboratory test of the processes involved were to be made. This could perhaps be achieved in an accelerated coordinate system through the use of a centrifuge which would in effect increase gravity. However, the prospects of success do not appear very encouraging. In other respects laboratory research might be of benefit in the design of our accelerator.

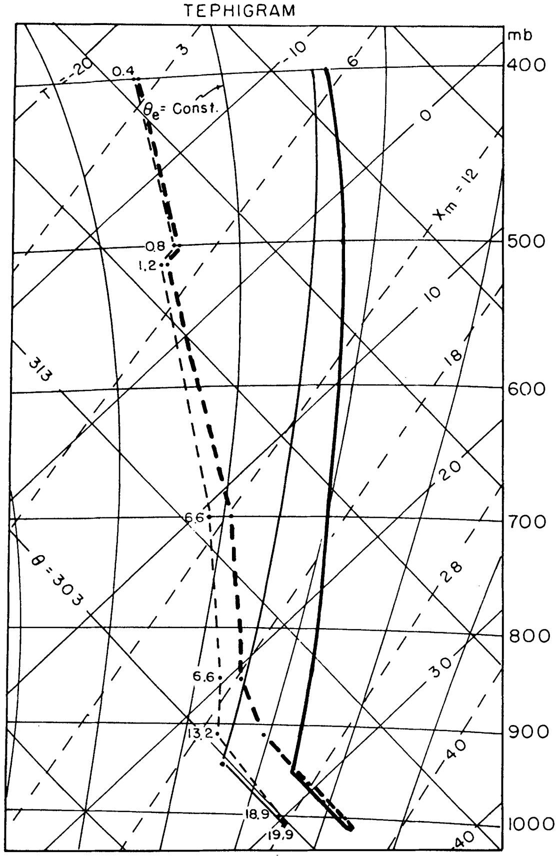

Fig. 3.

Plot of meteorological sounding taken at Brownsville on 20 August 1958 at 0000 GMT. The light dashed curve represents temperature in °C and the numbers to the left of each data point give the mixing ratio of water vapor to air in g kg^{-1}. The heavy dashed curve represents the corresponding virtual temperature. The light full curve gives the locus of a surface air parcel lifted first dry, then moist, adiabatically to the top of the sounding. The heavy full curve gives the corresponding virtual temperature of the the lifted parcel.

On the other hand semi-full-scale experiments might be useful as a preliminary step. These might require a tube of full height but small bore in the actual atmosphere. The large friction would then necessitate an energy source in the form of a blower to force the flow. Artificially prepared intake air of specified temperature and humidity could then be supplied for experimental purposes to study the condensation process and other effects. The radiation problem would, of course, be rather severe in a small-bore tube. Also, the cost of the equipment would be rather high, approaching that of a full-scale model.

6. We have avoided at the present stage of our work a discussion of engineering problems as such. In our previous paper it was suggested that a rigidly supported tube along a sufficiently steep and long mountain escarpment might be preferable to a balloon-supported arrangement. Nevertheless it could be that the second type is less costly from the standpoint of initial experimental procedures, and could later be more easily standardized for location at a variety of sites. Of course a balloon installation would be more vulnerable to high-wind damage, so that a location such as that along the coast of the Gulf of Mexico would have the drawback of exposure to frequent hurricane winds and other severe conditions. It also might be desirable that the balloon setup be combined with a rigid mountain slope structure at lower levels in certain locations. We should finally also note that the balloon-supported version could, at least in principle, be made collapsible and perhaps movable from one location to another. Numerous other engineering problems arise, although it is impossible to enter into details at present. Thus, for example, an elaborate electronic monitoring and control feature would have to be incorporated in the design of the equipment.

7. Quite properly as a welcome trend, we have seen in recent years a worldwide concern about damaging effects of some technological activities upon our local and planetary environment. Many of these effects are most difficult to eliminate, and it is often harder still to rectify the injuries already made. So far as we can judge, the operation of even a large number of units of our type for purposes of fresh water production should be quite benign from the standpoint of environmental protection. In any case, since the processes are controlled, the units could be taken out of operation at any moment desired, whereupon the original meteorological conditions would no doubt be restored.

8. It would be unrealistic to suppose that a test installation could be erected without the expenditure of a large sum of money, to which must be added maintenance expenses. Thus, any such move should be undertaken only after a large amount of scientific and engineering study. Even then the effort might best be looked upon as the construction of a research facility in addition to being a practical source of water, if successful, for the locality chosen. A price tag, based on what can best be termed as guesswork, for the simplest experimental installation in a favorable location would probably run to tens of millions of U. S.

dollars. More permanent units built to last according to good engineering standards could no doubt run much higher in cost.

In view of such estimates one object of research should be to find ways to render the operation of the device more efficient in such a way as to decrease the necessary size and cost. Thus, as we have hinted above, the unit could be erected above a shallow salt water lagoon heated by the sun, in order to evaporate added moisture into the intake air. (Addition of dye to the brine might cause the solar radiation to be absorbed more strongly near the free surface.) The gain in efficiency might then render successful a unit with a much shorter tube. Eventually, we believe, the generation of a captive and controlled rainstorm should become a reality.

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Address:

Massachusetts Institute of Technology, Department of Meteorology,
Cambridge, Massachusetts 02139, U. S. A.

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