AN ASSESSMENT OF IMPACT OF CLOUD SEEDING ON LOCAL RAINFALL- A CASE STUDY OF FIRST PART OF THE ISKI RAIN ENHANCEMENT PROGRAM CONDUCTED IN ISTANBUL, TURKEY DURING 1990-1991

Dr. Ali Umran Komuscu

Turkish State Meteorological Service
Division of Remote Sensing
Kalaba, Ankara 06120, Turkey

e-mail: aukomuscu@meteor.gov.tr

Abstract: Major metropolitan areas of Turkey suffered from extensive drought and associated water shortage during the late 1980s and early 1990s. Water levels at major dam lakes dropped below their critical levels in Marmara, and Central and Western Anatolian regions. The impact of resulting water shortages was greatest especially on the drinking water supplies during summer months when the temperatures peaked. A number of rainfall enhancement projects in response to the emerging water shortage problems developed and were put into implementation by the local authorities of Istanbul, Ankara, and İzmir. Nevertheless economic viability of the projects was not considered seriously. The efforts were directed to find immediate solution to supply water to local communities who suffered from the shortage of water in the urban areas. Istanbul Municipality and Istanbul Water and Drainage Works (ISKI) launched "ISKI Rain Enhancement" project, to meet immediate water demand of the city of Istanbul. It was the first operational rainfall enhancement program in the country and included cloud seeding in a nearly 2100 km^2 area covering four main water catchments which supply drinking water to the Istanbul Metropolitan area. The first rainfall enhancement phase covered October 1990 through March 1992, and later extended to 1993 and 1994. This study presents an analysis of the first phase of the ISKI rainfall enhancement program, which covered October 1990 through May 1991 period. The study focuses on rainfall data of target and control areas in and near the vicinity of the water basins where the cloud seeding was conducted in order to assess effectiveness of the seeding.

This study concludes that cloud seeding applications were effective to some extent in a limited geographical scale and above a certain rainfall threshold. Despite the fact that higher rainfall was observed in some target areas during the seeding days, the statistical analysis presented here raises questions about the proper assessment of such applications only by the "Double Ratio" method. The results indicate that the "Double ratio" method alone is not adequate to assess the impact of the seeding, and other statistical tools should be developed and applied in order to make a better judgment of the cloud seeding effects on the local rainfall. The analysis conducted in this study proved that the seeding had varying effect on the local rainfall and some of the seeding operations were more successful than others.

1. INTRODUCTION

Over 50 years of research and cloud seeding applications in more than 40 countries have demonstrated that properly-designed programs can increase seasonal rainfall appreciably and improve water resources. Water availability has always been a critical issue in Turkey, as the country is vulnerable to drought and the associated lack of water due to its semi-arid climate and variable rainfall characteristics. Precipitation enhancement efforts gained a lot of attention in the early 1990s in the country as a quick remedy to the water scarcity problem, especially in major metropolitan areas of the country (Komuscu, 2003). The prolonged drought conditions and the associated drop in water storage of main dam lakes generated renewed interest in means that might be used to better manage the water supplies for the water basins supplying water to major urban areas. The first rainfall enhancement efforts in Turkey date back to the early 1970s. In 1986, the State Planning Agency (DPT) initiated the first rainfall enhancement project in Turkey. The cloud seeding was applied over Keban Dam Lake, which is one of the largest dam lakes in the country, to improve the water capacity for energy production. A different approach to cloud seeding and possible enhancement in the country's rainfall was put forward by a research team at TUBITAK in the late 1990s. They argued that there was a connection between rain or any kind of precipitation and dust from the Saharan desert (Saydam and Polat, 1999). They investigated the rain-making qualities of the red Saharan dust in a laboratory environment by using a special cold chamber to see how dust and water droplets interact to form snow crystals. They concluded that any dust in the atmosphere usually would lead to the formation of ice crystals in clouds and then ultimately to precipitation. Those research efforts, however, need further work before they are confirmed on scientific grounds to prove that the dust originating from the Sahara can cause inadvertent weather modification over the country's rainfall.

The latest efforts involving cloud seeding were during the early 1990s when the major metropolitan areas of the country suffered from severe water shortage due to reduced rainfall (Figure 1). A sequence of cloud seeding projects were carried out in Istanbul in the early 1990s when the city experienced severe drought and prolonged water shortage. The year 1988 was one of the warmest in the historical climatological records of the country and the associated heat waves hit the major urban areas like Istanbul and Ankara. The years between 1988 and 1991 were characterized with rainfall far below the average in the overall country, and especially in the Marmara region and Central Anatolia. Istanbul received 456 mm rainfall in 1989, which was far below the long-term average of 700mm. In Figure 1, long-term rainfall records of four stations across Istanbul are presented and it is noticed that the city experienced a prolonged lack of rainfall between 1989 and 1997. The resulting water shortage urged the local authorities to take immediate actions to meet the demand for water in short range. As a result, Istanbul Water and Draingage Works (ISKI) initiated several rainfall enhancement programs with the aim of improving capacity of water reservoirs providing drinking water to the Istanbul metropolitan area. The first part of the program covered October 1990 through May 1991, which is the subject of this work.

Weather Modification Inc. (WMI) was contracted to implement the cloud seeding programs in Istanbul. It was in charge of providing aircraft, crew, equipment, and other supplies. Overall, WMI provided experienced personnel, one reliable aircraft, seeding equipment, a 5 cm C-band meteorological radar, and an L-band aircraft tracking radar (WMI, 1990).

In this study, rainfall data from target and control stations chosen for the cloud seeding operations in and around Istanbul were analysed with respect to the seeding days to assess impact of the application on the local rainfall for the first part of the ISKI Rain Enhancement Program. The control stations included

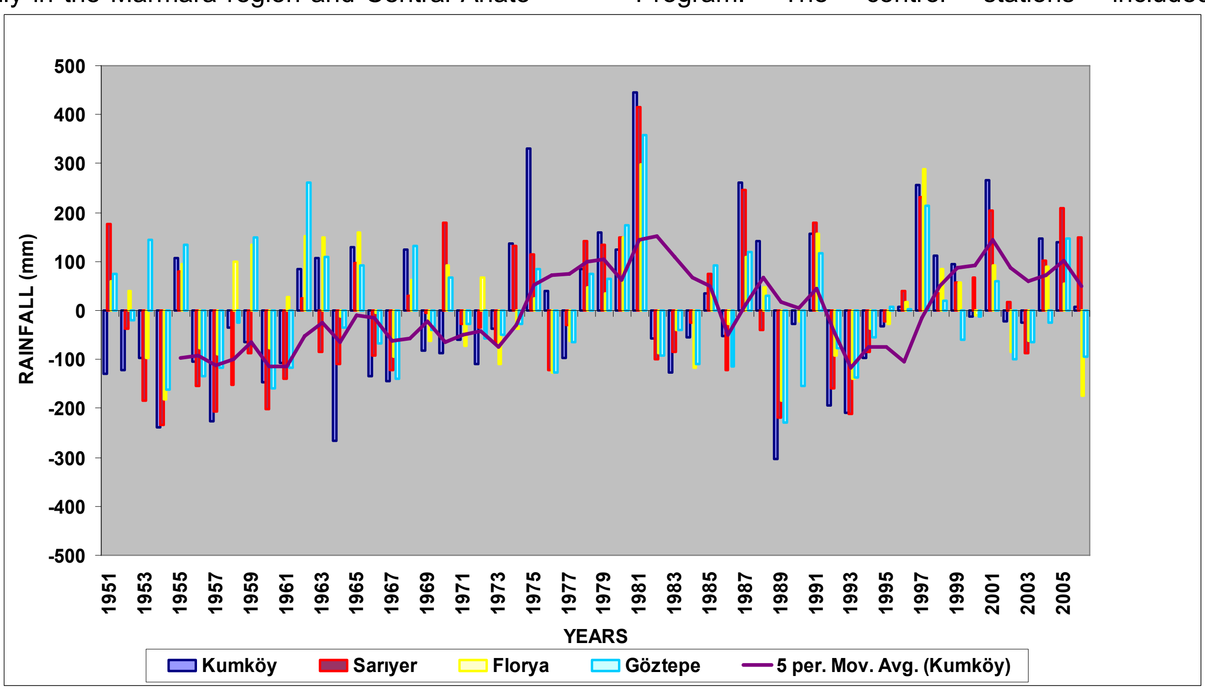


Figure 1. Long-term rainfall at selected stations in Istanbul between 1951 and 2006.

Alibeyköy, Kumköy and Florya stations, while the target area stations covered Büyük Çekmece, Terkos, Elmalı, and Ömerli water basins. Static cloud seeding was applied during the first part of the rainfall enhancement program. The hypothesis behind static seeding is that the introduction of an "optimum" concentration of ice crystals will augment the precipitation efficiency of a cloud by converting the reservoir of supercooled water droplets into precipitation sized particles (Ryan and Sadler, 1995).

2. OPERATIONAL CLOUD SEEDING IN ISTANBUL

2.1. ISKI Rain Enhancement Program

Weather Modification Inc.'s first association with ISKI and its Rain Enhancement Program began in the fall of 1990 with the first operational program occurring during 1990 - 1991 winter season (Omay et. al., 1993). The next phase of the implementation took place from April 26, 1993 to July 10, 1993, with another phase carried out from September 15, 1993 to December 31, 1993. After completion of the second implementation phase of the contract, ISKI and WMI negotiated an extension of the contract to take place from January 1, 1994 to March 31, 1994. The ISKI Rain Enhancement Program saw its fourth consecutive year in the 1993-1994 season, making it the longest running operational project of its kind in Turkey.

The program was designed to increase precipitation over the Terkos, Büyük Çekmece, Ömerli and Elmalı water basins to improve the drinking water supplies for the Istanbul metropolitan area and its surroundings (Figure 2). The assessment of all different phases of the program in Istanbul indicated an increase in rainfall over the target areas relative to the surrounding areas. It must be stated, however, that the below-average rainfall pattern that the Marmara region was under since the beginning of 1990 influenced the success of the project since certain meteorological conditions were not in place for the best results to occur (Omay et al. 1993).

The cloud seeding program implemented in Istanbul included several sub-phases.

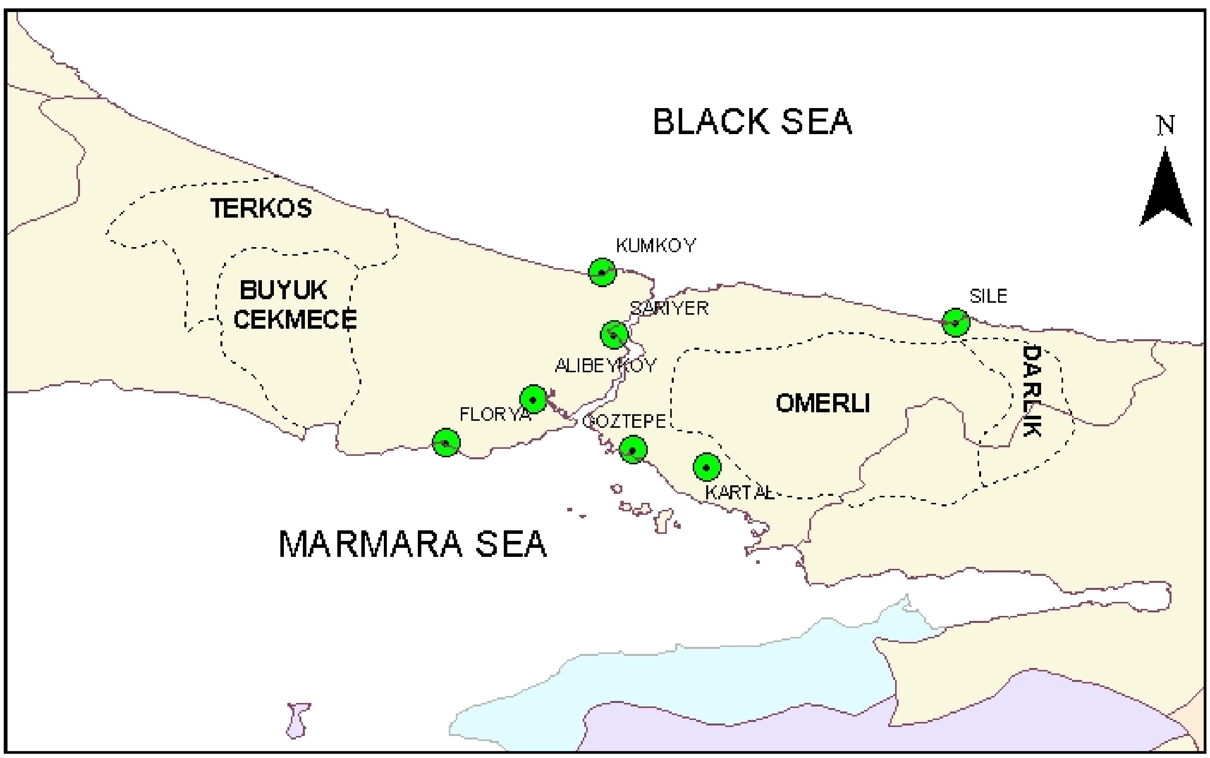


Figure 2. Target and control areas of the cloud seeding operations (the target water basins are surrounded by dotted lines and control stations are indicated by green filled circles).Only control stations Kumköy, Alibeyköy, and Florya are used in this analysis.

1. The climatology of cloud characteristics and rainfall distribution were assessed to determine suitability of clouds for the seeding and their frequency of occurrence.

2. The second phase included field programs, using an instrumented aircraft and weather radars with data-recording capability, during the months with the largest occurrence of convective clouds over Marmara and Black Sea. The field project objectives were to document the microphysics and dynamics of natural clouds.

3. The third phase included an analysis of the collected aircraft and radar data to determine the natural precipitation processes and effect of the seeding on these processes. This phase also include hydrological studies to determine the impact of possible rainfall increases on the water reservoirs.

4. Finally, data archival, display, and analysis of quantitative radar data were done as the final phase. The relatively low number of seeding flights conducted during the course of the program was a direct reflection of the below-average rainfall pattern that affected Istanbul for most of the winter season. Of course, there were seeding missions with better than average conditions and less than average conditions, but the majority was in the fair category.

3. ASSESSMENT OF THE RAIN ENHANCEMENT PROJECT

The assessment presented here reflects results from the report of Omay et al. (1993), which was prepared for the ISKI. In their study, the “Double Ratio” method was proposed to assess impact of the cloud seeding on the local rainfall. The method is described by the following equation (Miller et. al, 1979).

$$IC = \frac{(S / NS)}{(H / K)}$$

where,

IC = impact coefficient (decrease or increase of rainfall)
S = total rainfall in the targeted area during seeding period
NS = total rainfall in the control area during seeding period
H = 10 years of total rainfall in the targeted area
K = 10 years of total rainfall in the control area

When IC exceeds 1.0, rainfall is assumed to increase to the cloud seeding. If IC equals 1, there is no change in rainfall as a result of the cloud seeding applied. Table 1 summarizes the seeding operations for Oct. 1990-May 1991. Table 2 presents the IC for the water catchments in Istanbul where cloud seeding was applied. As a result of seeding, a 22 percent increase in rainfall was observed and nearly 60 x 10^6 m^3 water were stored in the dam lakes in the 4 major water catchments during the October 1990 through May 1991 period as a result of the seeding. It should be noted that the assessments were based on more than one control area in some cases. However, if one accepts that the large double ratio resulted from seeding, one also has to accept that seeding effects were produced at watersheds that were situated virtually under the path of the line seeding, and were produced by very few hours of seeding. It is likely that these statistical results are manifestations of a Type I error.

Table 1. Flight Summary of cloud seeding operations between October 1990 and May 1991.

Period	Flight Duration (hr)	Seeding Duration (min)	AgI consumed (gr)
October 1990	27.0	290	694
November 1990	28.3	497	1598
December 1990	16.6	400	1424
January 1991	9.7	227	870
February 1991	16.4	360	1452
March 1991	16.2	298	908
April 1991	15.9	459	1796
May 1991	10.0	114	456
TOTAL	**140.1**	**2648**	**9198**

Table 2. Impact Coefficients for the Target vs. Control Areas (10/90-5/91).

Water Catchment	H/K	S/NS	(H/K) / (S/NS)	Change %
Ömerli-Alibeykoy)/Alibeykoy	0.91	1.29	1.42	42
(Ömerli-Elmalı)/Kumkoy	1.05	1.22	1.16	16
(Ömerli/Elmalı)/Florya	1.20	1.38	1.15	15
(Terkos-B.Çekmece)/Alibeyköy	0.86	1.10	1.28	28
(Terkos-B.Çekmece)/Kumköy	0.80	0.86	1.08	0.8

The analysis presented below is an effort to bring additional insight into the assessment of the cloud seeding operations implemented between October 1990 and May 1991 in Istanbul by statistical analysis of the rainfall data of target and control stations.

4. ANALYSIS OF THE RAINFALL DATA

Table 3 shows the rainfall recorded at target and control stations during the cloud seeding between October 1990 and May 1991. The rainfall data has been analyzed at two steps. First, visual inspection of the data was done to detect variation in the rainfall. In the second step, a basic statistical analysis of the data involving correlation, regression, and Mann-Whitney tests were performed to determine linkage between the rainfall recorded at control and target stations.

The following illustrations indicate that impact of seeding on the local rainfall was very variable. The impact of seeding on the local rainfall was felt most at Ömerli and Elmalı water basins as compared to the other two water basins located on the European side of Istanbul. In fact there were cases when the target areas did not receive adequate rainfall as expected. Although there were some days when the daily rainfall at target locations exceeded the rainfall recorded at the control stations during the seeding, the overall rainfall recorded during the whole period at Büyükçekmece and Terkos water basins was below what was observed at the control stations. This reminds us of the effectiveness of the "Double Ratio" method to decide if the seeding was successful.

Table 4 presents correlation between the target and control stations included in the first part of the ISKI rainfall enhancement program. Considering the proximity of the target areas to control stations, those which were close to each other generally exhibited higher correlations while the remote target areas exhibited lower correlations with respect to their control stations.

In the next step of the analysis, regression between rainfall records of the control and target stations were calculated. The calculations include the control and target station pairs only, not all possible combinations of the pairs. In the illustrations, H denotes target stations and C denotes the control stations as summarized below. The target stations are presented on x scale of the regression while the control station data are presented at y scale of the regression, where $\alpha = 45$ ° is illustrated as a dashed line in the illustrations.

Target area Stations	Control area stations
H1: Ömerli	C1: Alibeyköy
H-2: Elmalı	C2: Kumköy
H-3: Terkos	C3: Florya
H-4: B. Çekmece	

Table 3. Rainfall (mm) observed at target and control areas during the seeding period.

Date/Stations	B. Çekmece	Terkos	Ömerli	Elmalı	Alibeyköy	Florya	Kumköy
22 Oct-90	10,2	21,4	17,4	15	18	12,9	21,3
23 Oct	10	7,5	10,1	14	8,6	9,8	9,2
24 Oct	10,2	0,3	6,9	6	2,5	0	3,1
25 Oct	0	1,4	12	13	8,1	7,5	6,9
5 Nov	14,6	29,5	34,2	29	32,5	32,4	25,2
9 Nov	34,5	31	44,5	68	6,4	27	27,2
10 Nov	1,5	0,8	2,5	7	6	1,9	4,8
11 Nov	0	2,8	0	1	7,1	3,3	3,5
28 Nov	7,6	11,3	25	31	15,7	26	7,1
30 Nov	9,7	16,6	10,7	17	18	5,5	17,3
14 Dec	18,5	13,6	16,3	22	18,2	25,4	15,3
21 Dec	0	0	2,6	3	5,5	0	0
24 Dec	1	1,8	2,9	4	11,6		0
28 Dec	1	0	0	2	0	0	0,6
2 Jan-91	7,2	8,9	12	8	0	9,7	12,4
25-Jan	0	0	0	0	0	0,3	0
30-Jan	0,1	3,8	9,3	11	6	3	6,8
17-Feb	15,7	4,2	15,3	17	18	0	20
4-March	3,8	2,1	5	5	2,8	0	0,1
6-March	5,7	2,3	6,4	6	5,5	6,3	1,7
16-March	14	17,8	7,2	7	0	16	9,3
17-March	5,2	4,4	2,1	7	9,9	8,9	10
29-March	4	0	0,7	0	2,2	2,3	0,8
14-Apr	0	0	0	1	3	0,3	2,3
23-Apr	0	6,6	1,2	1	0	0,8	2,8
25-Apr	8,5	0	1,6	2	1,8	2,9	2,1
30-Apr	8,3	12,9	14	16	9,7	9,8	13,3
18-May	5,2	10,5	0,5	6	0	9,4	22,8
19-May	3,5	1,9	41,2	20	6,5	8,5	2,3
25-May	10	7,8	4,3	8	8,8	13,6	5,5
Total	**210**	**221,2**	**305,9**	**347**	**232,4**	**243,5**	**253,7**

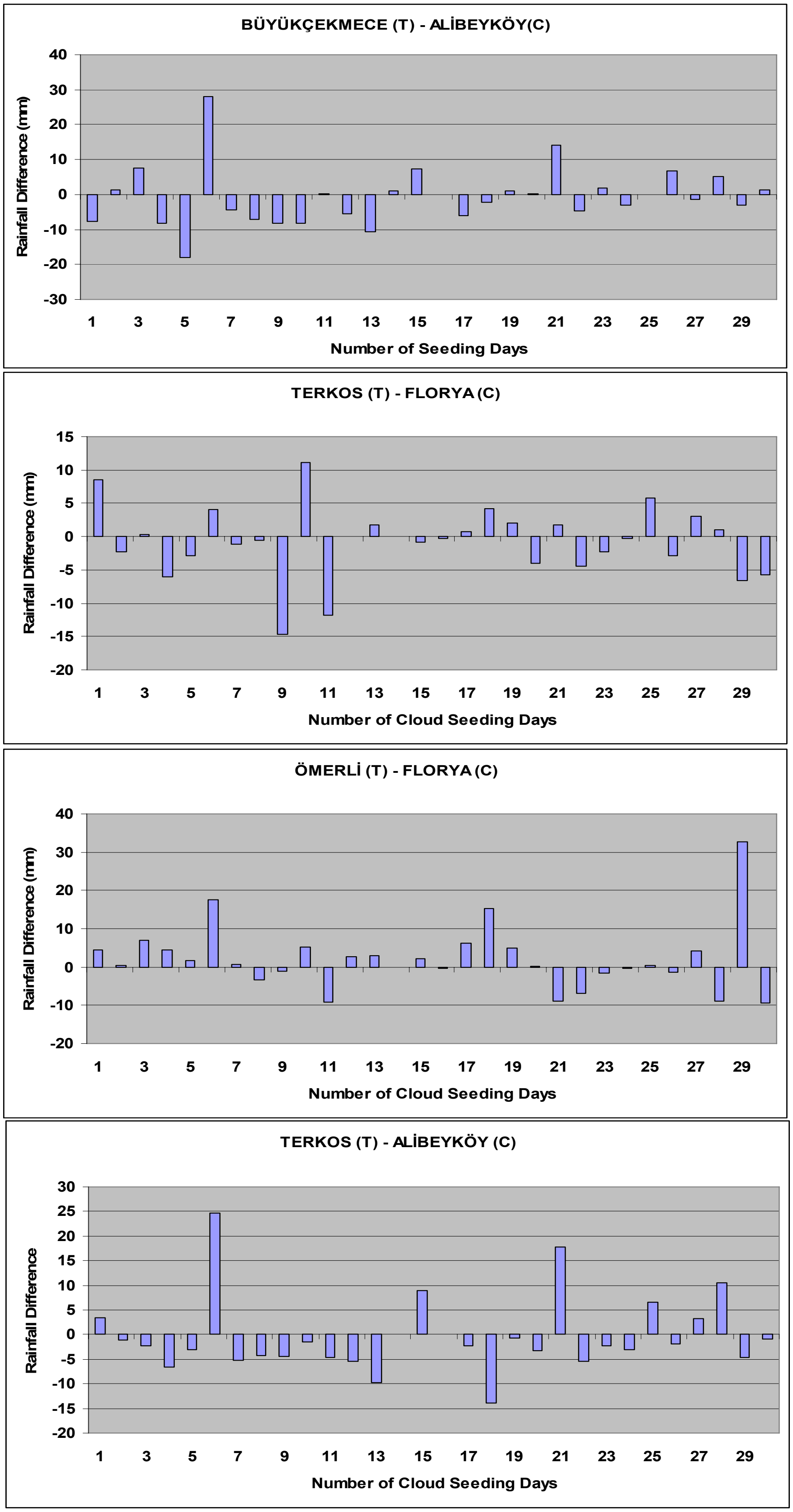
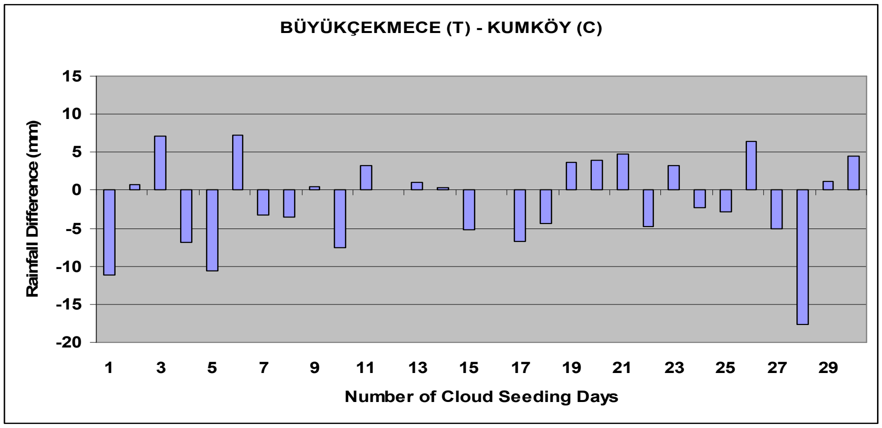


Figure 3. Difference in rainfall at target and control areas during the cloud seeding days.



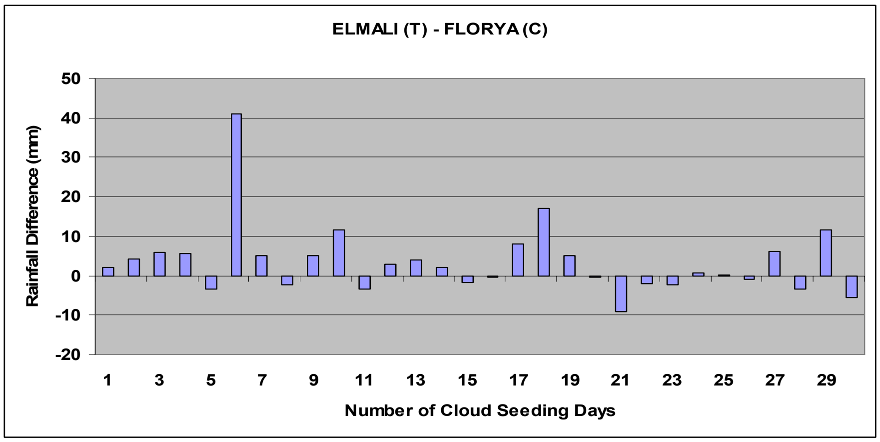


Figure 3. (continued)

Table 4. Correlation between Target and Control stations

Target/Control Stations	Alibeyköy	Florya	Kumköy
B. Çekmece	0,37	0,68	0,72
Terkos	0,55	0,82	0,85
Ömerli	0,51	0,70	0,68
Elmalı	0,46	0,75	0,68

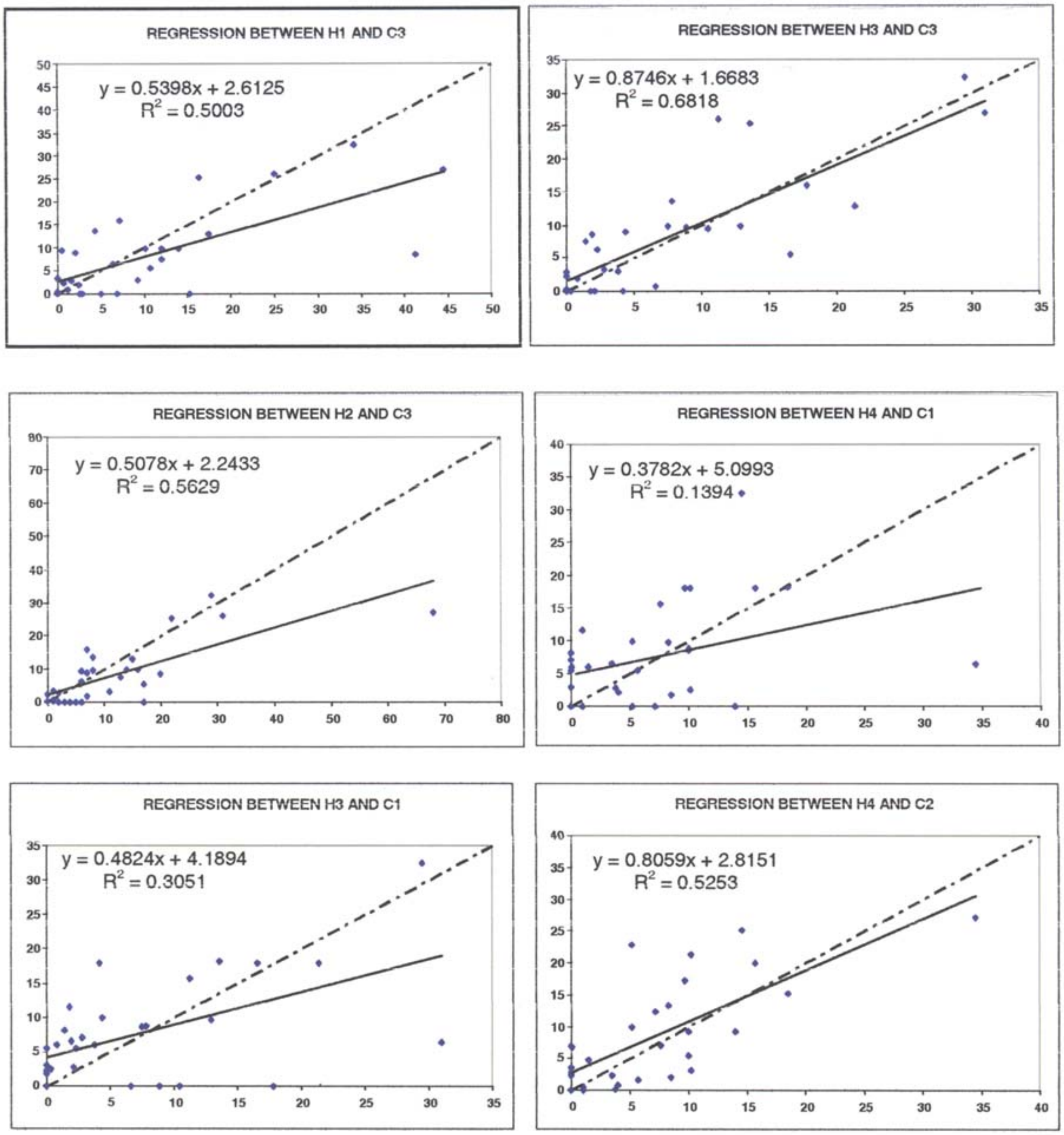


Figure 4. Regression results of rainfall data for pairs of the target vs. control stations.

The regression analysis indicates that the increase in the rainfall at target stations could be explained by cloud seeding at H1-C3, H2-C3, H3-C1, and H4-C1 cases. In other words, the observed rainfall in those cases was in favour of the target areas, meaning that the rainfall target areas received more rain as compared to the control areas in the areas indicated above, and therefore it can be argued that the seeding was successful to some extent. It should however be noted that impact of seeding on low values was minimal. For example, up to 10 mm impact of the seeding on the local rainfall in most stations was almost invisible.

Finally, the non-parametric Mann-Whitney test was applied to determine if the target and control station data come from the same population or not based on their median. In other words, we sought an answer for the question of whether the medians of the two populations differ significantly. The Mann-Whitney test is a non-parametric test to compare two unpaired groups. If the P value is small, one can reject the idea that the difference in medians is due to random sampling, and it is possible to conclude that the populations have different medians. On the other hand, if the P value is large the test indicates that the overall medians do not differ significantly.

Table 5 presents the results of the Mann-Whitney test performed on the control and target stations. The result indicates that the medians of the control and target area rainfall data were not significantly different from each other. The large P values also support this argument.

5. RESULTS & DISCUSSIONS

This study concludes that cloud seeding applications were effective only on a limited geographical scale and above a certain rainfall threshold. Despite the fact that higher rainfall was observed in some target areas during the seeding days, the statistical analysis presented here raises some questions about the assessment of such applications only by the "Double Ratio" method alone. In other words, other statistical tools should be used to assess the results of such cloud seeding applications. Moreover, not only statistical evaluations, but also physical proofs are needed to assess the success of the projects. Although response from the water basins were quite significant in some cases, it is still difficult to justify the cloud seeding results as no cost-benefit outcomes have been made available to prove that the method can be used as an operational water management tool. It also should be noted that severe drought conditions might diminish effectiveness of the cloud seeding as it is assumed that cloud seeding is more effective in non-drought periods. This is because seeding is predicated upon the availability of the right kinds of clouds. During severe to extreme droughts, the number of days with treatable convective clouds is relatively less. Therefore, if cloud seeding is done during severe drought conditions, results may not be satisfactory. Overall, the cloud seeding operations conducted in Istanbul certainly tackled the persistent drought conditions which severely affected the local water resources, but opportunities should be explored for scheduling the cloud seeding based on seasonal variations in rainfall and capacity of reservoirs to maximize its effectiveness and cost-benefit in future applications.

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Table 5. Results of the Mann-Whitney test for control vs. target stations.

Target	B. Çekmece	Terkos	Ömerli	Terkos	B. Çekmece	Elmalı
vs	vs	vs	vs	vs	vs	vs
Control	Alibeyköy	Florya	Florya	Alibeyköy	Kumköy	Florya
P value	0.7617	0.8014	0.5152	0.5791	0.5792	0.2115
Exact or approximate P value?	Gaussian	Gaussian	Gaussian	Gaussian	Gaussian	Gaussian
P value summary	ns	ns	ns	ns	ns	ns
Are medians signif. different? (P <	No	No	No	No	No	No
One- or two-tailed P value?	Two-tailed	Two-tailed	Two-tailed	Two-tailed	Two-tailed	Two-tailed
Sum of ranks in selected colums	894 , 936	897.5 , 932	959.5 , 870	877 , 953	877 , 953	1000 , 830
Mann-Whitney U	429	432.5	405.5	412	412	365
Target	Elmalı	Omerli	Omerli	Terkos	B. Çekmece	Elmalı
vs	vs	vs	vs	vs	vs	vs
Control	Kumköy	Alibeyköy	Kumköy	Kumköy	Florya	Alibeyköy
P value	0.3912	0.7171	0.9	0.4332	0.9705	0.3365
Exact or approximate P value?	Gaussian	Gaussian	Gaussian	Gaussian	Gaussian	Gaussian
P value summary	ns	ns	ns	ns	ns	ns
Are medians signif. different? (P <	No	No	No	No	No	No
One- or two-tailed P value?	Two-tailed	Two-tailed	Two-tailed	Two-tailed	Two-tailed	Two-tailed
Sum of ranks in selected colums	973.5 , 856.5	940 , 890	924 , 906	861.5 , 968	912 , 918	980.5 , 849.5
Mann-Whitney U	391.5	425	441	396.5	447	384.5

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