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An integrated methodological procedure for alternative drought mitigation in Greece

N. R. Dalezios, D. Bampzelis and C. Domenikiotis
Laboratory of Agrometeorology, Faculty of Agricultural Sciences, University of Thessaly
Fytokou street, Volos, Hellas
e-mail: babzel@uth.gr

Abstract: This paper presents an Integrated Methodological Procedure for Alternative Drought Mitigation in Greece. The examined alternative drought mitigation is rain enhanced through cloud seeding. It has long been recognized that cloud seeding is one possible approach for rain enhancement. This paper constitutes a synthesis of several studies with the objective of finding conclusive evidence leading to the design of a rain enhancement program in semiarid areas of northern and central Greece. These studies include the climatology and characteristics of rain, the detection of the severity, extent and periodicity of drought, the investigation of cloud climatology and characteristics as well as the structure and microphysics of clouds. These studies are expected to clarify whether natural processes are efficient and if seeding is likely to be effective. Furthermore an airborne glaciogenic seeding rain experiment case study is presented for rainfall augmentation from summertime towering cumulus clouds. Results indicate that droughts are characterized by short duration and mild severity, whereas wet periods appear less frequently with high severity. Insufficient rainfall amounts are also identified over the region especially during the agricultural period. It was also identified that cumuliform clouds are the dominant and precipitation producing types of clouds. These types of clouds that occur in large synoptic storms in winter and early spring and in convective storms in spring and summer are amenable for seeding. Finally, the controlled cloud seeding experiment quantified some of the cloud seeding effects and documented a microphysical seeding "signature" signifying that seeding material was participating in the precipitation formation processes.

Key words: drought, weather modification, rain enhancement, cloud climatology, cloud seeding

1. INTRODUCTION

Droughts are, by nature, regional phenomena and have been referred to as "non events", since their basic cause is the lack of precipitation events in a region over a period of time. Drought preparedness planning is considered an essential component of integrated water resources management due to the increasing scientific potential to cope more effectively with the extremes of climate and water resources variability, i.e., floods and droughts. Drought risk results from a region's vulnerability to extended periods of water shortage. Vulnerability to drought is dynamic and influenced by several factors. National or regional drought policies and preparedness plans should place emphasis on risk management rather than following the traditional approach of crisis management, where the emphasis is on reactive emergency response measures, which decrease self-reliance and increase dependence on government and donors.

The overriding principle of drought policy emphasizes on risk management through the implementation of preparedness and mitigation measures. Preparedness refers to pre-disaster activities designed to improve the level of readiness or increase the operational and institutional efficiency for responding to a drought episode. Similarly, mitigation includes short and long- term actions, programs, or policies applied during and in advance of drought that reduce the degree of risk to human life, productive capacity and property. Moreover, emergency response will always be a part of drought management, because it is unlikely that policy makers can anticipate, avoid or reduce all potential impacts through mitigation programs. There are also alternative drought mitigation measures and programs dealing with the so called marginal waters in the framework of water scarcity management in a region. Such an alternative measure is water augmentation from atmospheric water in terms of rain enhancement through cloud seeding. Other options that can be considered are desalination, water importation, recycling, evaporation suppression and vegetation management (Silverman, 1986). Desalination and importation require high construction costs. 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. The demand for augmentation of water availability to meet seasonal and long term water needs in a region, such as central and Northern Greece, is related to historical semiarid conditions and the lack of sufficient water (Dalezios et al, 1991). Rain enhancement is a supplementary non-structural intervention to increase the available water for all possible uses, i.e. agricultural, domestic and industrial, thus, becoming an important tool for drought mitigation in arid and semi-arid regions of the world (Howell and Grant, 1973). 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 does not require large permanent construction of 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.

The objective of this paper consists of the presentation of an integrated methodological procedure for alternative drought mitigation in central and northern Greece. The selected alternative drought mitigation measure is rain enhancement. The proposed and presented methodology consists of a sequence of feasibility studies, which are carried out in the following order. First, studies on synoptic climatology in order to identify the prevailing weather systems and the rain producing systems. Then studies on the climatology and characteristics of rain are carried out to justify potential shortage of water availability. This is followed by a study on drought severity, extent, duration and periodicities in order to assess the frequency and persistence of drought phenomenon. The analyses of rain characteristics support the findings of drought studies. Then, a study on cloud climatology and cloud features is carried out including also the structure and microphysics of clouds (Bojkov, 2007). Cloud types distribution and microphysics also support rain enhancement potential through cloud seeding. Finally, the proposed methodology is integrated with the presentation of the framework of a rain enhancement experiment, which was attempted in northern Greece along with a seeding case study on cumulus congestus clouds with positive response to seeding.

2. DROUGHT MITIGATION

There are several components of a drought risk reduction plan and strategy. Among them, is the availability of reliable information for decision making policies that encourage assessment and use the above information, a framework for risk management measures, as well as consistent and effective actions. The main goal of national drought plans remains the improvement of preparedness and response efficiency by reinforcing early warning and monitoring, impact and risk assessment, as well as mitigation and response. Initially, droughts were focusing on response efforts, whereas today the trend is on mitigation as the fundamental element of a drought plan. Thus, many plans adopt a more risk management approach to drought management, becoming more pro-active (Tsakiris, 2009).

Drought mitigation plans are based mainly on three fundamental components either they are applied to provincial, national or regional level. First, an early warning system serves as the basis for decision making during the development of a drought period. There is also a need for a dissemination system that distributes reliable and timely information. Second, it is important to undertake a risk assessment in order to determine the subject and the causes of risk, which is accomplished through impact studies of drought events. Third, it is necessary to specify appropriate mitigation actions in order to reduce the risk of each impact for future drought events (Wilhite et al, 2000). There are also response actions that are considered, although the main goal of the drought mitigation plan remains to reduce vulnerability to drought events. Several mitigation actions are briefly presented below.

Assessment programs include the development of criteria or triggers for specific mitigation actions in response to drought, the establishment of new data collection networks, the development of early warning and monitoring systems and monitoring climate and water supply conditions. Legislative actions include measures to protect environmental flows, to guarantee low-interest loans to farmers, to examine water rights for possible modification during water shortages and to impose limits on urban development. Similarly, augmentation of water supplies during droughts includes reviewing reservoir operation plans and rehabilitating reservoirs to operate at design capacity. Moreover, public awareness of the severity of drought involves periodic reports and pamphlets, informational meetings and workshops, as well as focal points for assistance and technical assistance on water conservation and other water related activities such as evaluation of water quantity and quality. Other mitigation actions involve water conservation programs such as implementing water, metering and leak detection programs, emergency response programs, resolution of water use conflicts and drought contingency plans.

Besides the conventional measures to combat drought referred to above, there exist important non-conventional measures, which utilize the so-called marginal waters and could be applied as a supplement employed to additionally support the efficiency of water management schemes in arid and semi arid regions. Specifically, marginal waters refer to waste waters, saline, sea and atmospheric waters. Non-conventional measures, which could have an important impact in arid areas, are the inclusion of water dams in small streams in conjunction with small hydroelectric works, the provision of desalination plants to convert brackish or sea water to drinking water and the reuse of wastewater effluents and water streams of inferior quality in agricultural applications or for the replenishment of the aquifers. At the present, the cost of the desalination is still too expensive for other than municipal domestic and industrial use, whereas wastewater reuse is at the present limited to a small percentage of irrigation water use, but is expected to become more significant in the near future. The incorporation of non-conventional measures to combat drought may assist the overall water management strategy conceived and be applied in arid areas in a number of ways.

The present paper deals with an alternative non-conventional measure for drought mitigation, namely atmospheric water. In particular, atmospheric water can assist to combat drought in terms of weather modification programs for rain enhancement through cloud seeding. Studies in several areas of the world have shown that drought periods are often characterized by a large decrease in the amount of rainfall per rainy day, by an increase in the continentality of the clouds and by a lack of rain producing clouds. As a consequence the corresponding reduced cloud cover results in subsidence of high level keeping the atmosphere significantly drier and more stable than normal. Rain enhancement in selected arid areas is expected to improve the quantity of water in the hydrological system. Needless to say, it has long been recognized that cloud seeding is one possible approach for rain enhancement in a region.

3. FEASIBILITY OF RAIN ENHANCEMENT

As already mentioned the proposed integrated methodological procedure for alternative drought mitigation involves a series of feasibility studies for rain enhancement potential in central and northern Greece. This section presents the results of a series of feasibility studies involving synoptic climatology, analysis of precipitation and cloud climatology, as well as microphysical features of clouds. In planning weather modification projects, either for research or operational purposes, it is necessary to first carry out studies on the structure and macrophysics 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. Figure 1 shows the map of Greece with the protected areas in the National Hail Suppression Program (NHSP) along the meteorological Stations.

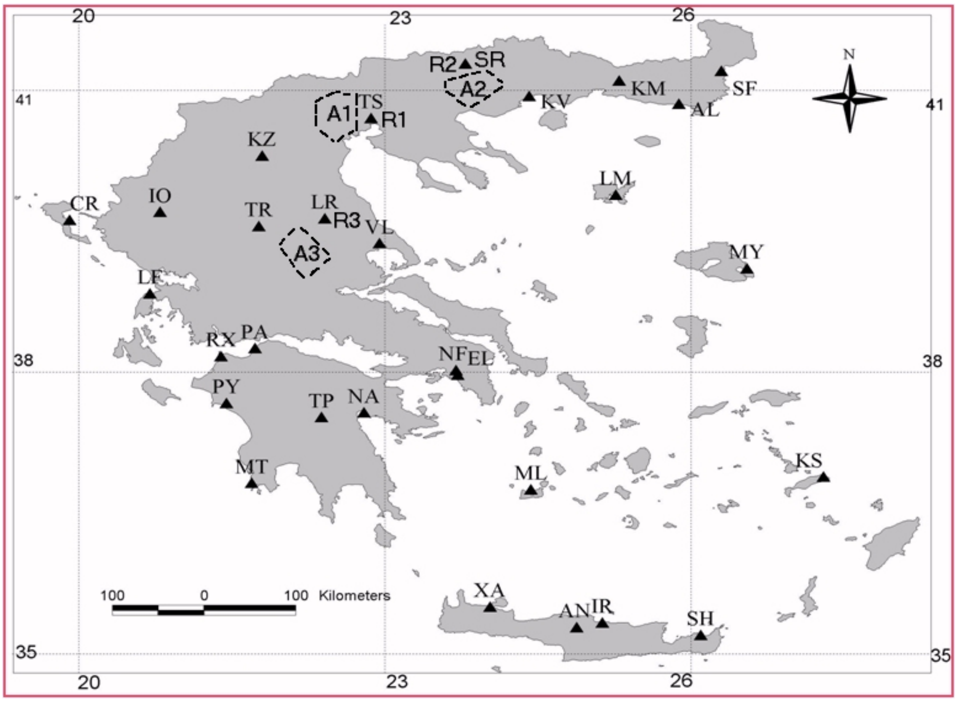

Figure 1: Map of Greece with the protected A1, A2 and A3 areas in the NHSP. R1, R2, R3 indicate radar locations. Meteorological stations used are also labeled in the map

3.1 Synoptic Climatology

Synoptic climatology involves the study and investigation of the prevailing weather systems and the precipitation producing systems at synoptic and sub-synoptic scale. The study also includes the temporal variability and occurrences as well as the areal extent of the prevailing weather systems. It has been summarized (Rudolph et al, 1988) that seedable clouds occur in two general types of storm systems in central and northern Greece: in large synoptic storms in winter and early spring that produce widespread precipitation over large areas and convective storms in spring and summer that produce localized precipitation. It is understood that this part of feasibility study should be integrated with rainfall and cloud climatology and the microphysical cloud features, which lead to the design of a potential rain enhancement experiment.

3.2 Rain Characteristics

Analyses of daily rainfall data sets in central and northern Greece indicate that the non-rainy days constitute the majority (about 270) throughout the year. Similarly, light rain constituted the major portion of the rainy days per year (Dalezios *et al*., 1996). The frequency of daily rainfall within the Larissa region for the period 1955-2000, which was taken as a sample station is shown in Figure 2. Only non-zero data were used. This figure shows that daily precipitation less that 2mm has a very high frequency of occurrence.

These findings, among others, can be used to improve and optimize environmental and agricultural planning and suggest that there are shortages of rainfall amounts during critical periods during the growing season in the above mentioned agricultural region.

It can be mentioned that rainfall falls mainly during November-May period and not during the summer months. The coefficient of variation, which is the standard deviation normalized by the mean for each month for the same station, is also shown in the same figure. These data show that typically winter months have less variability than the period from July to October. Note also that the standard deviation is approximately equal to the mean for July to October period.

This large degree of variability can also be seen in plots of the year-to-year variations of the monthly precipitation values as shown in Figure 3. The plots also show that, on average, every two to three years there is a precipitation deficiency and this is indicative of summer as well as winter precipitation values, whereas in other years there is precipitation excess.

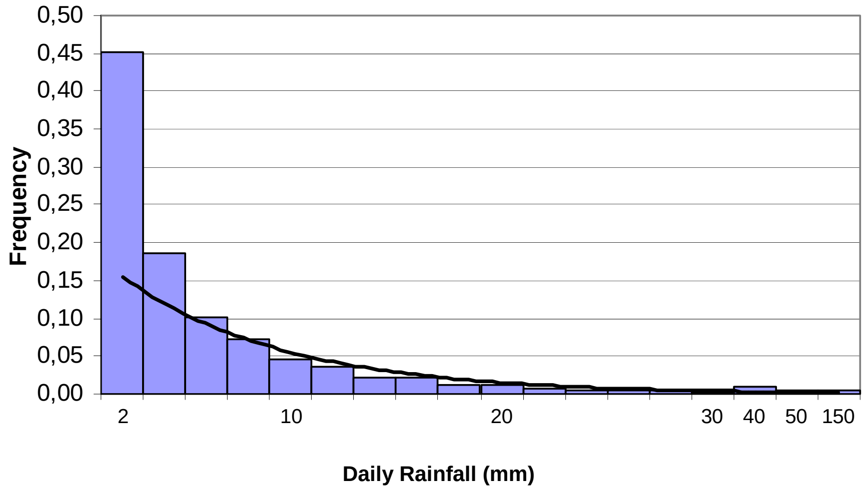

Figure 2: Average rainfall frequencies for the period 1955-2000 for Larissa meteorological station.

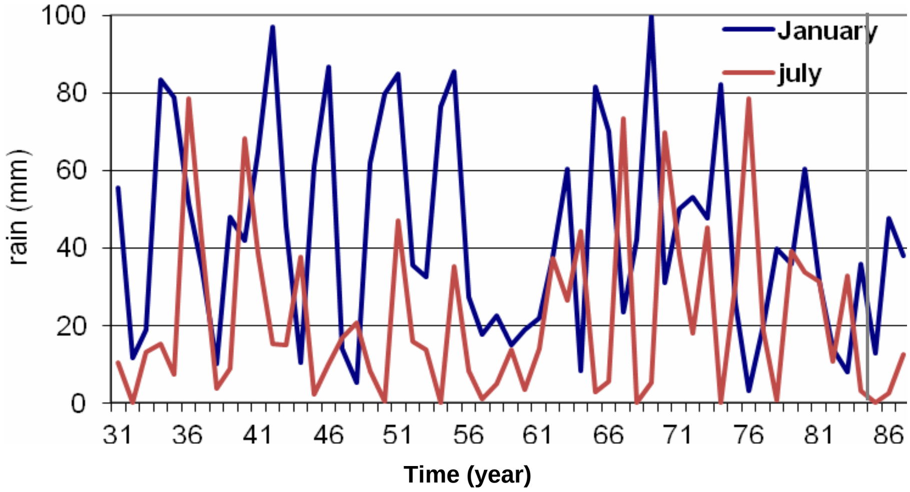

Figure 3: Year-to-year variation of monthly precipitation values for Thessaloniki station

This rainfall analysis involving frequency analysis, seasonal grouping of monthly rainfall and frequency analysis of daily rainfall data in central and northern Greece, shows some rainfall characteristics that are useful in assessing the need for further studies on the potential for rain enhancement.

3.3 Drought Characteristics

In general, droughts have been shown to be associated with the persistence of ridges or centers of high pressure systems at the middle level in the troposphere. Furthermore, the corresponding reduced cloud cover results in positive temperature anomalies in the lower atmosphere, which produces the middle-level pressure anomaly and favors subsidence at the high level keeping the atmosphere significantly drier and more stable than normal (Kochtubajda and Isaak, 1986). Studies in other areas of the world have shown that drought periods are often characterized by a large decrease in the amount of rainfall per day, by an increase in the continentality of the clouds and by a lack of rain-producing clouds.

There is no universal quantitative definition of drought, since such a definition must be oriented towards the particular problem. In the present study, drought is considered as a meteorological anomaly characterized by a prolonged and abnormal moisture deficiency (Palmer, 1965). A distinction should be made between agricultural drought and hydrological drought. Agricultural drought is described in terms of crop failure and is said to exist when soil moisture is depleted so that crop yield is reduced considerably. Hydrological drought is considered to be a period during which the actual water supply is less than the minimum water supply necessary for normal operations in a particular region (watershed). The relationship between the different drought categories can be explained as follows. First, a meteorological drought in terms of lack of precipitation is the primary cause of a drought. It usually leads to agricultural drought due to lack of soil water. If precipitation deficiencies continue, then a hydrological drought in terms of surface water deficits develops. The ground water is usually the last to be affected, but also the last to return to normal water levels.

To detect the onset of meteorological droughts in central and northern Greece and assess their severity, an "objective" index is used, namely the Palmer Drought Severity Index (PDSI). The PDSI is one of the few general indices, which do address some of the elusive drought properties such as severity, onset time and end time. Although the PDSI is referred to as an index of meteorological drought, the procedure considers precipitation, evapotranspiration, and soil moisture conditions, which are determinants of hydrological drought and, indirectly, of agricultural drought (Palmer, 1965). In addition, the PDSI is standardized for different regions and time periods, a necessary requirement for the areal assessment of droughts

Droughts in Greece are characterized by short duration and mild severity, whereas wet periods appear less frequently with high severity (Dalezios *et al*., 1991). Moreover, all stations in Greece exhibit high frequency cycles of drought, i.e. drought periodicities dominate, whereas in some regions low frequencies are also present. Spectral analysis indicated, in all regions, statistically significant high frequency periodicity of droughts with cycles varying from two to eight months. These findings are reflected in the developed Severity – Duration – Frequency (SDF) relationships and the produced tables, as well as in isoseverity mapping. Drought isoseverity mapping of Greece also shows smooth and similar patterns for droughts and wet periods, respectively. These patterns appear to indicate increasing severities from west to east as well as towards south southeast (Dalezios *et al*., 2000). Droughts have lower severities than wet periods for similar durations and return periods according to the Palmer severity classes (Table 1), indicating that, in general, wet spells have higher intensity than droughts.

Table 1: Classification of weather using PDSI or Z-index (from Palmer, 1965)

PDSI or Z-index Values	Weather Conditions
4.0 or more	extremely wet
3.0 to 3.99	very wet
2.0 to 2.99	moderately wet
1.0 to 1.99	slightly wet
0.5 to 0.99	incipient wet spell
0.49 to -0.49	near normal
-0.5 to -0.99	incipient dry spell
-1.0 to -1.99	mild drought
-2.0 to -2.99	moderate drought
-3.0 or less	extreme drought

The above results indicate that droughts in Greece seem to decrease or to remain unchanged in magnitude and severity, since, only the positive linear trends were statistically significant (Loukas *et al*., 2002). Therefore, cubic trends were used to reveal the short-term fluctuations of the Z-index monthly time series. This analysis showed that the Z-index time series at most stations exhibit very low fluctuations, which cannot be identified by the cubic trends (Figure 4).

These results indicate that for most stations, irrespective to region, dominate remarkable very high frequency cycles, i.e. periodicities from two to eight months, whereas in a few climatic zones low frequencies are also present at the same stations (Table 2). However, there are stations where the Z-index exhibits only recurrence intervals near or above two years. Moreover, at most stations in the southern region and the eastern region of Greece as well as stations in the central region, the Z-index has periodicities of one year (12 months) to 1.5 years (18 months). These regions are the driest areas of Greece. The analysis, also, detected that for many stations the Z-index has periodicities that are greater than two years (22 to 37 months). This periodicity can be related to quasi-biannual oscillation (QBO).

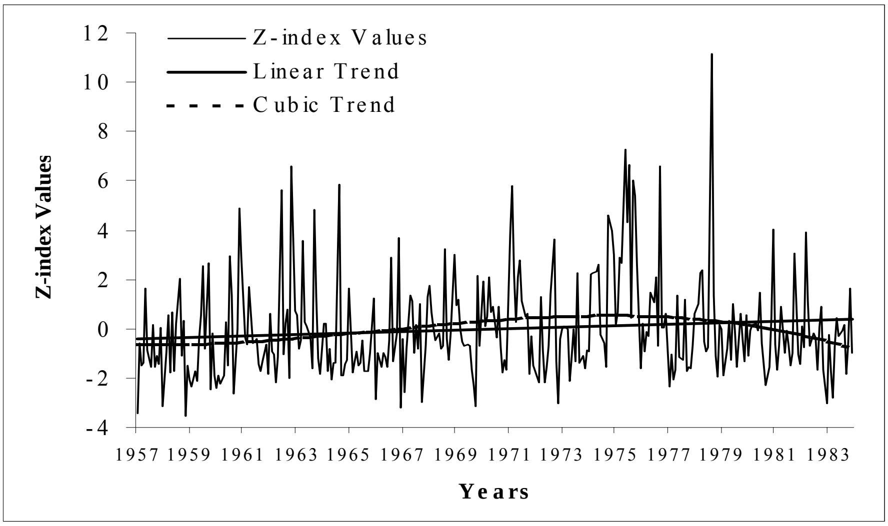

Figure 4: Linear and cubic trends for Z-index values in Limnos meteorological station

The results of this analysis indicated that, on average, more than 40% of the months in all stations experienced droughts, which means that drought is quite frequent phenomenon for all stations in Greece. This analysis, also, showed that the recurrence interval of monthly Z-index increases, on average, from west to east and from north to south. Most of the stations in all regions experienced rather mild to moderate monthly droughts (Table 3). However, there are stations where the Z-index takes values lower than -3, which means that droughts become also severe and extremely severe. Analysis of the common consecutive drought periods for all stations within a climatic region indicated that droughts with duration of one to three months were extended over the whole country of Greece, irrespective to region, and were the most frequently occurring drought periods for all regions (Loukas *et al*., 2002).

The analysis of drought characteristics has indicated that for central and northern Greece drought periodicities show mainly very high frequency cycles (2-8 months), but also low frequencies (i.e. 9-19 months), to medium-long (20-37 months) (Table 2). This finding combined with monthly precipitation variations (Fig.4) showing precipitation deficiencies every two to three years also justifies the need for further investigation for rain enhancement in the region.

3.4 Cloud Climatology

The results of the climatological cloud analysis indicate that cumuliform clouds, i.e. Cumulonimbus (CB), towering cumulus – cumulus (TCU-CU) and stratocumulus (SC) are the dominant precipitation producing types at the three stations of Larissa, Thessaloniki and Serres, respectively. However, there is a large portion of clear sky coverage with the high frequencies occurring during summer at the three stations. Moreover, stratiform (ST) 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 forcing, lower cloud bases and less entrainment. The microphysical structure of these clouds needs to be studied before definite conclusions are drawn. Cumulus fractus (CF) and stratus fractus (SF) clouds, which are related to extended and organized synoptic disturbances, are not dominant precipitating clouds during the cool season in northern Greece (Dalezios *et al*., 1996).

Table 2 Statistically significant (at 0.01 level) periodicities (in months) revealed by Power Spectrum Analysis of Z-index values (L=Long cycles, ML=Medium-Long cycles, M=Medium cycles and S=Short cycles).

Region	Station	L (>38 months)	ML (20-37 months)	M (9-19 months)	S (2-8 months)
Western	KZ				6.1, 4.7
	LF				6.1, 2.6, 2.2
	IO			16	6.2, 4.7, 4.4, 2.3
	CR				6.3, 6.1, 4.4, 2.6
	TP	46.3	22.4		6.2, 2.8
Southern	AN				3.6, 2.6
	SH		22.4	18.7, 14.6	2.6
	ML		30.5, 22.4	13.4	5.2, 4.8, 2.8, 2.6
	IR			17.7, 14.6, 13.4	2.6
	XA			18.7, 14.6	6.6, 2.5
	KS		22.4		
Eastern	AL		24	16	6.5, 5.4
	SF			16	6.5, 3.7
	MY		25.8, 22.4	12.4	6.1, 2.6
	KV			12.9, 11.2	5.2, 3.7
	KM		37.3, 25.8, 21		5.4, 3.7
Central	LR			14.6	7.3, 3.1, 2.8
	VL		37.3, 25.8		3.1, 2.8
	TR	108	25.8, 22.4		6.1
	TS		25.8, 22.4		6.7, 6.1
	EL		30.5, 22.4	14.6, 13.4	7.3, 2.7, 2.6
	NF		30.5	13.4	2.8, 2.7, 2.5
	NA		22.4	14.6, 13.4	4.1, 2.8
West	MT		25.8, 22.4		
Pelopon-	PY		22.4	18.7	5.9, 3.1, 2.9
nesian	PA		37.3, 22.4		6.2, 4.7, 2.9
	RX	108	22.4	9.6	6.5, 6.2

Table 3 Severity of common monthly drought episodes per region

Z-Index Class	Western		Southern		Eastern		Central		W. Peloponnesian	
	Cases	%	Cases	%	Cases	%	Cases	%	Cases	%
Near Normal	1	1.5	4	6.0	1	1.2	0	0.0	1	1.3
Incipient	12	17.9	8	11.9	11	13.6	9	13.6	5	6.5
Mild	30	44.8	34	50.7	52	64.2	40	60.6	42	54.5
Moderate	20	29.9	21	31.3	17	21.0	17	25.8	21	27.3
Severe	4	6.0	0	0.0	0	0.0	0	0.0	8	10.4
Extreme	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
Total	67	100	67	100	81	100	66	100	77	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 upper cloud cases were grouped under the name “other” (Tables 4, 5, 6). From Tables 4, 5 and 6 it is indicative that the dominant precipitation producing clouds at the three stations are CU, CB and SC, which are further analyzed and presented in Figures 5 to 8. 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 (Dalezios *et al*., 1996).

Table 4: Monthly climatological summary of total occurrences (No. of observations / No. of observations with rain) of several cloud types for Larissa 1955-1986 (CB: Cumulonimbus, TCU-CU: Towering Cumulus - Cumulus, SC: Stratocumulus, ST: Stratus, CF-SF: Cumulus Fractus - Stratus Fractus)

			LARISSA				
	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	1091 /175	98 /2	489 /53
MAY	742	144	181 /44	900 /18	677 /77	44 /3	457 /5
JUN	1015	167	157 /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 5: Monthly climatological summary of total occurrences (No. of observations / No. of observations with rain) of several cloud types for Thessaloniki 1959-1986.

			THESSALONIKI				
	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	1569 /80	189 /1	672 /175

Table 6: Monthly climatological summary of total occurrences (No. of observations / No. of observations with rain) of several cloud types for Serres 1972-1983.

			SERRES				
	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

The examination of the occurrence of precipitation clouds (Tables 4, 5 and 6) as a fraction of the total number of occurrences per cloud category in each month (Figure 6) addresses the problem of precipitation mechanisms within the cloud and their effectiveness on a seasonal and regional basis. The precipitation occurrences are generally decreasing from winter to summer months for almost all cloud categories at the three stations (Figures 7 and 8). 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 (Dalezios *et al*., 1996).

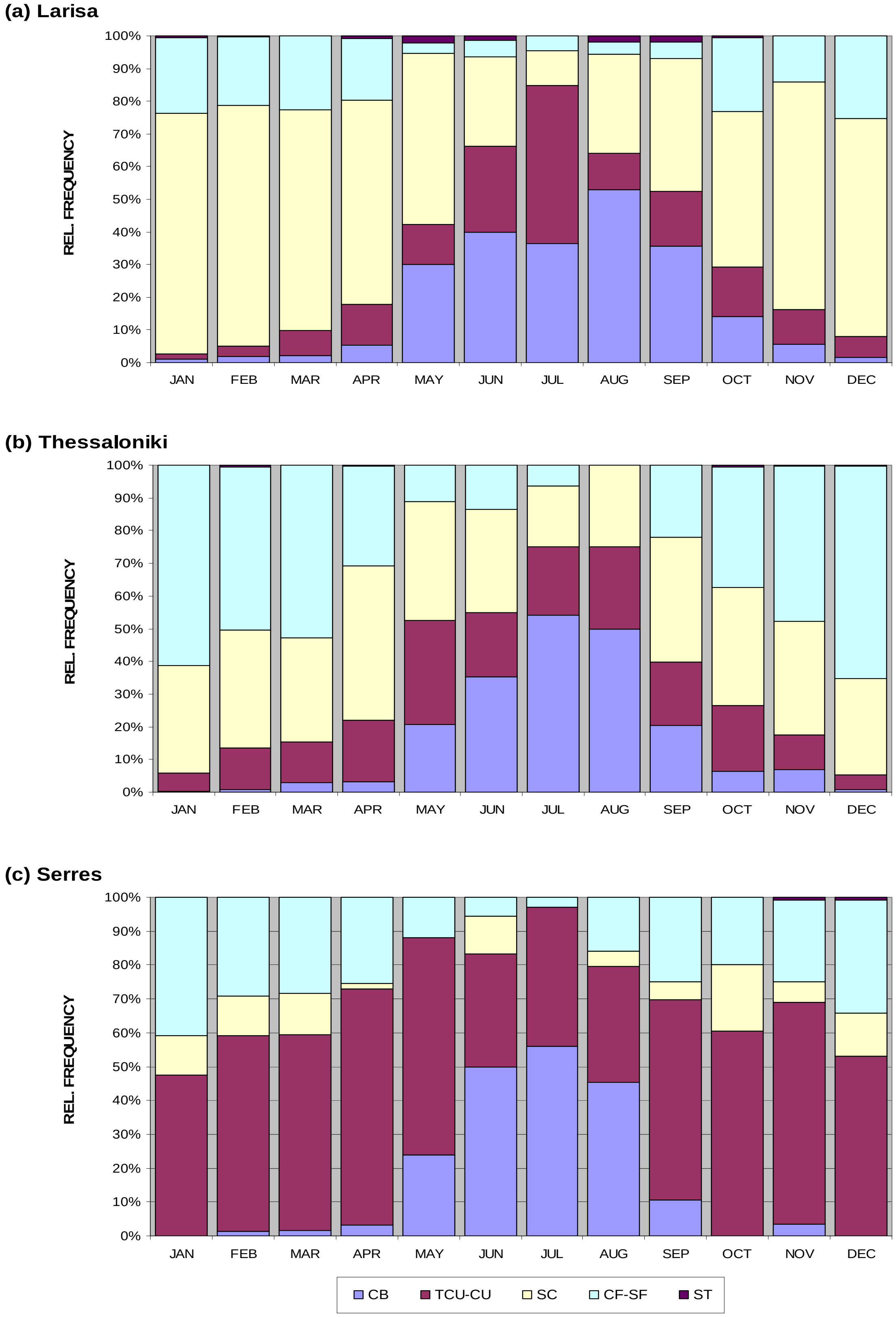

Figure 5: Monthly relative frequencies (%) of rainy cloud types: (a): Larissa (LR), (b): Thessaloniki (TS) and (c): Serres (SR).

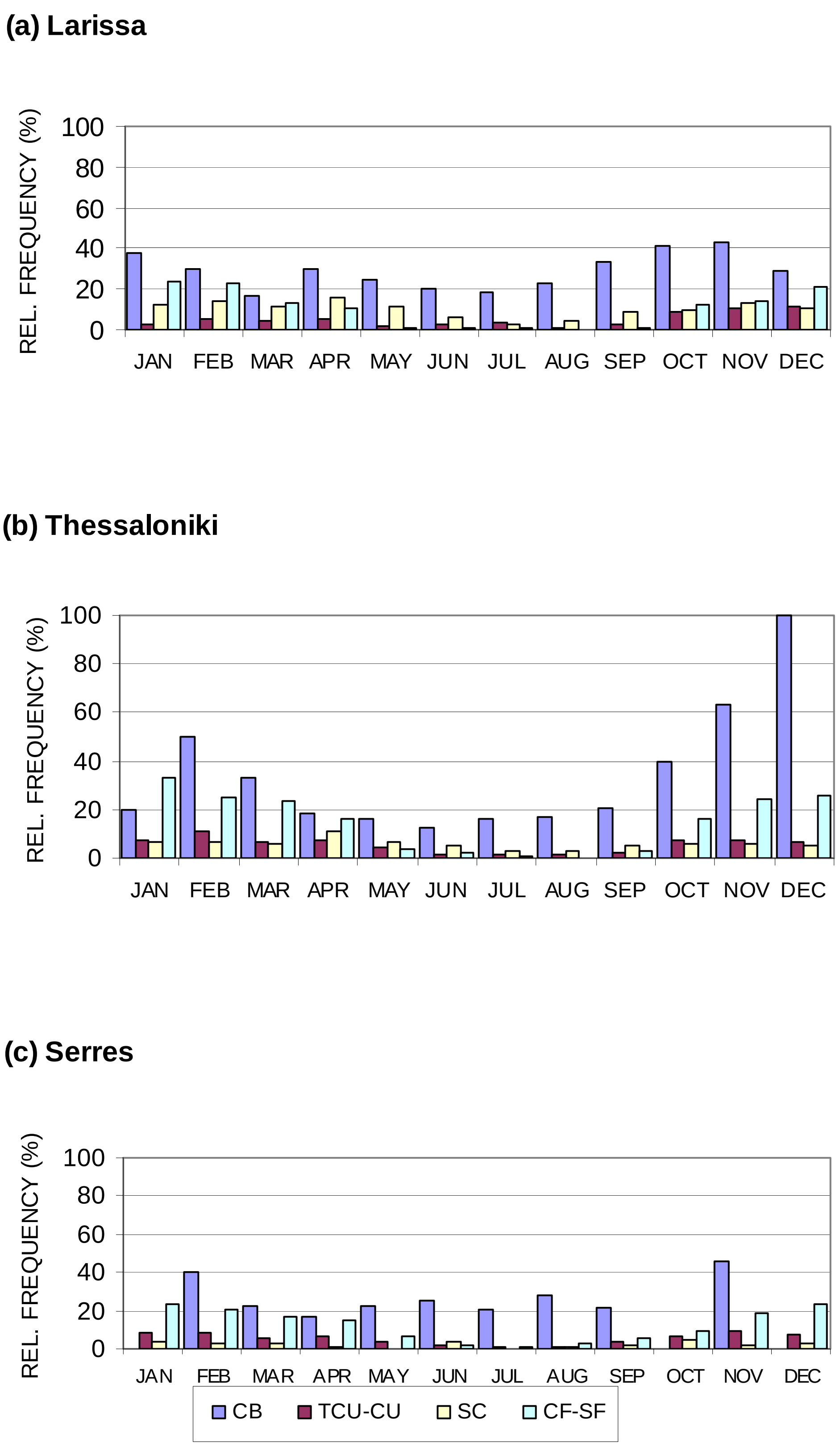

Figure 6: Monthly relative precipitation occurrences per cloud category of rainy cloud types for the stations (a): Larissa, (b): Thessaloniki and (c): Serres.

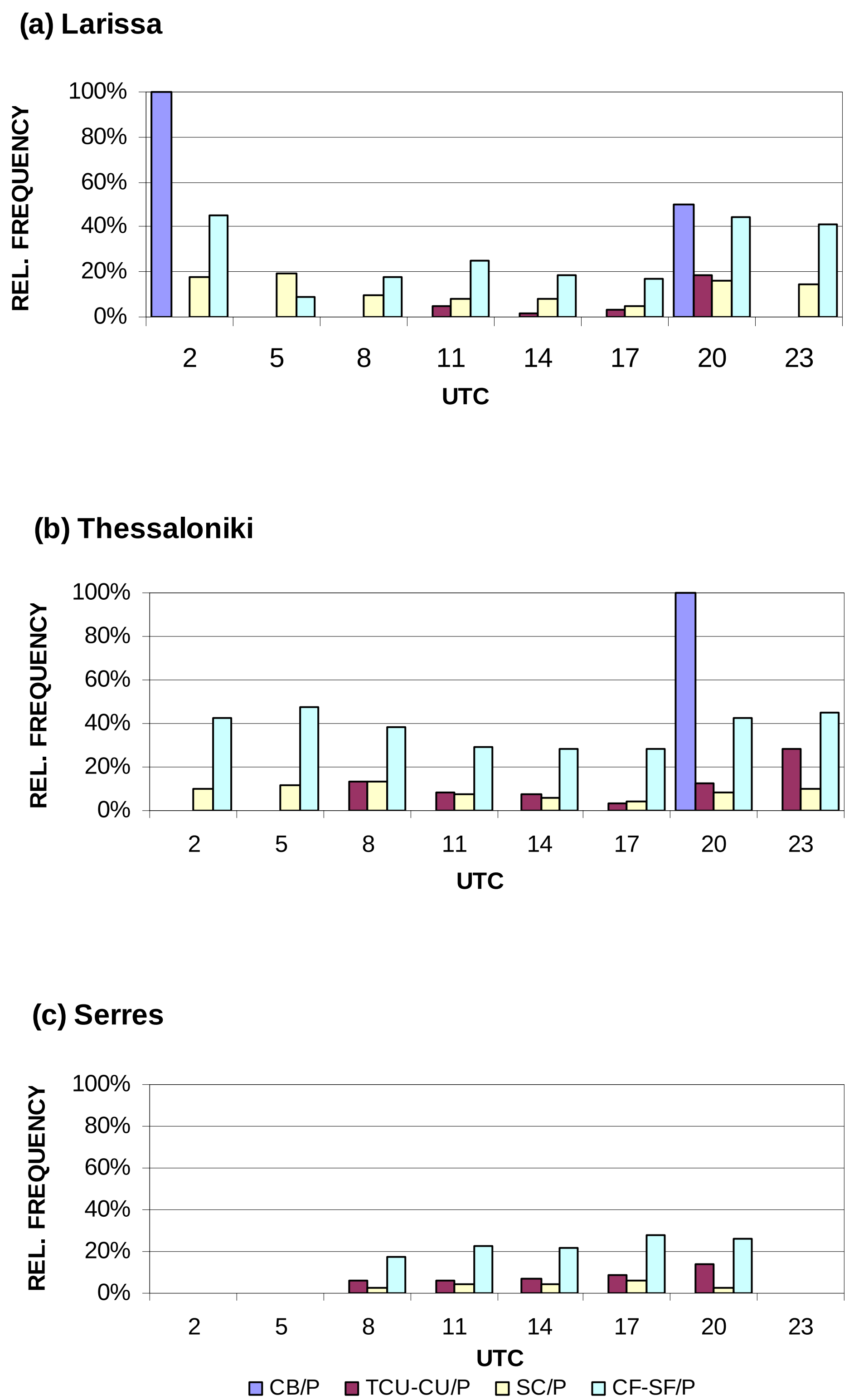

Figure 7: Diurnal variability of relative precipitation occurrences per cloud category of rainy clouds for the stations (a): Larissa, (b): Thessaloniki and (c): Serres during January.

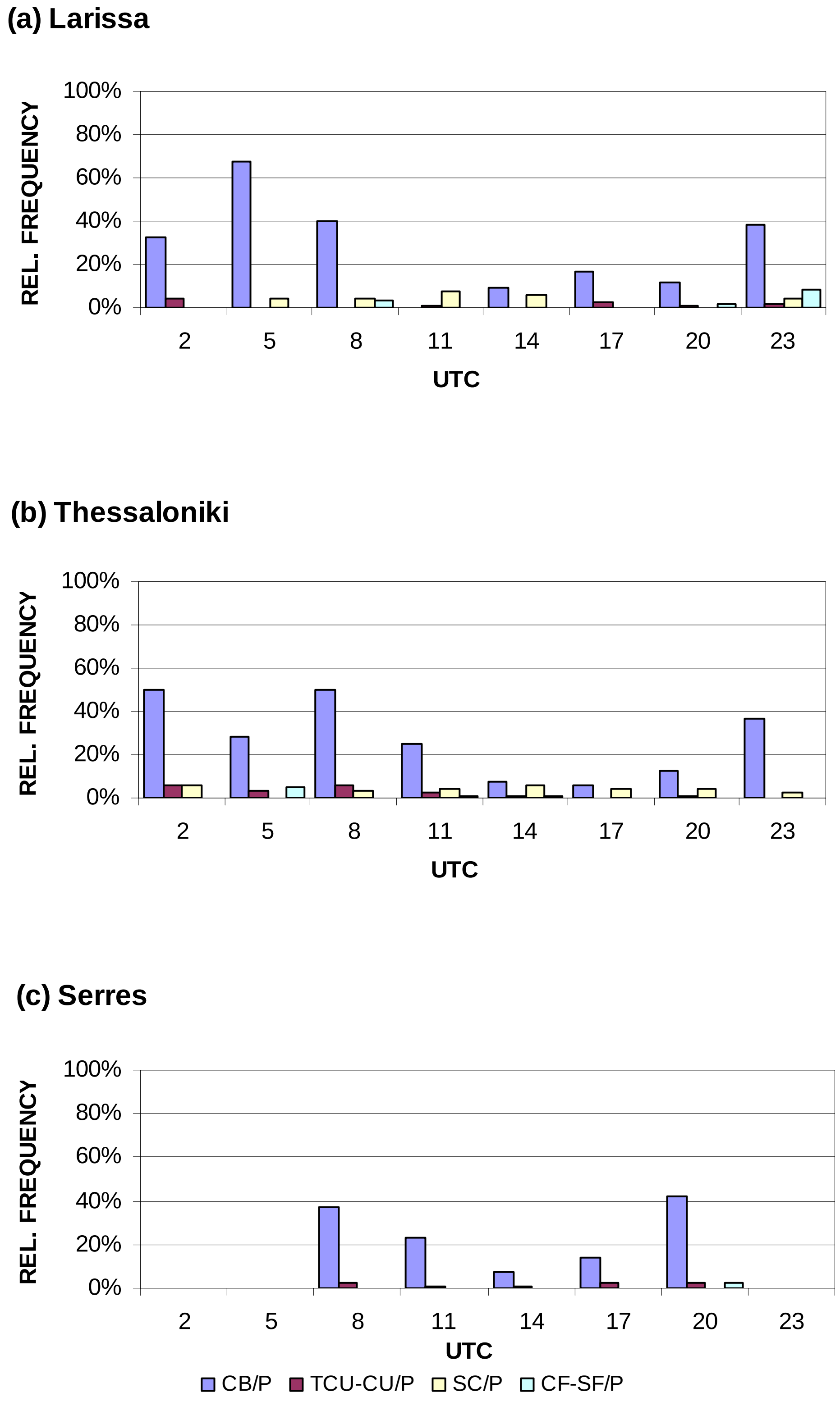

Figure 8: Diurnal variability of relative precipitation occurrences per cloud category of rainy clouds for the stations (a): Larissa, (b): Thessaloniki and (c): Serres during July.

3.5 Microphysics of clouds

The design of a weather modification program involves theoretical and experimental studies on storms and precipitation systems, as well as their structure and precipitation producing mechanism. 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 they are transported by the wind into the main storm, where they grow to hailstones along the edge of the main storm updraft (Krauss and Marwitz, 1984). Rimed ice crystals are assumed to be primary graupel embryos. The cloud seeding is concentrated on the time-evolving updraft of single cell of 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 a cloud base if the situation is not appropriate for cloud top seeding.

The distribution of cloud base temperature for 57 days with convective precipitation clouds in northern Greece is shown in Figure 9. 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°C 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).

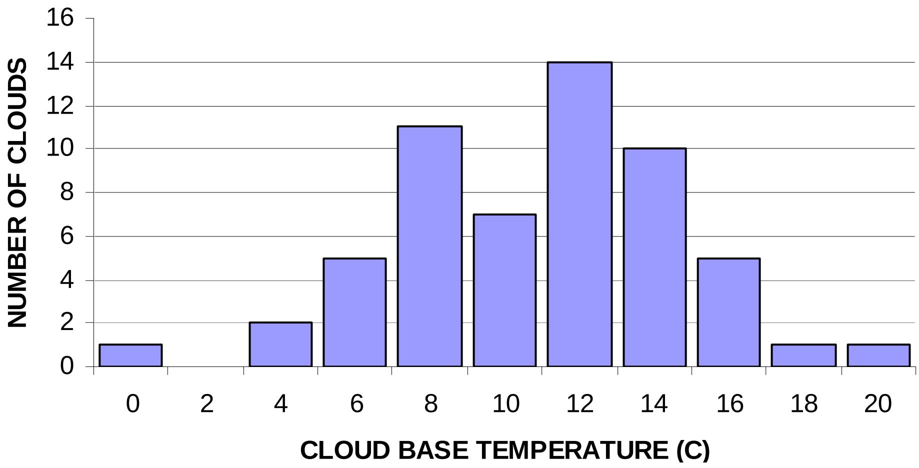

Figure 9: Frequency of cloud base temperature in convective clouds

These limited and rather simple measurements indicated concentrations of cloud droplets of the order of 1000 cm^{-3} and narrow size spectra (12.6μm mean diameter and 2.7 standard deviation), giving them a continental micro structure and a high degree of colloidal stability. The limited cloud droplet size distributions observed are similar to those used in calculations and observations 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.

Large droplets (greater than 50μm) can be expected to form on occasion 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 rimming. Additional ice crystals can then be formed when the larger drops freeze and fragment of the surface of the graupel. In general, ice multiplication seems most common in the cloud tops of cumulus congestus with large droplets and tops near -10^{o}C after the production of precipitation-sized particles. This is one possible explanation which is also valid for other experiments internationally. 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.

The first objective of the research seeder in the National Hail Suppression Program (NHSP) of Greece was to collect data to characterize the microphysics of cumulus clouds. These data were collected during specially designated research flights to maximize opportunities for successful completion of experiments. A summary of research cloud passes for 11 August 1987 is presented in Table 7. A total of 40 clouds were investigated in 84 clouds penetrations for research (Rudolph et al, 1988).

Table 7: 11 August 1987 Research aircraft cloud pass summary.

Cld	*Pass*	*Time (GMT)*	*Mean Temp* (C)	*Mean Alt.* (Kft)	*JW-LWC (g/m^3)* Mean	Max	*IPC (cts/s)* Mean	Max	*Cloud Width* (Km)
A	1	120308-120322	-9.6	17.4	1.24	1.9	3.7	10	1.35
	2	120635-120650	-9.1	17.2	1.68	2.6	4.1	8	1.45
	3	120928-120936	-9.4	17.4	0.67	1.7	3.3	10	0.77
	4	121211-121231	-7.8	16.6	0.16	0.7	2.8	8	1.82
	5	121902-121911	-7.6	15.8	0.16	0.4	9.1	23	0.96
	6	122455-122511	-7.6	16.0	0.09	0.3	33.5	105	1.52
B	1	123157-123318	-8.8	16.6	0.63	1.4	3.3	11	6.62
	2	123553-123650	-8.2	16.6	1.19	2.0	4.8	23	4.67
	3	123940-124013	-8.7	16.9	1.18	1.8	3.1	9	2.94
	4	124416-124459	-8.4	16.7	0.96	1.7	2.6	7	3.51

Based on research penetrations, a "typical" cumulus congestus vertical profile was produced (Figure 10). Typical temperatures/heights for the cloud were as follows: 8.5^{o}C/6550ft, 0.0^{o}C/9770ft, -5^{o}C/12400ft and -10^{o}C/15000ft. Mean penetration ice particle values (IPC)(count/s) ranged from 0 near -4^{o}C to a maximum of about 60 near -14^{o}C to about 25 near -19^{o}C. Mean liquid water contents (LVC) ranged from a low of 0.6 gm^{-3} at -4^{o}C to maximum values above 1.5gm^{-3} at -5^{o}C and -10^{o}C (Rudolph et al, 1988).

The cloud profile in Figure 10 shows relatively high ice particle concentration values located just above the height of liquid water content maxima. As with the 1986 cloud data, it appears that some form of ice multiplication mechanism is required to account for this. The most likely explanation is that large cloud water droplets (greater than 50 μm radius) exist in the high liquid water content region of the cloud. Large droplets can be expected in clouds in Greece due to the large liquid water content values and warm cloud bases. These large droplets rise in the updraft to near -10^{o}C level with some freezing during the ascent. At the same time ice crystals from near cloud top are descending in downdrafts. In those conditions, graupel and ice pellets form by rimming. Additional ice crystals can then be formed when the larger drops freeze and fragment on the surface of the graupel.

In general, ice multiplication seems most common in the cloud tops of cumulus congestus with large droplets and tops near -10^{o}C after the production of precipitation-sized particles (Research seeder, 1987). This is one possible explanation only. The ice multiplication mechanism can only be verified by measurements of the size distribution of cloud droplets and concentration of precipitation-sized particles. Such measurements require a wider range of particle-sizing instrumentation.

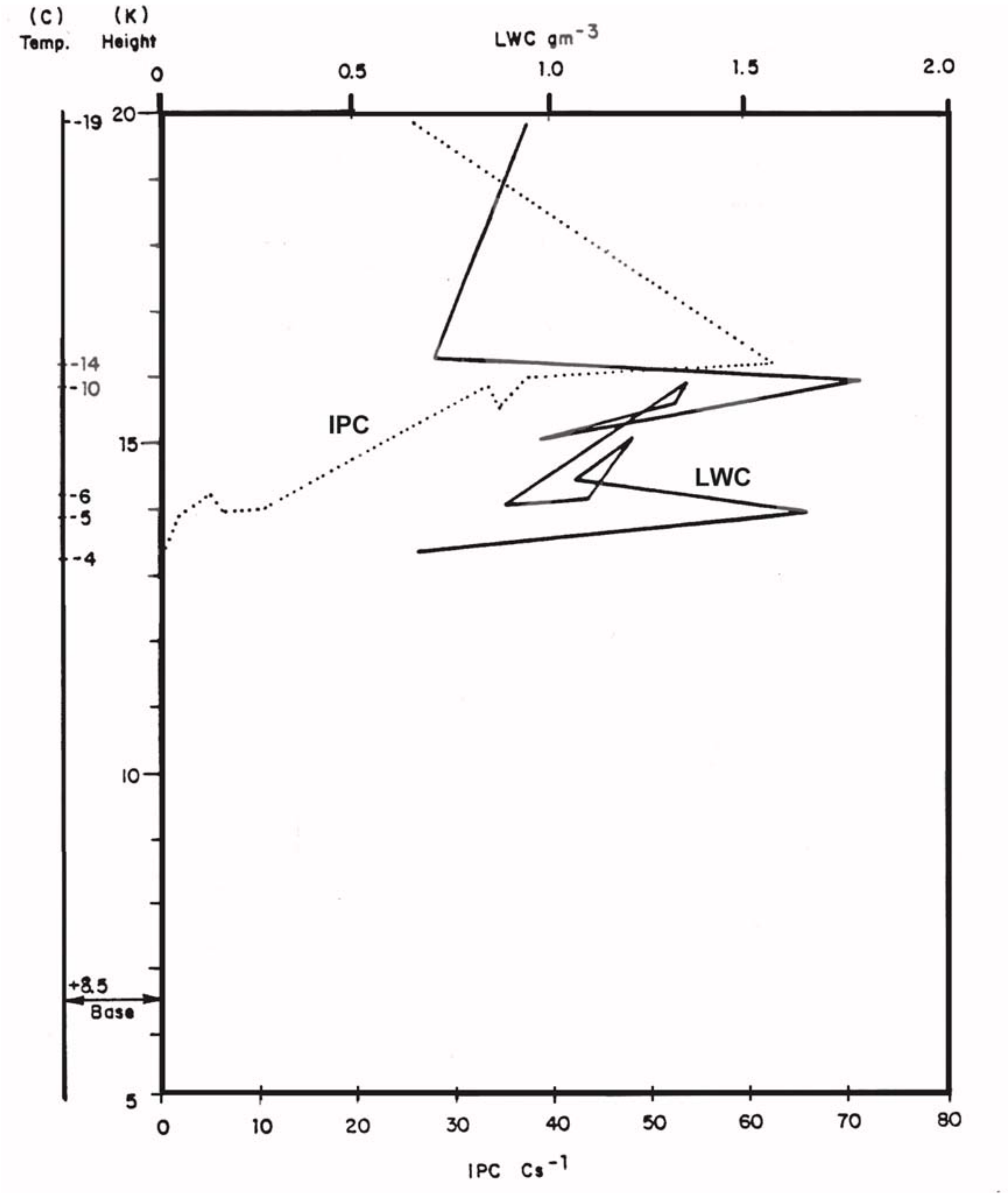

Figure 10: Vertical profile for "typical" cumulus bases research penetrations during 1987.

4. RAIN ENHANCEMENT

The above described feasibility studies can justify the rain enhancement potential in central and northern Greece. In particular, the prevailing weather systems in winter and summer incorporate seedable clouds. Moreover, rain characteristics show high frequencies of low rainfall amounts and periodic rainfall variation and deficiencies. Similarly, drought periodicities indicate high frequency cycles. Furthermore, cloud climatology depicts spatiotemporal variability in the observed cloud types and the microphysical characteristics support the feasibility of cloud seeding. The choice of winter versus summer rain enhancement programs or even "year-around" programs, is directly associated with the water needs of a region. A hierarchy of priorities in water use would help in answering critical questions, such as whether soil moisture during fall and winter is more important that precipitation during the crop growing season in central and northern Greece.

This section presents the design of rain experiment and how it was implemented in northern Greece, along with a cumulus congestus cloud seeding case study with positive response.

4.1. Design of Rain Experiment

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. In a great number of clouds, natural precipitation processes produce droplets in the droplet size spectrum towards higher values produced by seeding would result in precipitation on the ground.

The objective of rain experiment design is to determine the rain enhancement potential of cumulus congestus clouds in northern Greece. The experimental design is based on summertime cumulus experiments conducted in Montana, U.S.A. (Cooper and Lawson 1984) and the Canadian studies by English and Marwitz (1981). It is realized that the results from different locations may not be directly transferable when attempting to formulate a precipitation augmentation hypothesis in another geographical location. For the identification of the dominant precipitation formation mechanism in northern Greece although the ice phase is involved (Rudolph *et al*., 1987), the origin of the graupel particles can be either large frozen water drops (50 to 100 μm diameter) or nucleated ice crystals grown by vapour deposition followed by rimming.

Several objectives for the research seeder in northern Greece were identified:

1. To characterize the microphysics of cumulus congestus clouds in northern Greece and identify the dominant precipitation mechanism. This objective was to be accomplished by carrying out a series of cloud penetrations at different altitudes and temperatures, documenting their ice/water budgets and preparing a microphysical profile of these clouds. The analysis for this objective is described below.
2. To determine the feasibility of rain enhancement in cumulus congestus clouds in northern Greece. This objective was to be accomplished by carrying out a series of seeding experiments. The research seeder system would document the seeding signature, while the radar data would document the subsequent evolution of the radar detectable cloud. A case study is summarized below.
3. To document the microphysical characteristics of operationally seeded cloud turrets before seeding. This objective was to be carried out by the research seeder data acquisition system whenever the research seeder was used as an operational seeder in the NHSP.

Seeding Hypothesis: Two seeding hypotheses and one seeding agent (silver iodide) are being tested during the rain experiments in northern Greece. The two hypotheses have come to be called the static and the dynamic models. Simply stated, the static or ice-embryo mode assumes that the injection of a "moderate" amount of seeding material leads to the formation of earlier and more precipitation (Silverman, 1986). Dynamic seeding, on the other hand, is intended 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 models do not operate independently and each technique involves a combination of microphysical and dynamic effects. A moderate amount of silver iodide is arbitrarily defined as one 20g flare every kilometer of flight through a cloud. A large amount of silver iodide is arbitrarily defined as one 20 flare every 200m of flight through a cloud (Rudolph et al, 1988).

Seeding Procedure: The semi-isolated cumulus congestus cloud was defined as the experimental unit in northern Greece and a set of cloud characteristics has been specified which is believed to represent a cloud that will respond positively to seeding and is in its developing stage of evolution. For this study, a cloud must meet the criteria shown in Table 8 at the time of penetration by the instrumented research-seeder aircraft at the -5^{o}C level:

Table 8: Cloud penetration criteria at -5^{o}C level for northern Greece.

1. Firm and continuous cloud base indicative of inflow.
2. Cloud top indicative of active convection with no visual signs of glaciation or evaporation.
3. Radar echoe less than 15dbz.
4. Cloud depth greater than 1500m.
5. Cloud base temperature less than 0^{o}C but greater than -8^{o}C.
6. Johnson-Williams liquid water content(LWC) greater than 0.5 g/m^3 for 6 consecutive seconds (approximately 500m distance) in cloud.
7. Ice crystal concentration, as estimated by the IPC, less than 10 liter for all 500 m distance in the cloud.
8. Vertical velocity (from aircraft rate-of-climb indicator) greater than 2m/s (500 ft/min) anywhere in the cloud.
9. Cloud diameter greater than 1Km but less than 10Km.

When a cloud meets the selection criteria, the scientist on board the research-seeder aircraft declares the cloud as a test cloud. The aircraft then reverses the course and re-penetrates the cloud and apply either the moderate or large amount of silver iodide, or a placebo treatment. The treatments are applied to subsequent test clouds in the same order to maintain a balanced sample. Cloud penetrations continue to be made at the -5^{o}C for approximately 20 minutes to document the development of precipitation within the test cloud. The seeding treatment remains known only to the research seeder crew to preclude any bias in the analysis.

Evaluation: The response variables chosen to test key features of the static and dynamic seeding hypotheses are in-cloud: liquid water content, ice crystal and precipitation concentration; radar echoe height, duration and intensity. The experimental design has been tailored to confirm fundamental cause and effect relations of cloud microphysical processes within a relatively simple cloud dynamics framework.

4.2. Rain Experiment Case Study

A controlled cloud seeding experiment for rain enhancement was conducted on 11 August 1987. The research-seeder aircraft was launched at 11:31 UTC to study towering cumulus clouds, which were formed in the region. The environmental sounding recorder during the aircraft's ascent towards Area 2 is given in Table 9. An isolated cloud turret located at 055/26nm from the radar site (R1) at Thessaloniki (TS) airport (Figure 11) was selected for experimentation. No echoes were observed in the vicinity on the aircraft radar or the Filiron radar (R2). The cloud base was measured at 6500ft above mean sea level (MSL), the temperature at this height T=13.4^{o}C and cloud tops were observed to be about 19000ft. The first cloud penetration was made at 12:03 UTC at 17400ft (T=-9.6^{o}C). The test cloud contained a mean ice (IPC) count of 3.7/sec and a mean J-W LWC of 1.24gm^{-3} during the inspection pass. Since these conditions met the preliminary seeding criteria, the cloud was seeded with 4 droppable flares (80g Agl) on the next pass from 12:06:35 UTC, that is for 15sec. Six cloud penetrations were made between 12:03 UTC and 12:25 UTC (Fig.12).

The first three penetrations were at approximately the -9^{o}C level. Although the rain experiment plan calls for penetrations to be made near the –5^{o}C level, the cloud region between -5^{o}C and -10^{o}C was the general region of interest. The super cooled LWC was greater than 1gm^{-3} during most of the first passes, but this decayed to greater than 0.5gm^{-3} during the last three passes. A distinct ice crystal plume was detected on the fifth pass after seeding. On the next pass, the ice crystal had more than 100counts/sec. The sudden increase in the ice concentrations approximately 10 minutes after seeding is a characteristic response of Agl seeding. A radar echo was detected by Filiron C-band radar at 12:15 UTC approximately 9 minutes after seeding. A maximum reflectivity of 23 dBZ was measured at 3.5Km (11500ft) altitude within the test cloud. This echo lasted for about 13 minutes and disappeared by 12:28 UTC.

Table 9: Research seeder sounding, 11 August 1987.

ALTITUDE (K ft)	TEMPERATURE (C)	DEW POINT (C)
2	24.7	13.2
4	19.6	13.5
6	15.0	9.2
8	9.3	2.6
10	5.6	0.8
12	0.8	-2.6
12.5	0.0	
14	-4.3	-4.8
14.6	-5.0	
16	-8.8	-9.5
17.5	-9.9	-17.6
17.6	-10.0	
Cloud Base: 6500ft. Temp = 13.4		

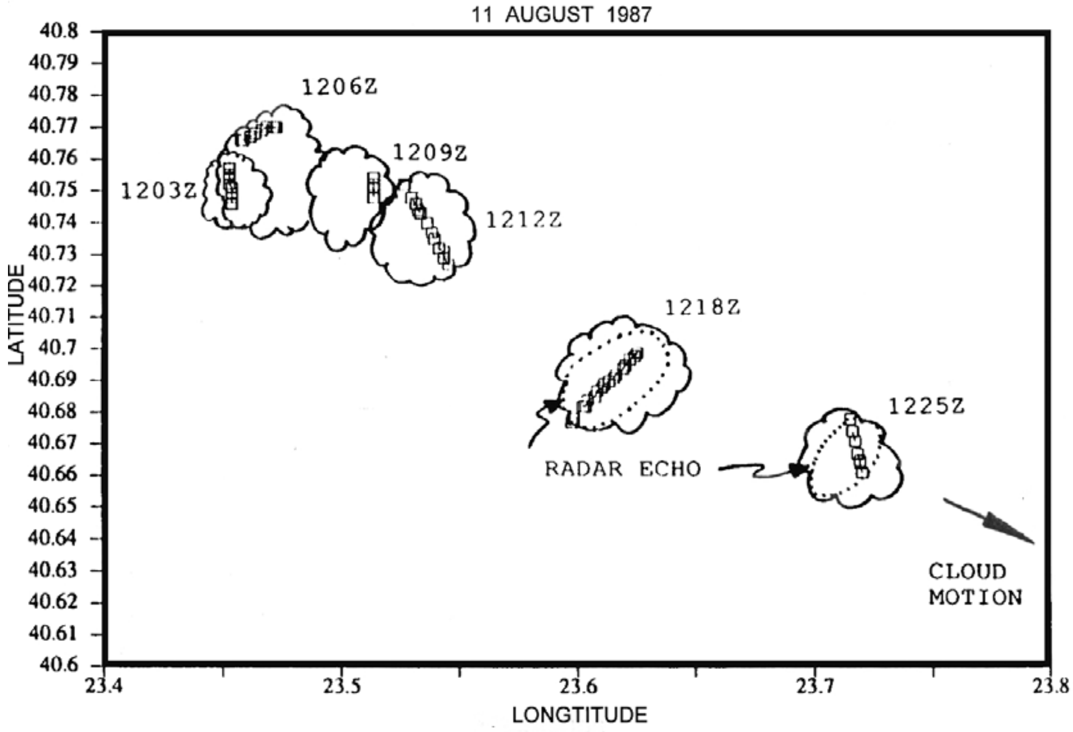

Figure 11: Schematic of cloud positions and research aircraft penetrations for rain experiment of 11 August 1987.

The controlled cloud seeding experiment on 11 August 1987 has quantified some of the cloud seeding effects regarding ice concentrations and timing within the clouds of northern Greece. A microphysical seeding "signature" was documented signifying that the seeding material was participating in the precipitation formation processes of the clouds. A radar echo formed within the test cloud. In general, at least 15 minutes are required for the artificial ice crystals created by seeding to reach precipitation size. The fact that the echo formed approximately nine (9) minutes after seeding suggests that the initiation of the echo may have been natural and that the seeding signature was merely superimposed upon the natural condition. A second possible explanation is that seeding created an over-abundance of ice crystals that formed aggregates which echoed within approximately 10 minutes. Since the liquid water content was observed to decrease considerably after about 6 minutes, aggregation may have been the dominant precipitation mechanism taking place. Since aggregates are typically low density particles, this could also account for the very weak echo. As in other parts of the world, entrainment is the primary obstacle to cloud lifetime and precipitation development in the Thessaloniki area. Clouds with longer lifetimes are likely more suitable candidates for rainfall increase.

5. SUMMARY AND CONCLUSIONS

An integrated methodology for alternative drought mitigation has been presented leading to rain enhancement potential in central and northern Greece. The methodology involved a series of feasibility studies, namely synoptic climatology, rain and drought features, cloud climatology and microphysics of clouds, as well as design of rain experiment and a cloud seeding case study with positive response.

Rainfall analyses results indicate that the non-rainy days are, on the average, about 170 throughout the year. Moreover, light rain dominates in the rainy days per year and daily precipitation less than 2mm has a very high frequency of occurrence in central and northern Greece. Drought analysis was also implemented using PDSI. The results indicate that droughts in Greece are characterized by short duration and mild severity, whereas wet periods appear less frequently with high severity. Spectral analysis indicated, in all climatic zones of Greece, statistically significant high frequency periodicity of droughts with cycles varying from two to eight months, whereas in a few climatic zones low frequencies are also present at the same stations. Furthermore, trend analysis of the Z-index using linear and cubic trends indicated that droughts in Greece seem to decrease or to remain unchanged in magnitude and severity, since, only the positive linear trends were statistically significant.

A climatological and microphysical analysis of convective and precipitation producing clouds in central and northern Greece was conducted. The objective was to investigate the possibility of rain enhancement potential in Greece through some preliminary analysis and experimental results. The results of the climatological cloud analysis indicate that cumuliform clouds (CB, TCU-CU, SC) are the dominant and precipitation producing types during the warm period at Larissa, Thessaloniki and Serres stations. However, there is a large portion of clear sky coverage with high frequencies occurring during the same period at all three stations. Moreover, stratiform cloud types show higher frequencies during cool period than in other months in all stations. Furthermore, SC clouds are frequently occurring clouds during cool period 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 forcing, lower cloud bases and less entrainment.

In summary it can be concluded that the methodological procedures with the series of feasibility studies covers all the aspects to justify the investigation of rain enhancement through cloud seeding. The implemented design of rain enhancement in northern Greece along with the presented rain experiment case study provide initial positive results for the integration all the additional components leading to a rain enhancement experiment.

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