Reports

Areal Spread of the Effect of Cloud Seeding at the Whitetop Experiment

Abstract. *With reference to arguments that weather modification technology is sufficiently advanced for the federal government to finance cloud-seeding operations as a means of alleviating water shortages, an analysis of the Whitetop rain stimulation experiment was performed. The average 24-hour precipitation in six concentric regions up to 180 miles from the center of the target on 102 days of cloud seeding was less than that on the 96 experimental days without seeding. For distances less than 30 miles, the apparent loss of rain due to seeding was 32 percent. With the increase in distance, this apparent loss decreased to a minimum of 9 percent for gages between 120 and 150 miles from the center. However, the 48 gages at distances between 150 and 180 miles showed a 22 percent apparent loss of rain due to seeding. The estimated average loss of rain within the whole region of about 100,000 square miles was 21 percent of what would have fallen without seeding. When a 5-year experiment, expected to produce a 5 to 10-percent increase, shows a 20-percent decrease in rainfall, the relevant technology does not appear reliable enough for practical use.*

The present study is motivated by the continuing discussion of whether cloud-seeding technology is advanced sufficiently to justify federal expenditures on large-scale, cloud-seeding operations, as distinct from experiments, contemplated as a means of alleviating water shortage, and so forth. Arguing in favor of such policy, MacDonald adduces (*1*) three cloud-seeding experiments, one in Australia, one in Israel, and one in the United States. Of these, it is the American experiment, known as the Whitetop project, that is particularly relevant to policy discussion. One of the largest experiments performed in the United States (1960–64), it was organized and conducted by Braham (*2*), with proper randomization ensuring (*3*) that any changes in the distribution of rainfall would be ascribable to seeding and not to any other cause. Also (*2*), the Whitetop trial was a rain-stimulation experiment, conducted in a region where agriculture suffers from insufficient summer rainfall and where it was hoped to demonstrate that modest increases in precipitation might be achieved through cloud seeding.

The results of cloud-seeding experiments are being variously reported, occasionally in terms of precipitation "in the clouds," perhaps noticeable on the radar scope or otherwise, but not necessarily reaching the ground. Unless otherwise indicated, this report is concerned only with precipitation on the ground as measured by rain gages.

All the earlier evaluations of the Whitetop trial known to us (*4*) are concerned with the finely defined average effect of seeding "per fair hour," experienced at varying localities at the particular times when the plume of seeding material is estimated to be directly overhead. All these studies, conducted by different statistical methods, agree that, at the central part of the plume ("Missouri Plume") of silver iodide smoke, the seeded precipitation was less than that without seeding by about 50 percent (some $P < .01$). Contrary to the relevant passage in the report of the NAS-NRC Panel on Weather and Climate Modification (*5*), and contrary to his own testimony before the U.S. Senate Committee on Commerce (*6*), MacDonald now concludes (*1*) that seeding at the Whitetop experiment may have led to a rather substantial decrease in total rainfall, even though radar observations indicated local increases in the clouds.

Our investigation was undertaken because of the very local and "very momentary" character of the earlier findings which makes them not strictly relevant to the present policy discussion. For example, a decrease in rain experienced in a given locality during a particular hour when the seeding material is overhead, may be compensated for in the very next hour when the winds carry the plume of seeding material to another location. On the other hand, it is the effect of seeding on the total rainfall over a region surrounding the target that is particularly important from the point of view of the weather modification policy of the government.

The calculations reported here were performed with such policy matters in mind. Specifically, an effort was made to determine (i) the differences in the 24-hour precipitation amounts at different distances from the center of

Table 1. Estimated effects of cloud seeding in Whitetop experiment using 127 gages. Unit of observation: 24-hour period. S, seeded; NS, not seeded.

Region	Gages (No.)	Frequency of wet days				Mean rainfall: Per wet day				Mean rainfall: Per experimental day			
		S (%)	NS (%)	Change (%)	P*	S (in.)	NS (in.)	Change (%)	P*	S (in.)	NS (in.)	Change (%)	P*
A	10	69	66	+5	.77	.195	.315	−38	.037	.134	.207	−35	.083
B	15	75	74	+1	.94	.188	.270	−30	.053	.140	.200	−30	.084
C	20	82	77	+7	.46	.169	.228	−26	.093	.139	.176	−21	.23
D	25	86	86	0	.86	.152	.214	−29	.044	.132	.185	−29	.054
E	28	86	89	−3	.79	.179	.195	− 8	.58	.155	.173	−11	.49
F	29	89	96	−7	.14	.177	.191	− 7	.63	.158	.183	−14	.36
Entire	127	93	96	−3	.61	.158	.190	−17	.22	.147	.182	−19	.17

* Throughout *P* represents the two-tail significance probability. The reader is warned that, because of the identity of experimental days, the consecutive values of *P* are not mutually independent.

the Whitetop target, averaged over the 102 days with seeding and over the 96 experimental days without seeding, and (ii) the probability (P) of obtaining such differences, or larger, purely through unavoidable chance variation.

The rain gages used (Fig. 1) were those installed for the Whitetop Project (*2*) and those of the U.S. Weather Bureau network, for which the observations are published in *Climatological Data*. Because the seeding was done for a maximum of 6 hours beginning at 10 a.m. or 11 a.m., only those gages that were read in the morning hours were included. Other conditions imposed on the gages were (i) that during the experimental period, 1960–64, they were not moved far from their original sites, and (ii) that they have a reasonably continuous record, with no more than occasional gaps which could be convincingly filled by interpolation.

The method of evaluation, explained elsewhere (*7*), based on optimal $C(\alpha)$ tests, consists of an effort to answer the following three questions: (i) Did the seeding affect the frequency of "wet" days, that is, days with some rainfall in the given region? (ii) Did the seeding affect the average precipitation per wet day? (iii) Did the seeding affect the precipitation in the region, averaged per experimental day, the possible effect being either through (i) or through (ii) or both? Braham (*2*) gives an exact definition of "experimental day." Briefly, these were days with general westerly air flow and with high precipitable water at Little Rock and at Columbia, Missouri, as observed at 6 a.m.

The process of securing the data for the present evaluations, including checking and interpolations, proved cumbersome and time-consuming. In September 1968 preliminary calculations were reported (*8*), based on the data of 127 rain gages (Table 1). Since that time data of 47 more gages in the region have been processed, and it is judged that these two sources are practically exhausted. Because of the interest of the degree of influence of 47 additional rain stations used, the results of both sets of calculations are reported (Table 2). In addition to the number of gages, the differences between the two tables reflect corrections in the assignment of gages to regions A through F. Originally this was done through approximate measurements of distances performed on a map. For Table 2 these distances from the target center were computed from the published coordinates of all the rain stations. As a result, a few reassignments of gages to other regions proved necessary.

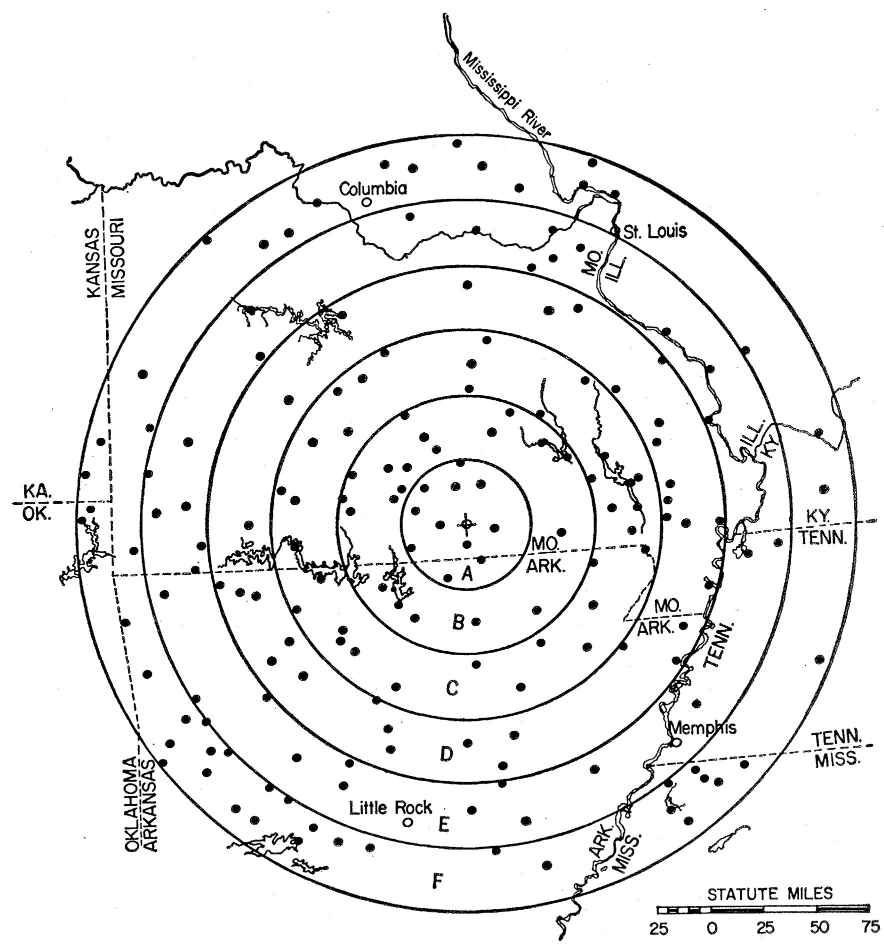

Fig. 1. Approximate map of the region around the Project Whitetop target. Solid circles mark the location of rain gages used for the evaluation. The radii of the concentric circles are multiples of 30 miles; the letters *A*, *B*, *C*, *D*, *E*, and *F* designate the region within the inner circle and the regions within the successive rings, respectively. For example, region *B* is the area bounded by the 30 mile (inner) circle and the 60 mile (second) circle. Additionally, the area within the outermost circle is designated as "entire" (Tables 1 and 2).

It will be seen that, in spite of the addition of a substantial number of rain gages and in spite of some reassignments, Tables 1 and 2 are remarkably consistent, indicating the likelihood that, with the exception of gaps in the distribution of gages, particularly in region F, further additions of gages will not materially affect the general picture of the effects of seeding.

[*Note added in proof*: The results in Tables 1 and 2 are reinforced by independent findings of Flueck obtained in connection with his paper referenced under (*4*), but not published with it. Working with all the gages used in Whitetop (predominantly in regions A and B, their numbers varying from 35 to 47, against 31 in our Table 2) and with time period of 13 to 14 hours after the commencement of seeding, Flueck found that the average seeded precipitation was less than that unseeded by 38 percent of the latter. This indicated decrease is in general conformity with the 30- to 35-percent decrease for 24-hour precipitation amounts, recorded in our Tables 1 and 2.]

Figure 2 was constructed to bring out more clearly the continuity of the effect of seeding as observed at increasing distances from the center of the target.

Table 2 and Fig. 2 exhibit most unexpected results. It appears that over all the six regions the average seeded precipitation was consistently less than that on experimental days without seeding. As anticipated, the apparent effect of seeding is greatest in the central region A, where it amounts to a 32-percent loss in rain. Then there is a decrease in this loss with a minimum of 9 percent in region E, followed by a 22-percent loss in region F.

In interpreting these results two sources of bias must be remembered:

Table 2. Estimated effects of cloud seeding in Whitetop experiment using 174 gages. Unit of observation: 24-hour period. S, seeded; NS, not seeded.

Region	Gages (No.)	Frequency of wet days				Mean rainfall: Per wet day				Mean rainfall: Per experimental day			
		S (%)	NS (%)	Change (%)	P*	S (in.)	NS (in.)	Change (%)	P*	S (in.)	NS (in.)	Change (%)	P*
A	11	64	68	−6	.66	.220	.305	−28	.15	.140	.206	−32	.12
B	20	75	75	−1	.93	.179	.257	−30	.051	.133	.192	−31	.070
C	33	83	80	4	.70	.167	.219	−24	.12	.139	.176	−21	.21
D	31	87	86	1	.96	.151	.208	−27	.050	.132	.179	−27	.072
E	31	85	77	−5	.49	.181	.189	− 4	.77	.154	.169	− 9	.56
F	48	91	98	−7	.079	.164	.195	−16	.25	.149	.191	−22	.12
Entire	174	95	99	−4	.24	.152	.184	−17	.20	.144	.182	−21	.13

* Throughout *P* represents the two-tail significance probability. The reader is warned that, because of the identity of experimental days, the consecutive values of *P* are not mutually independent.

(i) the lack of uniformity in the distribution of gages, and (ii) the probable lack of uniformity in the effects of seeding over the area of each region. With regard to the first, ring F is particularly bad, with only one gage in its part in Tennessee and with only a few in Illinois. With regard to the second point, it is plausible that the effect of seeding on precipitation at a given point would depend on whether this point is downwind or upwind from the source of seeding material. Because of the particular selection of experimental days, with westerly flow, the effects of seeding in the east would be different from those in the west. Thus, even though the first six lines in Tables 1 and 2 are meant to refer to particular regions A through F, it is realistic to think of them as representing the localities where the relevant rain gages are concentrated. A glance at Fig. 1 shows that this applies to ring F more strongly than to the others.

In computing the last lines of Tables 1 and 2 an effort was made not to exaggerate the effect of seeding averaged over the entire area studied. The method adopted, based on the fact that, generally, the apparent effect of seeding is stronger near the center than on the outskirts, consists of weighted averaging. Dealing with daily precipitation amounts, average rainfall was computed over all the gages in any particular region A through F. Next, these means were averaged with weights proportional to the areas of the regions A to F. Possible questions as to whether the above results depend on one or two outlying observations are answered by the histograms (Fig. 3).

The estimate of the average seeding effect in the entire region is a 21-percent loss of rain. In the absence of a real effect, chance alone could produce such an estimate of loss, or a larger one, about once in 15 independent trials.

From the point of view of the question as to whether the current state of weather modification technology justifies its use for alleviating water shortages, Fig. 2 and the relevant columns of Table 2 appear decisive. As already mentioned, the Whitetop experiment was conducted in a locality where summer precipitation is critical. In fact, the possibilities of increases due to seeding as modest as 5 to 10 percent have been mentioned as something to be hoped for. When instead of such gains the experimental results show losses averaging 20 percent over an area of some 100,000 square miles, then even the slightest possibility that these losses were caused by seeding must be considered as disqualifying the underlying technology.

Actually, the evidence in support of the causal relation between seeding and loss of rain appears quite strong. The significant 50-percent decrease within the Missouri Plume combines convincingly with the 30-percent loss of daily rainfall in region A. The impression of continuity of the effect is extended to the other regions (Fig. 2) and the negative effect of seeding may well continue beyond ring F.

While possibilities that cloud seeding may cause decreases in rainfall are admitted by authorities (*9*) in meteorology, decreases on this vast scale do not appear to have been contemplated. The situation is aggravated by the absence of an intelligible theory, even

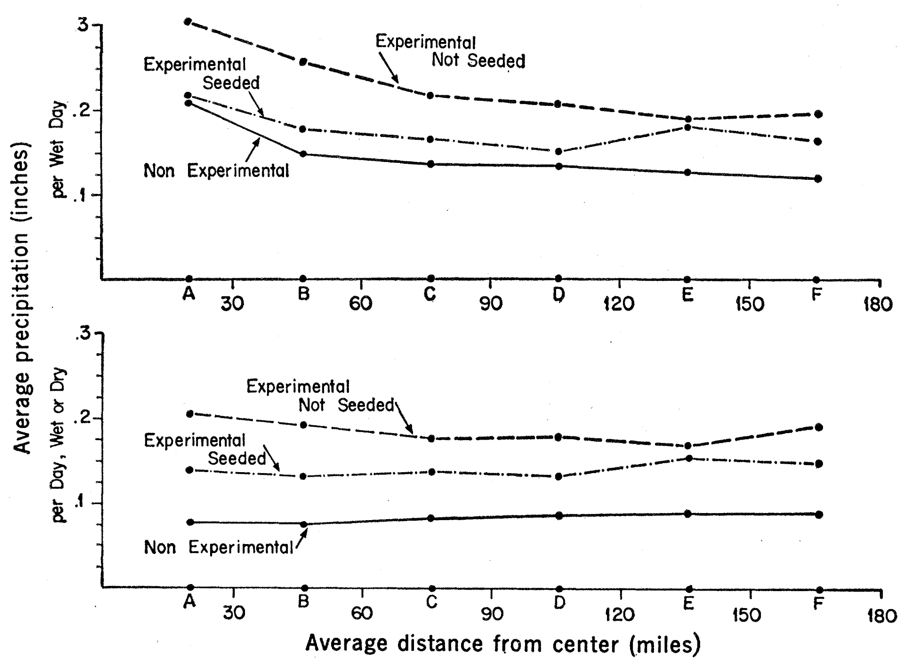

Fig. 2. Average daily precipitation versus average distance from target center. (Top) Precipitation averaged per wet day; (bottom) precipitation averaged per day whether wet or dry. In each case the upper curve represents experimental days not seeded, the middle curve represents experimental days seeded, and the lower curve represents the 267 days of June, July, and August 1960–64, which were not classified as experimental.

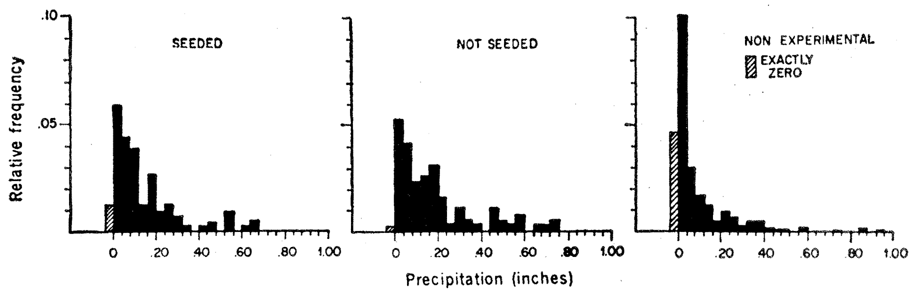

Fig. 3. Average daily rainfall over the entire region studied. Left, days seeded; center, days not seeded; right, nonexperimental days.

a hypothesis, on the mechanism through which cloud seeding conducted as a "local measure" could have large effects some 150 miles away. In the Whitetop experiment these large effects are negative, but in the Swiss experiment Grossversuch III, even more impressive positive effects of "local seeding" were found (*8*) at comparable distances from the target.

Clearly, further studies are indicated, not only to verify the results described above (even with great care, blunders are difficult to avoid) and not only to bring in data of more gages [several are known to exist (*10*) in St. Louis alone, but thus far we were not able to secure the data; and, through some more daring interpolations, a few more gages might be used for which the data are published], but also to present studies that are more "in depth." It seems particularly important to analyze the results of a few other experiments that have been in progress for several years. Here, however, there is the difficulty that quite a few of the experiments have been conducted with the cross-over design, involving seeding on every experimental day over one of two alternative targets, selected at random. The distances between the alternative targets range from almost zero to about 40 miles. From the point of view of the effects that seeding may have at distances of some 150 miles, the data of such experiments are not usable.

Advance in weather modification study may be speeded up by establishing facts revealed by already completed experiments. Two reviews of such experiments were recently published (*11, 4, 3*), intended to be comprehensive. (A mistake in these listings must be corrected: We are indebted to E. J. Smith for the information that the Darling Downs II experiment listed separately is an integral part of Darling Downs I.) Of the two experiments with indicated positive results discussed by MacDonald (*1*), these reviews include the Israeli trial but not the Australian experiment. The reason is that this particular Australian experiment is not really relevant. It was concerned with seeding of individual clouds and, in the words of MacDonald (*1*): "The subsequent behavior of the cloud was observed and any rain which fell from it was measured. Data were then stratified. . . ." The corresponding passage from Smith (*12*) reads: "The subsequent history of the cloud was observed, and any rain which fell from it was measured by means of an impactor mounted on an aircraft. . . ." Thus, the increases recorded in this experiment refer to the rainfall "in the clouds" rather than that reaching the ground. The experiment is interesting and important, encouraging further research, but cannot be used as an argument in favor of seeding operations intended to increase rain. Smith's own interpretation is that the result observed "suggests the desirability of experiments to find out if this type of cloud seeding can increase the rainfall over an area."

At the bottom of his first column (*1*) MacDonald asserts that before 1957 there were no properly randomized cloud seeding experiments. Actually, there were at least two such trials performed in the United States in 1953–54 and the experimenters, Hall (*13*) and Spar (*14*), deserve recognition for their pioneer work. Both experiments are worthy of attention. Hall must be given credit for inventing targets adjustable to wind conditions which appear as precursors of the "Missouri" and the "Chicago Plumes" used by Braham. Also, Hall's experiment has the distinction that, if one abandons the original statistical methodology, one finds (*15*) that, for each of his three types of targets, but particularly for Targets III, the indicated effect of seeding is an increase in the rainfall. If the data were reliably collected, then this conclusion is also reliable.

Spar's experiment SCUD (*16*) is very remarkable indeed because, through an ingenious selection of predictor variables, which ought to be tried elsewhere, the precision of the comparison of seeded and not seeded precipitation attained in this trial appears way above anything we saw in other experiments (*17*).

Our conclusions are: (i) Two excellently performed, large cloud-seeding experiments, Grossversuch III and Whitetop, indicate strongly not only that cloud seeding can affect rain, but also that its effect can spread over very large areas, by increasing rain (*18*) as in Grossversuch III or by decreasing it as in Whitetop. (ii) The conditions in which increases or decreases due to seeding occur are largely unknown, which makes it questionable whether weather modification technology exists as such. (iii) On the other hand, the benefits to humanity from the identification of these conditions would be enormous, which encourages further research. (iv) The most important need in such research is the accumulation of well-documented facts which can be obtained only through large, properly designed, and carefully conducted randomized experiments, of the type of those of Battan in Arizona, of Grossversuch III in Switzerland, and of Whitetop in Missouri.

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24 January 1969

Surfacing of Pacific Equatorial Undercurrent: Direct Observation

Abstract. *Measurements of current speed and direction from the sea surface to below 400 meters made on the equator in the eastern Pacific in April 1968 indicate that the Equatorial Undercurrent extends from 300 meters to the sea surface. These measurements, when compared with previous observations, indicate that eastward motion at the surface is a result of surfacing of the undercurrent caused by a release of the surface wind stress.*

During Eastropac (Eastern Tropical Pacific) Expedition 75 (R.V. *Thomas Washington,* 15 February through 15 April 1968), 5 days were spent on the equator about 400 miles west of the Galapagos Islands (0°07′S,97°40′W). On two of these days detailed measurements of current speed and direction were made from the sea surface to below 400 m. The measurements made on 1 April are here described (*1*).

Current measurements were made with two Richardson current meters (Geodyne Corporation) spaced 10 m apart on the lowering wire, capable of transmitting information through the supporting cable to analog and digital recorders on deck. Measurements were made at 10-m intervals from the sea surface down to 440 m. A measurement at each depth usually lasted about 4 minutes and consisted of about 70 samples of speed and direction from each current meter.

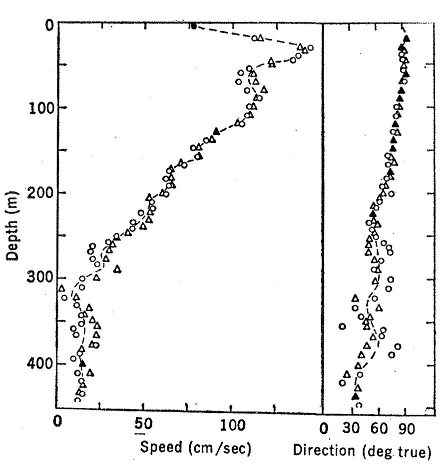

Fig. 1. Current speed and direction profiles taken on 1 April 1968 at 0°07′S,97°40′W. The ordinate in this figure represents the depth as interpreted from records of the pressure sensor. Open circles represent values from the lower current meter; open triangles represent values from the current meter 10 m above; closed triangles represent values from both current meters.

During the measurements, the position of the ship relative to a reference buoy was determined every 10 minutes. An estimate of current speed and direction was obtained from the analog traces by determining the average relative velocity at 10-m intervals and adding these values to the ship's velocity relative to the reference mooring. Figure 1 shows an averaged profile of the speed and direction between the sea surface and 440 m. The horizontal distance between the two adjacent symbols identifying the two different current meters in the figure represents the combined effects of time variation in the current velocity and inaccuracies in the determination of the absolute velocities. The greatest difference in speed between two successive measurements at the same depth is 12 cm/sec; this value will be taken as a measure of the maximum error in the observations.

Between the surface and 200 m, the eastward component of the velocity is at least 94 percent of the value shown in Fig. 1, since the direction is within 20° of due east. The speed profile shows a maximum of 143 cm/sec between 30 and 35 m with a slight secondary maximum of 113 cm/sec at 90 m. Below the secondary maximum, the current speed gradually decreases in a nearly stepwise manner to a minimum of 13 cm/sec at 315 m.

The current direction from the surface to 100 m is within 5° of due east. Below this depth the direction tends toward the north, reaching a relative minimum of 55° true north at 240 m. At greater depths, observations of current direction are somewhat erratic because of the lower absolute speeds, but flow is generally toward the northeast. Because near-surface estimates of current direction with this type of current meter are affected by the magnetic field of the ship, the values given at the surface (Fig. 1) are averages of four successive observations of the ship's velocity relative to the reference buoy taken while the ship was drifting just before the current measurements were made.

The speed profile can be compared with profiles of temperature and salinity measured with an *in situ* profiling device (Bissett-Berman salinity-temperature-depth system) immediately after completion of the current measurements (Fig. 2). The upper speed maximum is in the thermocline (16° to 18°C) and coincides with a layer of increased salinity (35.05 to 35.10 parts per thousand). Salinity inversions in this layer are probably the result of dynamic mixing between less saline surface water and the water of high salinity associated with the core of the undercurrent. The secondary speed maximum is also associated with a slight increase in salinity (35.01 to 35.05 parts per thousand) and with nearly isothermal water.

Below 20 m the profile of east-west velocity resembles observations of the Equatorial Undercurrent made in 1958 and 1961 by Knauss (*2, 3*). Table 1 summarizes the pertinent features of the two sets of observations near 97°W with the zonal component of the observations described here. The depths

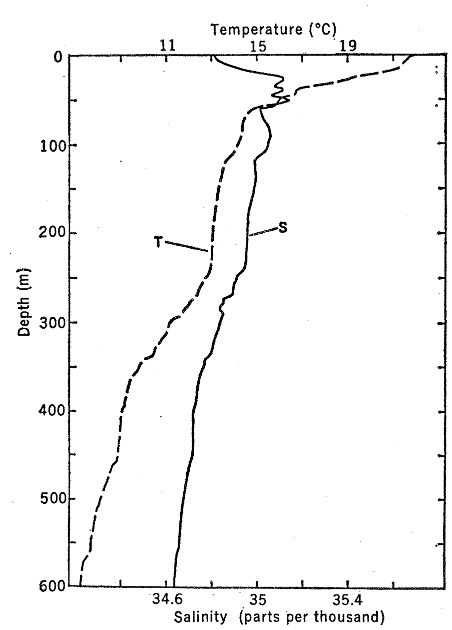

Fig. 2. Temperature and salinity from *in situ* instruments immediately after completion of the current meter station.