CLIMATOLOGICAL AND MICROPHYSICAL CLOUD FEATURES TOWARDS RAIN ENHANCEMENT FOR AGRICULTURE IN GREECE

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Abstract. A climatological and microphysical cloud analysis in central and northern Greece is conducted in order to find conclusive evidence and results leading to the design of rain enhancement programs. Clouds are grouped in six categories according to precipitation characteristics and the related synoptic weather patterns. The results of the climatological cloud analysis indicate that cumuliform clouds are the dominant precipitation producing cloud types in central and northern Greece with high frequency of occurrence during summer. Moreover, stratiform cloud types show higher frequencies of occurrence during winter months than in other months in the examined region.

A microphysical cloud analysis was also conducted during several operational seasons in the National Hail Suppression Program (NHSP) of Greece. The microphysical measurements have attempted to provide evidence of the precipitation formation process and to delineate several cloud features in central and northern Greece.

1. INTRODUCTION

Precipitation enhancement is a non-structural intervention to increase the available water mainly for agriculture, irrigation, recreation, hydropower generation, as well as domestic and industrial water supplies in semiarid regions around the world. The water demands are related to historical semiarid conditions in these regions, such as Greece and the lack of adequate water resources to meet seasonal and long-term water needs (Dalezios *et al.*, 1991). The enhancement of winter and/or summer precipitation in central and northern Greece in the context of water management offers a unique opportunity to increase the quantity and improve the quality of the water in the hydrological system. It has long been recognized that cloud seeding is one possible approach for rain enhancement over a region. However, clouds are one of the most crucial, but least understood components of the climate system.

Cloud seeding is an attractive approach to water augmentation, because it does not require large permanent construction or major fixed operation and maintenance costs. A decision for cloud seeding can be made on an annual or seasonal basis or even on a storm-to-storm basis within a season. At the present time cloud seeding seems to be the most cost-effective means for securing additional water in a region (U.S.B.R., 1987). Other options that can be considered are desalination, importation, evaporation suppression and vegetation management (Silverman, 1986). Desalination and importation require high construction costs. Evaporation suppression technology is usually not adequate for existing reservoirs. The combined effect of weather modification and vegetation management on the same area seems to increase water more than if the two were applied separately.

In planning weather modification projects, either for research or operational purposes, it is necessary to first carry out studies of the climatology of rain and clouds and studies of the structure and microphysics of clouds. These preliminary investigations should clarify whether the natural processes are efficient, and therefore, seeding is likely to be effective. If seeding experiments appear to be physically feasible, then the prospective benefits and cost of seeding should be investigated to determine if experiments are economically justified.

This paper constitutes one part of a series of studies with the objective of finding conclusive evidence leading to the design of a rain enhancement program in semiarid climates such as Greece (Dalezios, 1989; Dalezios and Christodoulou, 1989; Dalezios *et al.*, 1991). A climatological and microphysical analysis of clouds in central and northern Greece is conducted, which identifies the observed convective and stratiform clouds, the precipitation producing and non-precipitating cloud types and their frequency of occurrence. During the operational seasons of the National Hail Suppression Program (NHSP) of Greece microphysical cloud measurements were conducted for rainfall augmentation from summertime towering cumulus clouds. The paper is organized as follows: in section 2 background information is provided on drought assessment and design of weather modification experiments in Greece; in section 3 climatological cloud features of precipitation producing and non-precipitating cloud types are presented along with their temporal and regional variability; in section 4 microphysical cloud features are described from measurements during the NHSP of Greece; and in section 5 the rain enhancement potential is also addressed.

2. BACKGROUND

The NHSP was mainly designed as an operational cloud seeding program to reduce hail damage over three distinct agricultural areas, namely two areas, A1 (2,340 km^2) and A2 (1,306 km^2), in northern Greece and one area, A3 (2,400 km^2), in central Greece (Fig. 1). During the 9-year history of the NHSP (1984-1993), significant experience and knowledge have been gained. Besides operations, a research component was also designed to study the dynamic and microphysical characteristics of the potential hail producing clouds and to permit credible scientific evaluation of the effects of cloud seeding. The research part included a 5-year (1984-1988) statistical evaluation experiment with exploratory and comfirmatory stages in Area A1 using a cross-over randomization scheme (Karacostas, 1989; Dalezios and Spanos, 1995). The experimental unit was determined to be any declared hail day. Seeding was conducted through injection of silver iodide (AgI) either at cloud base or at cloud top when the following two criteria were met: a cell existed over area A1 or it was within 20 min of entering the area; and the cell was exhibiting a radar reflectivity factor of > 35 dBZ at an altitude between -5 °C and -30 °C in the cloud. The adopted seeding hypothesis was based on the conceptual model of the beneficial competition theory (Foote and Knight, 1977). Limited observations in convective clouds in northern Greece supported the ice phase or graupel embryo precipitation process and were consistent with the beneficial competition theory (Krauss and Papamanolis, 1989).

Analyses of rainfall data sets in central Macedonia of northern Greece indicate that the non-rainy days constitute the majority (about 270) throughout the year (Dalezios and Bartzokas, 1993 and 1995). Similarly, light rain constituted the major portion of the rainy days per year. These findings, among others, can be used for improving and optimizing agricultural planning and suggest that there are shortages of rainfall amounts during agriculturally critical periods in the rainfed portion of the above mentioned agricultural region (Dalezios and Bartzokas, 1995). Moreover, drought assessment studies in central and northern Greece using the Palmer Drought Severity Index (PDSI) demonstrated that there are drought periods (Table 1) in the region with significant extent in time as well as short drought periods during summer and winter months (Dalezios and Christodoulou, 1989; Dalezios *et al.*, 1991). Frequency analysis of PDSI (or the equivalent Z-index) time series was conducted at three stations in central and northern Greece, namely Larissa (LR) in central Greece, and Thessaloniki (TS) and Serres (SR) in northern Greece, respectively (Fig. 1). Frequency analysis revealed a climatological domination of droughts with increasing severity from north to south (Table 2). During drought periods, storm and cloud frequency is generally low, therefore, the emphasis is mostly placed on small and medium size clouds. The cloud seeding process is affected by the cloud temperature, its physical composition and the growth of precipitation particles (Braham, 1986).

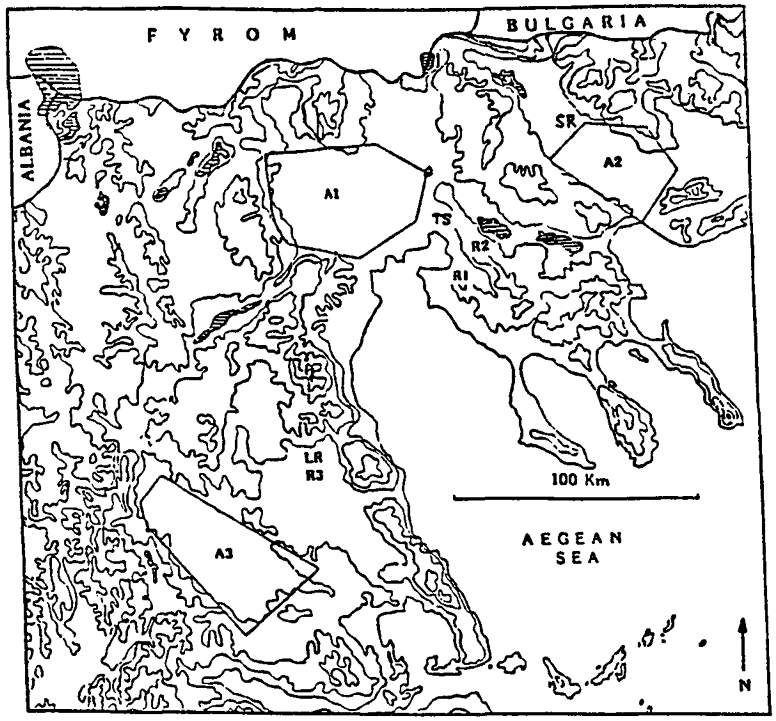

Fig. 1. Map of the Protected Areas in the NHSP with elevation contours at 200, 600, 1200 and 1800 m. R1, R2, R3 indicate radar locations and LR, TS and SR the meteorological stations.

Seedable clouds occur in two general types of storms that affect central and northern Greece: large synoptic storms in winter and early spring that produce widespread precipitation over large areas that include both mountains and valleys; and convective storms in spring and summer that produce localized precipitation. The choice of winter versus summer precipitation enhancement programs or even 'year-around' programs is directly associated with the moisture and water needs of a region. A hierarchy of priorities in water use would assist in answering critical questions such as whether soil moisture during fall and winter is more important than precipitation during the crop growing season. Since agriculture remains the main water user, the priority regions and crops can be identified.

TABLE 1: Weather Classification using PDSI.

PDSI	WEATHER
>4.00	Extremely wet
3.00 to 3.99	Very wet
2.00 to 2.99	Moderately wet
1.00 to 1.99	Slightly wet
0.50 to 0.99	Incipient wet spell
0.49 to -0.49	Near normal
-0.50 to -0.99	Incipient drought
-1.00 to -1.99	Mild drought
-2.00 to -2.99	Moderate drought
-3.00 to -3.99	Severe drought
<-4.00	Extreme drought

3. CLIMATOLOGICAL CLOUD FEATURES

It is essential to identify the dominant cloud types in central and northern Greece. Three synoptic stations were selected to represent the three project areas. The data were extracted from eight synoptic observations conducted daily at stations LR and TS during approximately the last thirty (30) years (1957-1986). The data sample is considerably smaller at station SR, where only daylight observations for twelve years (1972-1983) were conducted. The nature of cloud observations poses certain limitations on the accuracy and representativeness of such data. Cloud classification and observations depend on station location, hour of the day and to some extent on the observer himself. Similar preliminary studies were conducted elsewhere (Kochtubajda and Isaac, 1986). Recorded clouds were grouped in six categories according to precipitation characteristics and the related synoptic weather patterns.

Table 2. Relative Frequences (%) of Z-Index Time Series.

Class center	Stations		
	Larissa (LR)	Thessaloniki (TS)	Serres (SR)
-5.0	0.0	0.0	0.0
-4.0	0.0	0.3	0.7
-3.0	2.6	3.9	1.4
-2.0	19.1	18.5	20.3
-1.0	28.2	23.9	23.1
0.0	17.5	22.1	17.5
1.0	15.7	11.6	15.4
2.0	8.1	9.2	12.6
3.0	2.6	5.7	5.6
4.0	2.9	1.5	2.1
5.0	1.3	1.5	0.7
6.0	1.3	0.6	0.0
7.0	0.0	0.6	0.0
8.0	0.2	0.6	0.0
9.0	0.0	0.0	0.6
10.0	0.0	0.0	0.0
11.0	0.5	0.0	0.0
Sum	100.0	100.0	100

A first investigation of the data set showed that precipitation cases, exclusively related to mid and upper clouds, do not exist. Thus, only lower clouds were chosen to represent the five precipitation categories and all mid and upper cloud cases were grouped under the name "other" (Tables 3, 4, 5). A seventh category represented the clear weather cases. In particular, five cloud types were selected from the recorded synoptic observations (WMO, 1956) as follows: Cumulonimbus (CB) (coded CL=3 and CL=9), Cumulus Congestus and Cumulus (TCU-CU) (coded CL=1 and CL=2), Stratocumulus (SC) (coded CL=4 and CL=5), Stratus (ST) (coded CL=6), Cumulus Fractus and Stratofractus (CF-SF) (coded CL=7), where the last category also includes Altostratus (AS) and Nimbostratus (NS).

The results of the analysis are presented in Tables 3, 4 and 5 and Figures 2 to 5. In particular, Tables 3 to 5 summarize the total occurrences along with the number of observations with rain of each cloud type on a monthly basis for LR, TS and SR stations, respectively. From Tables 3, 4 and 5 it is indicative that the dominant precipitation producing clouds at the three stations are CU, CB and SC, which are further analysed and presented in Figures 2 to 5. Moreover, in these Tables it is shown that there is a large portion of clear-sky coverage with the high frequencies occurring during summer at the three stations. Mean monthly precipitation amounts are also presented in order to obtain a general assessment of the annual precipitation regimes (Fig. 6). Furthermore, in Figures 2 to 5 some features of the precipitation cloud types are emphasized. Specifically, the relative frequencies of cloud types occurrence are shown in Figure 2. The relative frequency of precipitation occurrence per cloud category is shown (Fig. 3) along with their diurnal distribution (Figures 4 and 5) at the three stations LR, TS, and SR, respectively.

3.1 Temporal Variation of Precipitating Clouds.

In Figure 2 the contribution of each cloud type to the total number of precipitation cases is presented. Precipitation during the warm season falls mainly from cumuliform clouds (CB, TCU-CU). During the cool season most of the precipitation is related to SC and CF-SF clouds of rainy weather. The contribution of stratiform clouds to the total number of precipitation cases is minimal. Precipitating stratiform cloud types (ST, SC) show higher frequencies of occurrence during the cool

Table 3. Monthly climatological summary of total occurrences (No of observations/No of observations with rain) of several cloud types for Larissa (1955-86).

	CLEAR	OTHER	CB	TCU-CU	SC	ST	CF-SF
Jan	671	134	8/3	166/5	1858/224	292/2	299/70
Feb	607	108	20/6	222/11	1768/246	168/1	303/70
Mar	721	102	30/5	423/19	1450/165	168/0	411/55
Apr	675	151	50/15	623/35	1019/175	98/2	489/53
May	742	144	181/44	900/18	677/77	44/3	457/5
Jun	1015	167	1577/32	883/21	373/22	20/1	553/4
Jul	1503	135	128/24	848/32	269/7	10/0	559/3
Aug	1466	175	125/28	736/6	363/16	17/1	547/2
Sep	1408	112	108/36	672/17	474/41	25/2	433/5
Oct	1095	113	82/34	430/36	1155/114	93/1	440/54
Nov	883	79	37/16	295/31	1521/201	178/0	295/41
Dec	779	97	14/4	148/17	1616/174	269/0	308/66

Table 4. Monthly climatological summary of total occurrences (No of observations/No of observations with rain) of several cloud types for Thessaloniki (1959-86).

	CLEAR	OTHER	CB	TCU-CU	SC	ST	CF-SF
Jan	726	139	5/1	277/20	1784/120	100/0	679/224
Feb	586	96	6/3	365/41	1755/117	66/2	653/162
Mar	641	66	27/9	545/37	1669/96	101/0	672/159
Apr	610	116	49/9	731/53	1212/133	53/1	542/86
May	598	137	196/32	1072/49	850/56	15/0	459/17
Jun	879	142	230/29	973/16	504/26	12/0	485/11
Jul	1406	116	159/26	880/10	342/9	2/0	547/3
Aug	1351	113	152/26	819/13	485/13	4/0	500/0
Sep	1324	92	72/15	631/14	542/28	15/0	516/16
Oct	1073	110	33/13	549/41	1265/73	66/1	469/75
Nov	822	79	30/19	377/29	1602/95	160/1	538/130
Dec	814	106	2/2	180/12	1596/80	189/1	672/175

Table 5. Monthly climatological summary of total occurrences (No of observations/No of observations with rain) of several cloud types for Serres (1972-83).

	CLEAR	OTHER	CB	TCU-CU	SC	ST	CF-SF
Jan	302	20	1/0	936/77	530/19	7/0	277/66
Feb	297	29	5/2	979/85	536/17	2/0	209/43
Mar	272	13	9/2	1193/71	527/15	1/0	213/35
Apr	192	23	24/4	1276/85	309/2	0/0	209/31
May	154	21	97/22	1423/59	231/0	1/0	159/11
Jun	248	35	108/27	1226/18	170/6	0/0	165/3
Jul	445	19	91/19	1106/14	94/0	0/0	176/1
Aug	421	16	72/20	1122/15	159/2	2/0	227/7
Sep	608	18	28/6	960/33	159/3	0/0	245/14
Oct	589	27	10/0	961/64	421/21	2/0	220/21
Nov	396	26	11/5	1034/97	527/9	11/1	188/36
Dec	375	21	0/0	929/71	556/17	19/1	196/45

season than in other months at the three stations with SC being the dominant precipitation producing cloud type and CF-SF showing higher frequencies at the stations of northern Greece (TS and SR) than in central Greece (LR).

The examination of the occurrence of precipitating clouds (Tables 3, 4 and 5) as a fraction of the total number of cloud occurrences per cloud category in each month (Fig. 3) addresses the problem of precipitation mechanisms within the cloud and their effectiveness on a seasonal and regional basis. The occurrences are generally decreasing during summer months for almost all cloud categories at the three stations. A plausible assumption especially for the low depth clouds is the absence of ice phase during summer months. Ice phase is the important factor in the initiation of the ice-crystal precipitation process (Krauss and Papamanolis, 1989). Another reason is the precipitation falls through an increasingly high temperature layer during summer months. In such conditions light precipitation seldom reaches the ground due to the evaporation of droplets.

In Figures 4 and 5 the diurnal variability of relative precipitation occurrences per cloud category are presented for the months of January and July to represent winter and summer at the above three stations, respectively. In January (Fig. 4) and for all cloud categories precipitation is not favoured at noon and early afternoon hours. During spring, at stations TS and SR, CB clouds are frequently related to precipitation during early or late afternoon hours, but precipitation occurrences from TCU-CU clouds for all stations is minimized at noon. A similar patern is also observed in the daily variation of SC and CF-SF. During July (Fig. 5) precipitation from CB clouds dominates in all stations with a daily minimum at noon and maximum at night. During fall the daily variation of CB clouds becomes more complicated with two maxima and minima.

3.2 Regional Variation of Precipitating Clouds.

The climatic summer precipitation minimum, which is less than 20 mm in Larissa, is increased toward Thessaloniki and Serres to over 25 mm (Fig. 6). This is expected because synoptic disturbances that trigger atmospheric instability usually affect only the north part of Greece during summer (Maheras, 1988). At Larissa, the small contribution of CB clouds to precipitation events during July is probably related to the long distance they have to travel in order to precipitate over that station. Convective clouds originate over the mountains (Spanos, 1993) and mid-summer wind fields are generally weak resulting in quasistationary storms. Thus it is not unusual for CB clouds to be reported without precipitation. However, weather radar echo climatologies (Spanos, 1993) suggest that convective clouds usually precipitate over the mountains. On an annual basis Serres station shows the highest frequency in cumuliform (CB, TCU-CU) precipitating clouds of all stations. This is related to the annual frequency of synoptic disturbances (Maheras, 1988) affecting the station and to topographic effects. Serres station is located in a narrow valley with mountain chains to the east and west. A great number of the observed CB clouds form and/or pass over the station, where precipitation is recorded.

Stratocumulus clouds associated with precipitation are more frequently observed at Larissa station and less frequently at Serres station especially during winter (Fig. 3). A stratocumulus cloud screen dominates central and southeast stations of Greece during cold outbreaks. In such cases a synoptic disturbance moves east of the Greek peninsula with prevailing high pressures and anticyclonic circulation over the Balkans. In this pattern, cold air masses that are travelling over Aegean Sea from northeast are enriched in moisture by evaporation from the sea surface and produce SC clouds when forced to ascent the east-coast mountains in Greece. This was also observed during seeding operations for the 1994 rain enhancement project in central Greece (Rudolph *et al.*, 1994). The number of generally occurring and precipitating SC is decreased from Larissa station towards the north (Thessaloniki, Serres) following the decrease in wind path (fetch) over the water. The frequency of precipitating CF-SF clouds at Larissa is the lowest of the three stations. This can be attributed to the fact that less synoptic disturbances affect the south stations and Larissa on an annual basis (Maheras, 1988).

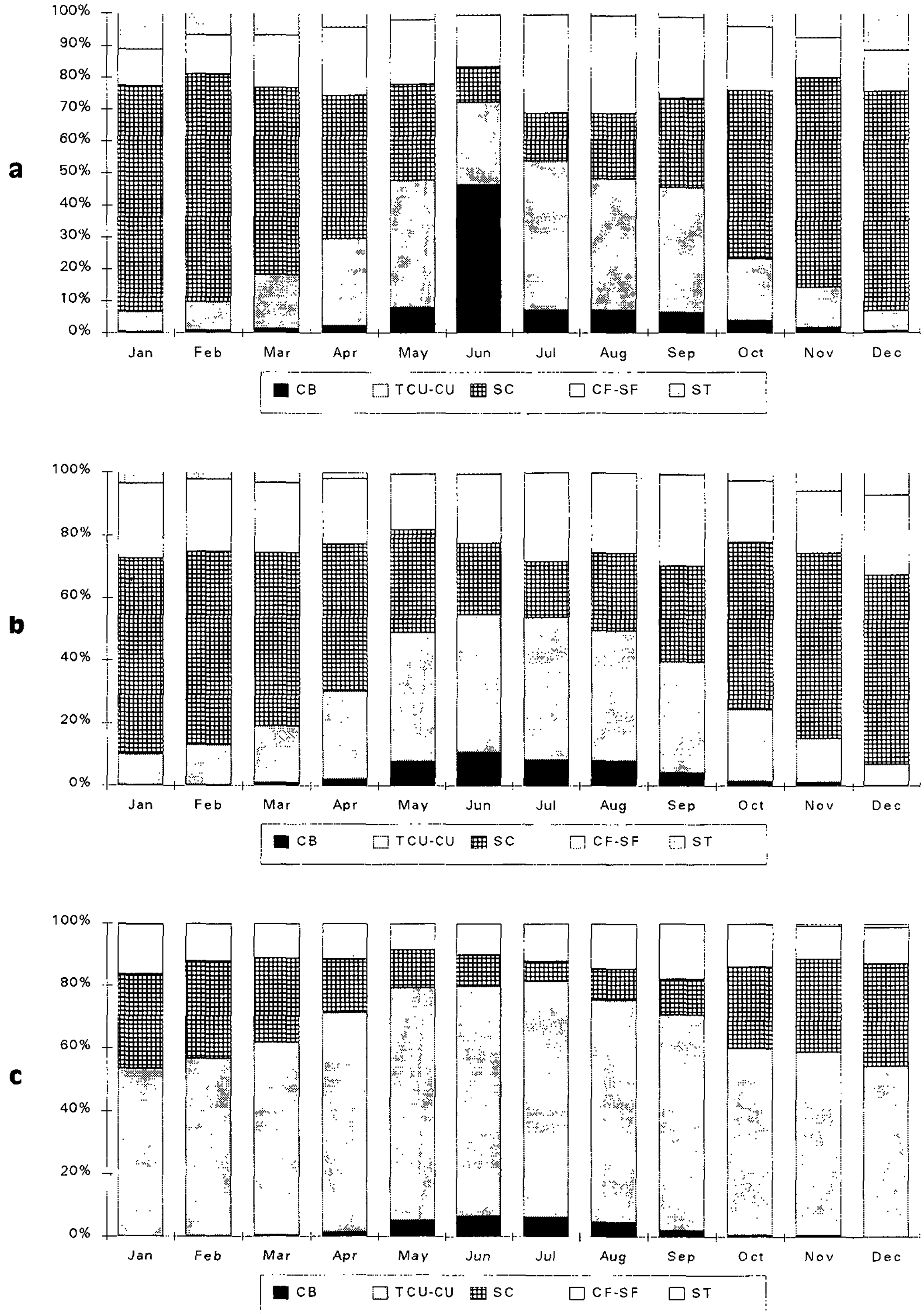

Fig. 2. Monthly Relative Frequencies (%) of Rainy Cloud Types : a. Larissa (LR), b. Thessaloniki (TS) and c. Serres (SR).

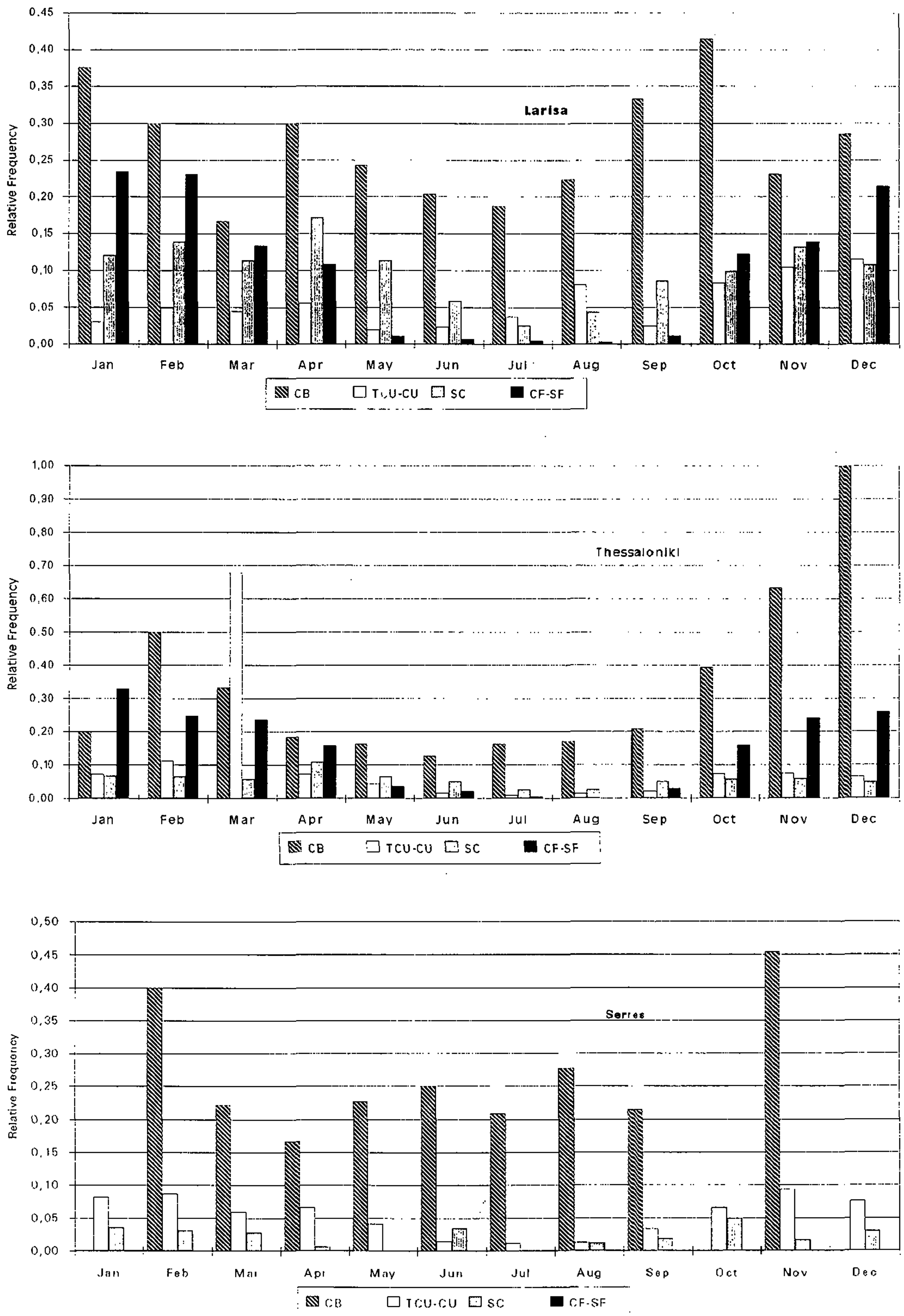

Fig. 3. Monthly Relative Precipitation Occurrences per cloud category of Rainy Cloud Types for the stations Larissa, Thessaloniki and Serres.

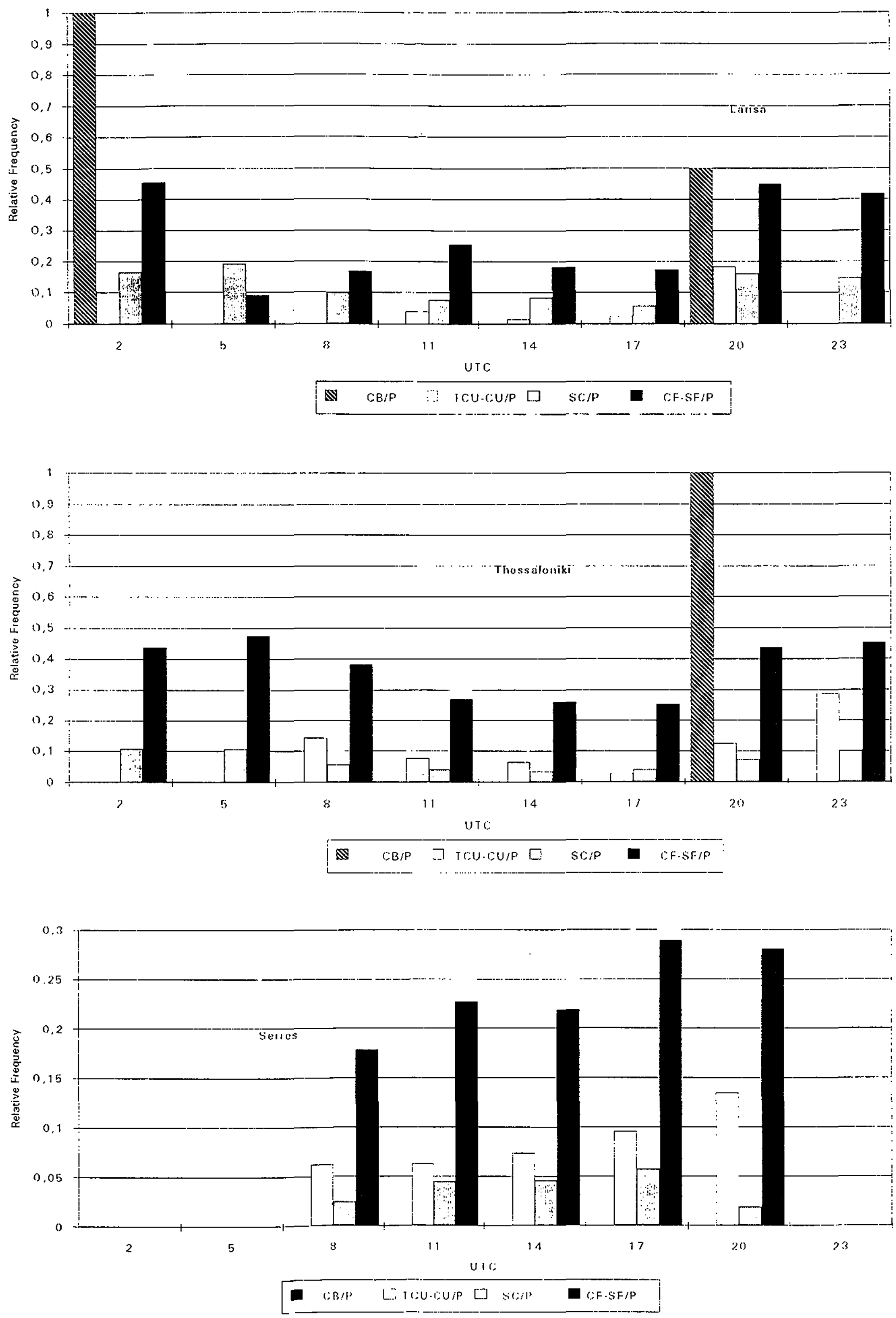

Fig. 4. Diurnal Variability of Relative Precipitation Occurrences per cloud category of Rainy Clouds for the three Stations (Larissa, Thessaloniki and Serres) during January.

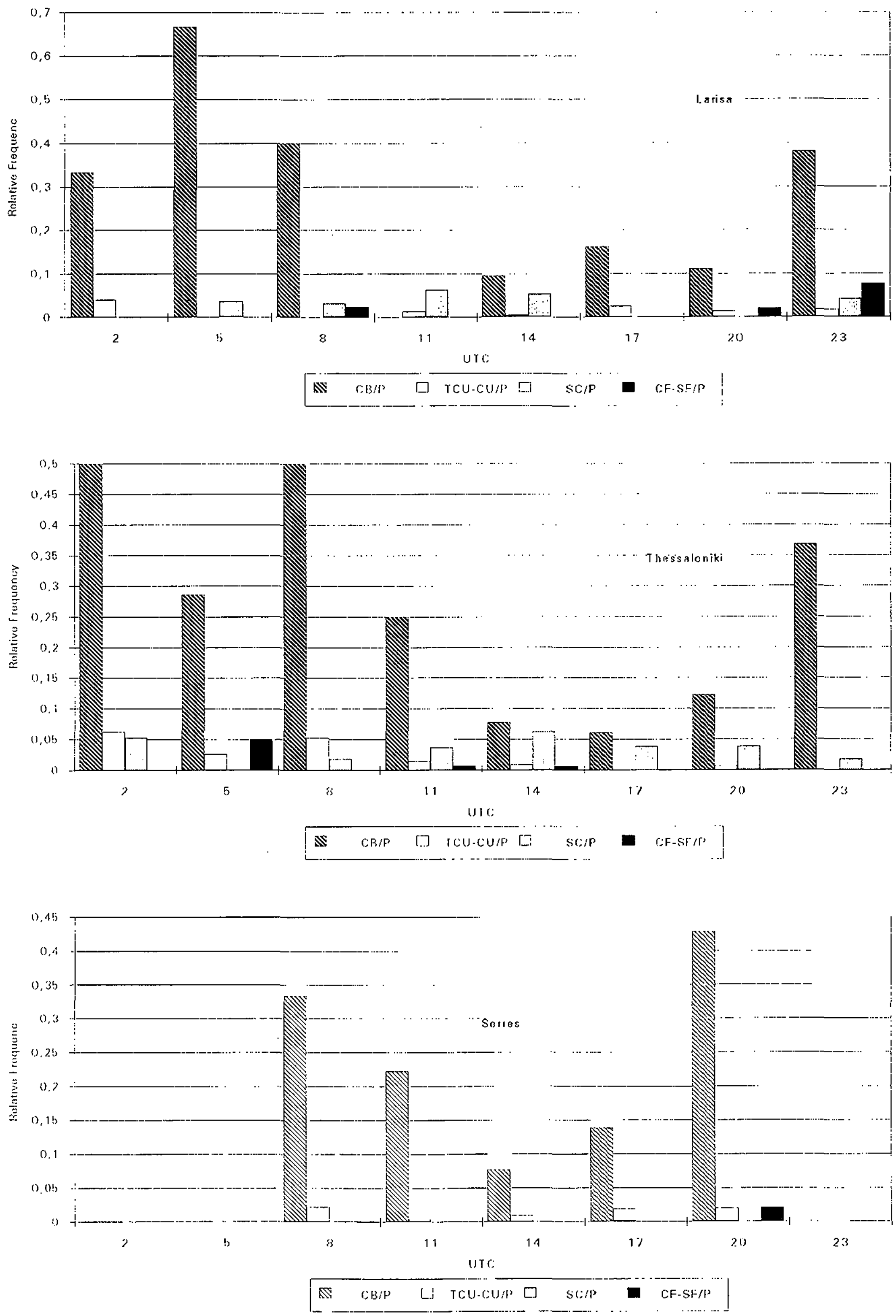

Fig. 5. The same as in Figure 4 but for July.

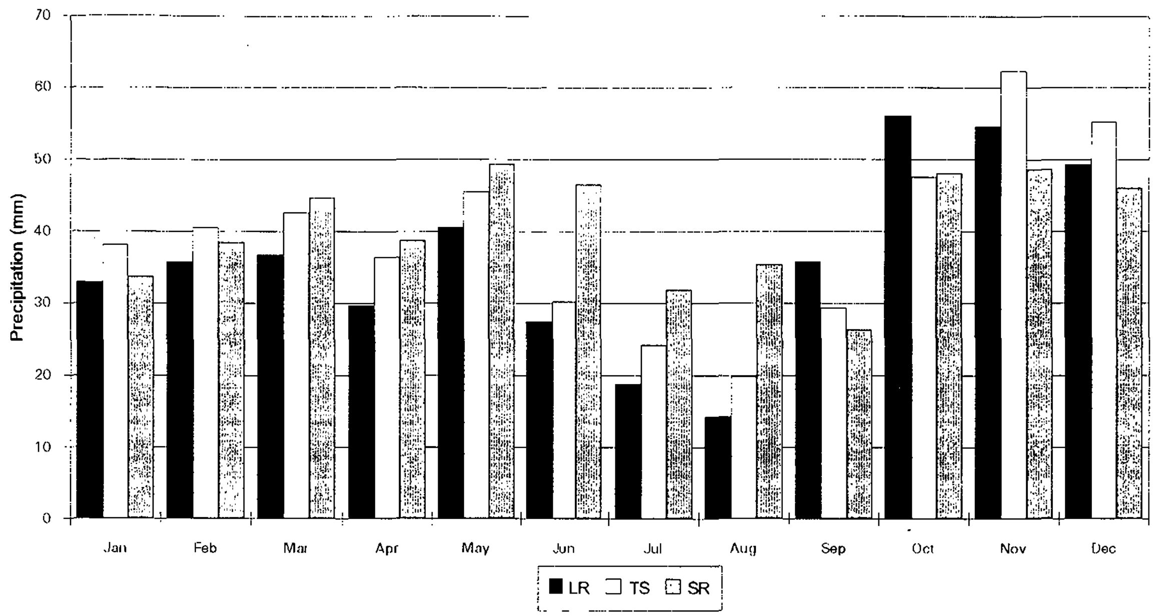

Fig. 6. Mean monthly Precipitation for the stations : Larisa (LR) Thessaloniki (TS) and Serres (SR).

4. MICROPHYSICAL CLOUD FEATURES

The design of a weather modification program involves theoretical and experimental studies of storms, their structure and the precipitation producing mechanisms. The basic conceptual model of the precipitation processes leading to the formation of precipitation within a severe storm in Greece assumes the involvement of graupel embryos, which grow within "feeder clouds" and then are transported by the wind into the main storm, where they grow to hailstones along the edge of the main storm upfraft (Dennis *et al.*, 1970; Heymsfield *et al.*, 1980; Krauss and Marwitz, 1984; and others). Rimed ice crystals are assumed to be the primary graupel embryos.

The cloud seeding hypothesis in Greece was based on the cloud microphysics concept of "beneficial competition", which assumes a lack of natural ice nuclei in the environment and that the injection of AgI results in the production of a significant number of "artificial" ice nuclei. The cloud seeding is concentrated on the time-evolving updraft of single cell or daughter clouds, and on the updrafts of developing feeder clouds that flank mature multi-cell storms. The cloud seeding takes place between the -5 °C and -10 °C levels (near the cloud top of developing feeder clouds) or at cloud base if the situation is not appropriate for cloud top seeding (Henderson, 1986).

The distribution of cloud base temperature for 57 days with convective precipitating clouds in northern Greece is shown in Fig. 7. The average cloud base temperature is +9.9 °C (standard deviation 3.6 °C). The data are a combination of aircraft measured cloud base temperatures and estimates from afternoon radiosonde soundings. Aircraft measured cloud base temperatures agreed quite well with the lifted condensation level of the soundings using the maximum surface temperature and mixing the humidity profile over the lowest 80 mb. Previous studies based on theoretical calculations and observations for different geographical areas (Johnson, 1982) suggest that the cloud base temperature separating coalescence and ice processes is between 10 and 15°C. On the average, cloud base temperatures in northern Greece are approximately 10°C colder than those in Florida (active coalescence) and about 5°C warmer than those found in the Great Plains of the United States (ice phase). Also, the cloud base temperatures in northern Greece are, on the average, about 5°C colder than those from the Nelspruit area of South

Africa, which has an active coalescence process (Mather *et al.*, 1986).

Some limited microphysical measurements have been made with an instrumented aircraft penetrating 'developing ' convective clouds. In addition to aircraft measurements of temperature, dew point, airspeed, and pressure, cloud liquid water content was measured with a Johnson-Williams (JW) hot-wire device and ice crystal concentrations were measured using a depolarizing laser ice particle counter (IPC). The JW is not sensitive to liquid water droplets with diameters larger than about 50 µm (Baumgardner, 1983) and liquid drops do not register on the IPC, therefore, the aircraft instrumentation was not capable of directly detecting precipitation size drops.

The size distribution of the cloud droplets is a key parameter governing the coalescence growth process. In order to determine the cloud droplet size distribution within clouds in northern Greece, the University of Wyoming "cloud gun" was used during the month of September of 1988 (Rudolph et *al.*, 1988). The device was a soot-coated slide device based on samplers designed by Squires and Gillespie (1952) and Clague (1965), which utilized a carbon-dioxide compressed gas pistol as its means of propulsion. Three soot slides were collected approximately 600 m above cloud base (mean temperature 14°C) of cumulus congestus clouds in their development stages on two days. These limited and rather simple measurements indicated concentrations of cloud droplets of the order of 1000 cm^{-3} and narrow size spectra (12.6 µm mean diameter and 2.8 standard deviation), giving them a continental microstructure and a high degree of colloidal stability. The limited cloud droplet size distributions observed are similar to those used in calculations (e.g. Warshaw, 1968) and observations (e.g. Squires, 1958) indicating no significant coalescence production of precipitation, at least during this time of year and for these clouds.

Microphysical measurements made with the research-seeder instrumented aircraft penetrating 'developing' cloud turrets generally indicate that natural ice does not readily form at cloud temperatures warmer than -10°C. As an example, the data collected by the research-seeder aircraft on 25 May 1988 from three cloud penetrations of an isolated developing cumulus congestus is summarized in the following discussion. On 25 May 1988, the cloud base temperature was 7.5°C (1.5 Km MSL) and the aircraft measurements were made between -9°C and -13°C. The first cloud penetration (at 1039 UTC) indicated essentially no ice and liquid water concentrations >3gm^{-3} within the central core. The second penetration (at 1041 UTC) indicated the first appearance of cloud ice, but liquid water concentrations were still high (e.g. >3gm^{-3}). The third penetration (1047 UTC) showed three cores of liquid water >1gm^{-3}, but with ice concentrations greater than ten per litter, primarily in the downdrafts. This ice apparently formed at the upper (colder than -12°C) regions of the cloud and then descended through the cloud.

Large droplets (greater than 50 µm) can be expected to form on occcasion in clouds of northern Greece due to the warm cloud bases. Conditions are suitable for large droplets to form in the updrafts with some freezing during ascent before reaching the -10°C level (Hobbs and Rango, 1985). At the same time ice crystals from near cloud top are descending downwards. In those conditions, graupel and ice pellets form by riming. Additional ice crystals can then be formed when the larger drops freeze and fragment on the surface of the graupel (Hallett and Mossop, 1974). In general, ice multiplication seems most common in the cloud tops of cumulus congestus with large droplets and tops near -10°C after the production of precipitation-sized particles. This is one possible explanation only, but other researchers (e.g. Dennis, 1970) have come to similar conclusions. The ice multiplication mechanism can only be verified by measurements of size distribution of cloud droplets and concentration of precipitation-sized particles. Such measurements require a wider range of particle measuring instrumentation than has been available in Greece.

In contrast with trade wind cumuli, which can develop rain when they are only 2 Km deep and have tops as warm as +10°C, the convective clouds of northern Greece not readily produce rain if their tops are warmer than -10°C. No evidence from the aircraft or radar observations has been

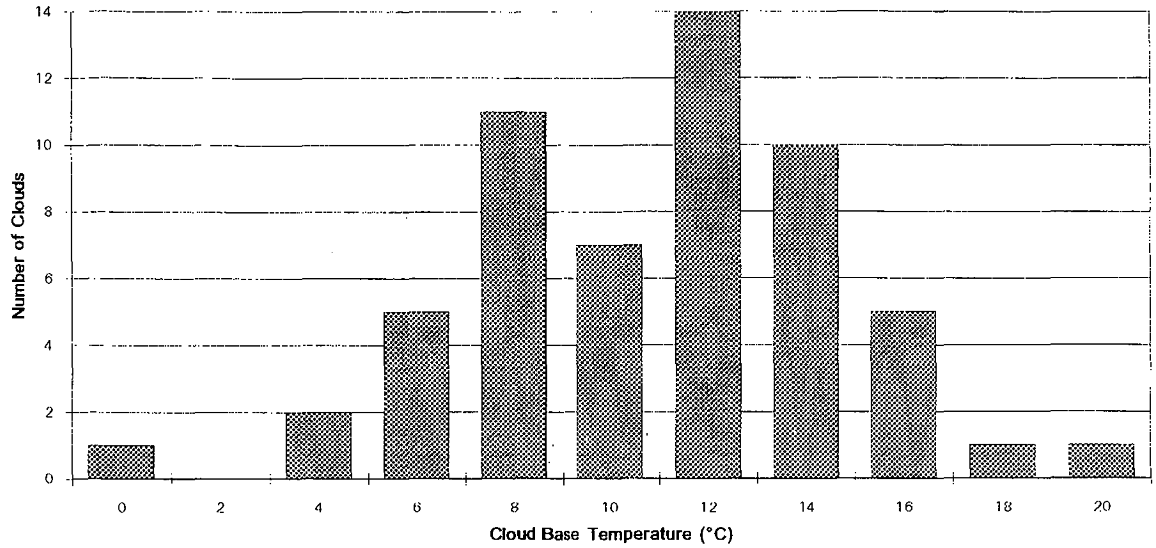

Fig. 7. Frequency of Cloud Base Temperature in Convective clouds.

found to indicate that precipitation-sized drops develop by a coalescence process before reaching the freezing level. The warm season convective clouds of northern Greece typically form within air masses, which originate over the Atlantic Ocean and travel across Europe. As a result, these clouds tend to have a continental microstructure characterized by a high concentration of small drops, a narrow spectrum and a high degree of colloidal stability.

5. RAIN ENHANCEMENT POTENTIAL

There are two goals for conducting seeding operations for precipitation enhancement. The first is to enhance precipitation from precipitating clouds and the second is to make more clouds to precipitate. Evidence supporting the first goal was presented (Rudolph et al., 1988) in a case study of target and control precipitation on an operational day (19 June 1988) of the NHSP. The total precipitation amount recorded in each raingage (including the contribution by melted hail) in the target and control areas was compared using the Mann-Whitney U-test. Total precipitation was found to be greater in the target area (Rudolph et al., 1988) than in the control area (P-value 0.110). Also the ratio of water equivalent hail mass from hailpads to total precipitation in raingages was smaller in the target area (P-value 0.003). This day was selected for analysis since it was the only day on which most of the raingages were checked immediately before hail fell in both target and control areas. Towards the second goal two seeding hypotheses and one seeding agent (AgI) were tested during a limited number of rain experiments on summer cumuli. The two hypotheses were static (Silverman, 1986) and dynamic modes (Orville, 1986). The static mode assumes that the injection of moderate amount of seeding material leads to earlier and more precipitation. Dynamic seeding is intented to invigorate clouds by altering their water and heat budgets through the injection of a large amount of glaciogenic material. It is realized that the two modes do not operate independently and each technique involves a combination of microphysical and dynamical effects.

A limited number of experimental case studies was analysed during the 1987 operational season of the NHSP for the assessment of glaciogenic seeding effect on summertime towering cumulus clouds. The semi-isolated cumulus congestus cloud was defined as the experimental unit and a set of cloud characteristics were specified, which was believed to represent a cloud that would respond positively to seeding. In designing the cloud seeding experiment, a cloud must meet the following criteria at the time it is penetrated by the instrumented research-seeder aircraft at the -5°C level: radar echo less than 15 dBZ; cloud depth greater than 1500m; cloud top temperature less than 0°C but greater than -8°C; J-W liquid water content (LWC) greater than 0.5 gm^{-3} for 6 consecutive seconds (approximately 500 m distance) in cloud; ice crystal concentration, as estimated by the IPC, less than 10/litter for all 500 m distances in the cloud; cloud diameter greater than 1 km but less than 10 km. Distinct ice crystal plumes were detected (e.g., case study on 11 August 1987), approximately 12 minutes after seeding with more than 100 counts/litter. The sudden increase in the ice concentration was a characteristic response of AgI seeding (Issac and Douglas, 1972). In the same experiment a radar echo (peak value of 23 dBz) appeared 10 minutes after seeding and lasted for 13 minutes, but precipitation on the ground could not be confirmed with surface observations. The fact that the echo formed approximately 10 minutes after seeding suggests that the initiation of the echo may have been natural and that the seeding signature was superimposed upon the actual conditions. A second possible explanation is that seeding created an over-abudance of ice crystals that formed aggregates, which echoed within 10 minutes.

6. SUMMARY AND CONCLUSIONS

A climatological and microphysical analysis of convective and precipitation producing clouds in central and northern Greece was conducted. The objective was to find conclusive evidence and results leading to the design of a rain enhancement program in Greece. The results of the climatological cloud analysis indicate that cumuliform clouds (CB, TCU-CU, SC) are the dominant precipitation producing types at the three stations of LR, TS and SR, respectively. However, there is a large portion of clear sky coverage with the high frequencies occurring during summer at the three stations. Moreover, stratiform cloud types show higher frequencies of occurrence during the cool season than in other months at the three stations. Furthermore, SC clouds are frequently occurring clouds during cool season in central Greece, which are shallow clouds formed by forced updrafts on the northeast slopes of mountains. In these conditions clouds are likely much more amenable to seeding due to topographic forcings, lower cloud bases and less entrainment. The microphysical structure of these clouds needs to be studied before definite conclusions are drawn. CF-SF clouds, which are related to extented and organized synoptic disturbunces, are the dominant precipitating clouds during the cool season in northern Greece.

The microphysical measurements of summertime towering cumulus clouds indicate that the average cloud base temperature was found +9.9 °C. The cloud base climatology helps compare clouds in central and northern Greece with clouds in other places, but it doesn't give evidence about whether cloud seeding can enhance rain in Greece. In general, the ice multiplication mechanism seems most common in the cloud tops of cumulus congestus with large droplets and tops near -10 °C after the production of precipitation sized particles. It is assumed that the natural precipitation process is the ice process and the limited observations suggest that small clouds lack natural ice. However, these small clouds do not rain and perhaps cannot be made to rain before they die due to entrainment. Slightly larger clouds may generate enough ice for the rain process to operate, but making more ice may make them less efficient. During the cloud seeding experimental case studies in 1987, possitive indications suggest that seeding material was participating in the precipitation formation process. In general, further airborne glaciogenic seeding experiments of summer cumuliform clouds for rain enhancement should be conducted in central and northern Greece. Nevertheless, the Serres (SR) region of northern Greece shows some advantages due to topographic effects, which are responsible for transferring most of the cumuliform precipitation over the region and it is also supported by the conducted seeding experiments during the NHSP.

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REFERENCES

Baumgardner, D.G., 1983 : An analysis and comparison of five water droplet measuring instruments. J. Climate Appl. Meteor., 22, 891-910.

Braham, R.R. Jr., ed., 1986: Precipitation Enhancement A Scientific Challenge. Meteor. Monogr., Vol. 21, No 43, AMS, Dec., 171 p.

Clague, L.F., 1965 : An improved device for obtaining cloud droplet samples. J. Appl. Meteor., 4 549-551

Dalezios, N.R., 1989: Pre-Investigative Study of Precipitation Enchancement Potential for Northern Greece. Final

Report M88-388 for ELGA, Greece, Intera Technologies Ltd., 178 p.

Dalezios, N.R. and M. Christodoulou, 1989: Feasibility of Reain Enchancement for Northern Greece. Proceedings, 5th WMO Sci. Conf. on Weather Mod. and Applied Cloud Physics, Beijing, China, WMO, 8-12 May, 325-328.

Dalezios, N.R., Z.G. Papazafiriou, D.M. Papamichail and T.S. Karacostas, 1991: Drought Assessment for the Potential of Precipitation Enhancement in Northern Greece. "Theoret. and Applied Climatology", 44, 75-88.

Dalezios, N. R., and A. Bartzokas, 1993: Phenomenological Features of Daily Precipitation in Agricultural Regions. IAHS, Publ No 213, 51-57.

Dalezios, N.R. and A. Bartzokas, 1995: Daily Precipitation Variability in Semiarid Agricultural Regions of Macedonia, Greece. Hydrol. Scie. Journal, 40 (5) 569-585.

Dalezios, N.R. and S.I. Spanos, 1995: Operational Efficiency Assessment of Hail Suppression for Agriculture in Greece. J. of Wea. Mod., Vol. 27 (1), 21-35.

Dennis, A.S., C.A. Schock and A. Koscielski, 1970: Characteristics of Hailstorms of Western South Dacota. J. Appl. Meteor., 9, 127-135.

Foote, G.B. and C.A. Knight (eds) 1977: Hail, A Review of Hail Science and Hail Suppression. Meteor. Monogr., No 38, AMS, Boston, 277p.

Hallett, J., and S.C. Mossop, 1974 : Production of secondary ice particles during the riming process. Nature, 249, 26-28.

Henderson, T.J., 1986: The Hail Suppression Program in Greece, Preprints : 10th Conf. on Weather Mod., Arlington, Amer. Meteor. Soc., 342-347.

Heymsfield, A.J., A.R. Jameson and H.W. Frank, 1980: Hail Growth Mechanisms in a Colorado Storm. Part II : Hail Formation Processes. J. Atmos. Sci. 37, 1779-1807.

Hobbs, P.V., and A.L. Rango, 1985 : Ice particle concentrations in clouds. J. Atmos. Sci., 42, 2523-2549.

Isaac, G. A., and R. H. Douglas, 1972 : Another 'time lag' in the activation of atmospheric ice nuclei. J. Appl. Meteor., 11, 490-493.

Johnson, D.B., 1982: Geographical Variations in Cloud-Base Temperature. Preprints Conf. on Cloud Physics, Chicago, Amer. Meteor. Soc, 187-189.

Karacostas, T.S., 1989 : The Greek National Hail Suppression Program: Desighn and Conduct of the Experiment. Proceedings, 5th WMO Sci. Conf. on Weather Mod. and Applied Cloud Physics, Beijing, China, WMO, 8-12 May, 605-608.

Kochtubajda, B. and G.A. Isaac, 1986: A Summertime Cloud Climatology of Central and Southern Alberta. Interim Report, Alberta Research Council, 12p.

Krauss, T.W., and J.D. Marwitz, 1984: Precipitation Processes within an Alberta Supercell Hailstorm, J. Atmos. Sci., 41, 1025-1034.

Krauss, T.W. and N. Papamanolis, 1989: Precipitation Formation Processes within Hailstorms of Northern Greece. 5th WMO Sci. Conf. on Weather Mod. and Applied Cloud Physics, Beijing, China, WMO, 8-12 May, 321-324.

Maheras P., 1988: The Synoptic weather types and Objective delimitation of the winter period in Greece. Weather, 43, 40-45.

Mather, G.K., B.J. Morrison, and G.M. Morgan, Jr., 1986: A Preliminary Assessment of the Importance of Coalescence in Convective Clouds of the Eastern Transvaal. J. Climate Appl. Meteor., 25, 1780-1784.

Orville, H.D., 1986: A Review of Dynamic-Mode Seeding of Summer Cumuli. In Braham R.R. Jr. (ed.): Precipitation Enhancement A Scientific Challenge. Meteor. Monogr., Vol. 21, No 43, AMS, Dec., 43-62.

Rudolph R., L. Davis, N. Papamanolis and F. Robitaille 1994: 1994 EYDAP Spring Rain Enhancement Project. Final report submitted to the city of Athens Water Company. Thessaloniki, Jun 1994.

Rudolph, R.C., T.W. Krauss, C.M. Sackiw, B. Kochtubajda and W.D. Wilson, 1988: Greek National Hail Suppression Program, 1987 Annual Report. Prepared by INTERA Technologies Ltd. for Agricultural Insurance Organization, Athens, 209 p.

U.S. Bureau of Reclamation, 1987: Project Skywater: Water Augmentation through Cloud Seeding. Interim Report, Apr., 13 p.

Silverman, B.A., 1986: Static Mode Seeding of Summer Cumuli. A Review. In Braham R.R. Jr. (ed.): Precipitation

Enhancement A Scientific Challenge. Meteor. Monogr., Vol. 21, No 43, AMS, Dec., 7-24.

Spanos, S.I., 1993: Climatologie Limitee de l' Activite Convective en Macedoine centrale (A limited Climatology of convective activity in central Macedonia). Publications de l' Association International de Climatologie, Volume 6, 389-397.

Squires, P., 1958: The Microstructure and Colloidal Stability of Warm Clouds. Pt. L., Tellus, 10, 256-262.

Squires, P., and C.A. Gillespie, 1952 : A cloud-droplet sampler for use on an aircraft. Quart. J. Roy. Meteor. Soc., 78, 387-393.

Warshaw, M., 1968: Cloud Droplet Coalescence : Effects of the Davis-Sartor Collision Efficiency. J. Atmos. Sci., 25, 874-876.

WMO, 1956: International Cloud Atlas, Abridged Edition.