

THE FORMULATION OF A CLASSIFICATION PROCEDURE FOR
SPECIFIC USE ON CUMULUS CLOUD WEATHER MODIFICATION
EXPERIMENTS

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PREFACE

The central theme of this study concerns the use of classification schemes on weather modification experiments designed to investigate the possibility of increasing rainfall from individual cumuli or cumulus cloud systems. The principal objectives of these experiments are the evaluation of treatment effects and the identification of situations where seeding with artificial ice-nuclei is likely to have positive results. The classification of experimental units into categories that are associated with significantly different physical processes aids the evaluation process and the formulation of seeding strategies in the desired manner.

As part of this study a classification scheme, which stratifies convective events on the basis of the synoptic situations which give rise to and maintain the convection, is formulated. In chapter seven and eight this scheme and another scheme presently being employed on a cumulus cloud weather modification experiment are examined statistically. Investigations show that the formulated scheme attains the objectives of classification to a greater degree. Certain attributes of the second scheme, permit the development of a classification procedure whereby the most effective stratification of experimental units can be accomplished.

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ABSTRACT

Natural variability of atmospheric phenomena hinders assessment of treatment effects on cumulus cloud weather modification experiments. Classification of weather situations, particularly convective events, attended by significantly different physical conditions, reduces variability within the set of experimental units and assists the evaluation process. Classification schemes may aid formulation of seeding strategies if situations defined by a scheme display varying response to ice-nuclei seeding. Categorization of synoptic systems which initiate and support convection reduces cumulus cloud variability in the desired manner. Efficient identification of recurring synoptic situations can be performed by means of surface synoptic charts and satellite imagery. Failure to recognize constraints imposed by large-scale physical processes on cumulus cloud characteristics in regions with heterogeneous synoptic regimes prevents effective classification of convective events.

CHAPTER I

INTRODUCTION

The science of weather modification was initiated to investigate the possibility of reducing detrimental weather phenomena (hail, tornadoes) and increasing the beneficial effects of weather, particularly rainfall, by technological means. Since 1946 a number of weather modification experiments have been conducted to examine the postulate that rainfall can be increased by the artificial stimulation of precipitation formation processes in cloud systems. Most of these experiments were designed to assess the potential of increasing rainfall from summer-time cumulus clouds and cumulus cloud systems by artificial ice-nuclei seeding. Even where inquiry has been restricted to summer-time convective events, significant differences are found in the response to treatment from one climatic region to another. In addition to the influence of geographical location, atmospheric processes in an area differ considerably from day to day, depending on the prevailing weather situation. Consequently, the outcome of cumulus cloud weather modification experiments have been varied. In a report to the United States National Academy of Sciences by the Review Panel on Weather and Climate Modification on the results of investigations made in this regard, the following conclusions are noted:

The Panel now concludes on the basis of statistical analysis of well-designed field experiments that ice-nuclei seeding can sometimes lead to more precipitation, can sometimes lead to less precipitation and at other times the nuclei have no effect, depending on the meteorological conditions.... It is concluded that the recent demonstration of both positive and negative treatment effects from seeding convective clouds emphasizes the complexity of the processes involved.

The effects indicate that a more careful search must be made to determine the seedability criteria that apply to the convective clouds over various climatic regions. (Panel on Weather and Climate Modification, 1973, p.4,7).

Cumulus cloud modification experiments completed since 1973 have emphasized the current limitations of weather modification and provided direction for future research (Grant and Cotton, 1979). The Weather Modification Advisory Board (1978) have reviewed recently completed weather modification experiments. The Colorado River Pilot Project was evaluated by comparing seeded and non-seeded days for all experimental days. Elliot *et al* (1978) have shown that no significant differences result from ice-nuclei seeding. In post-event analysis, if physical seedability criteria are incorporated, positive changes are noted for seeded clouds which met the seeding criteria prior to treatment. The Florida Area Cumulus Experiment (FACE) has discovered that, for days with moving echoes, treatment effects are positive while stationary echoes appear to react favourably but no changes are observed in measured rainfall for these cases (Woodley *et al*, 1977 and Biondini *et al*, 1977). Dennis *et al* (1975), on the North Dakota project have concluded that positive response to seeding occurs on days which show dynamic seedability. The Israeli II cumulus cloud experiment has produced the most conclusive results. The analyses of Gagin and Neumann (1976) shows that increases in rainfall of 13 - 15% are observed for seeded cases and that the increases are significant at the 2,2 - 3,8% level. The authors stress the need to combine randomized seeding operations with studies of physical processes, thereby ruling out the possibility that positive statistical results occur by chance. These recent experiments have not produced results which alter the conclusions made by the Panel on Weather and Climate Modification but have confirmed existing problem areas and provided direction for future research.

PROBLEM AREAS OF WEATHER MODIFICATION

Two main obstacles need to be overcome if cumulus clouds are to be modified successfully by artificial means. The first is controlling the enormous amounts of energy expended in convective storms. Since large

quantities of energy are involved in atmospheric processes, the amount of energy required to produce any desired change is correspondingly great. Thus weather modification techniques have been directed towards controlling energy exchanges, particularly those associated with condensation and sublimation, in the cloud systems. However, since development and decay of cumulus clouds is a delicate balance of constructive and destructive forces operating in the clouds, undesirable side effects may result if the artificially induced energy changes are too great or too small. Successful modification therefore depends on initiating a redistribution of appropriate amounts of natural energy so that the desired changes are produced. Natural variability within the set of experimental units is the second and more important obstacle since it hinders the determination and sound evaluation of treatment effects. Without any interference by man, a cumulus cloud may behave in several, totally different ways. Of two apparently identical cumuli or cumulus systems with similar looking clouds, one may cause torrential downpours while the other produces little rain. Financial and time constraints prohibit the investigation of each cumulus cloud on every experimental day. Thus a principal problem facing the investigator in the design and evaluation of a weather modification experiment is the devising of appropriate *modus operandi* to cope with the large natural variability of physical and dynamical processes.

One method is randomization, a procedure whereby treatment of the experimental material is allocated and/or evaluated in an unbiased manner. This approach divides the entire population of experimental units, be they single clouds or days, into a treated and untreated sample of cases. By application of statistical techniques an assessment can be made of the overall effects of seeding in the area concerned. However, the method does not help to identify the cumuli which will respond best to ice-nuclei treatment. Classification is a second, more effective method of reducing

natural variance within the set of experimental units. This approach requires that the weather modification experiment be viewed as one where the convective events can be partitioned into a number of categories associated with different physical and dynamical processes. If the meteorological situations associated with each category are clearly defined by the criteria for classification and are readily identifiable, then random variability within the set of experimental units can be reduced substantially, thereby simplifying the evaluation process. Should evaluation show that the scheme by which classification is performed stratifies convective events into categories of varying response to ice-nuclei seeding then the scheme may be able to assist, additionally, in the formulation of seeding strategies. It is important that the classification criteria differentiate on the basis of established meteorological principles. This fact is emphasized by the following report from the 1959 Skyline Conference:

The degree of success so far achieved by various programs in weather modification is, in large measure, due to detailed and skilled analyses of data which combines sound statistical techniques and enlightened meteorological insight. (Skyline Conference on the Design and Conduct of Experiments in Weather Modification, 1959, p.5).

Consequently, a classification scheme should distinguish recurring meteorological situations and enable quick and easy identification of those situations.

REVIEW OF CLASSIFICATION TECHNIQUES

Most schemes formulated to stratify weather situations have involved classification of surface synoptic maps. The foremost aims in classifying weather map patterns into types are to define characteristic weather situations and to describe recurring weather conditions. The articles

by Gold (1920), Kriek (1943) and Elliot (1951) are representative examples of the many studies which have attempted to satisfy the aims of weather map classification. Lund (1963) employed statistical methods to partition a set of winter synoptic maps according to sea level pressures. Longley (1967) applied Lund's map classification procedure to the stratification of southern African weather maps. Weather map classification has been limited largely to forecasting applications in the westerlies. The use of satellite imagery in classification schemes has been restricted to the categorization of tropical (Fritz *et al*, 1966; Oliver, 1969) and extra-tropical (Streten and Troupe, 1973) cloud vortices.

The classification of smaller experimental units, such as individual cumuli, is much more difficult since on any one day cumulus cloud variability can be considerable. Consequently, most weather modification experiments have avoided use of classification and have merely stratified cumulus clouds into those eligible and those not eligible for treatment on the basis of a set of seeding requirements and thereafter dividing the eligible ones into treated and non-treated clouds on a random basis. Where classification has been used the criteria have been based on a subjective consideration of the cloud population such as the extent of vertical development and cloud shape rather than on physical processes. For example, on the Colorado River Pilot Project, *a posteriori* analysis showed that thick clouds with warm tops ($>29,0^{\circ}\text{C}$) produce 10% more rainfall when seeded if winds are light to moderate, forecasting is accurate and no operational suspensions arise. (Elliot *et al*, 1978). On FACE the data were classified on the basis of cloud motion. Biondini (1976) concluded that clouds in different categories respond to seeding in a significantly different manner. In this classification procedure the control

exercized by large-scale motion on cloud characteristics is recognized. In fact cumulus cloud variability is limited to a very large extent by constraints that large-scale weather systems exercise on smaller-scale circulations. The processes of condensation, cumulus cloud development and precipitation formation, all of which are related to convective storm seedability, are controlled by synoptic processes which determine horizontal convergence and atmospheric moisture, instability and energy distributions. Consequently, cumulus storms can be classified effectively by a scheme which stratifies the synoptic systems which give rise to and maintain the convection. In addition, since the prevailing synoptic situation dictates to a large degree the success with which cumulus storms may be modified by artificial means, such a scheme may aid in the formulation of seeding strategies.

In this study a scheme which stratifies convective events by classification of the synoptic situations that initiate and support the convection is formulated. The criteria for classification represent the principal meteorological processes attending the various situations and are identified by means of satellite imagery and surface synoptic charts. Physical case-studies are undertaken to consider whether the identification process of the classification scheme can be improved. Statistical analyses are performed to examine and evaluate how and to what extent this scheme and a second scheme, currently being used on a cumulus cloud weather modification experiment, attain the objectives of classification mentioned above. Investigation indicates that the formulated classification scheme significantly reduces natural variation within the set of experimental units and thereby reduces the number of such units needed in the evaluation process. Secondly, it is shown from theoretical considerations that

this scheme, which distinguishes the atmospheric processes associated with convective storm development, may enable the stratification of convective events into categories of varying response to ice-nuclei seeding. Thereafter, by combining attributes of both schemes, a procedure is formulated whereby the most effective classification of experimental units can be performed both in real-time and after the event.

CHAPTER 2

CLASSIFICATION AND CUMULUS CLOUD MODIFICATION

Cumulus cloud variability is determined by the moisture, instability, energy and windflow characteristics of the storm environment. Since the prime objective of classification is reduction of convective event variability it is with respect to these variables that a classification procedure should reduce random variance. Ideally the procedure should also stratify cumulus storms into categories of varying response to ice-nuclei seeding. The potential for augmenting rainfall from cumulus clouds by treatment with artificial ice-nuclei is directly related to the ability of the storms to produce precipitation naturally. This ability can be measured directly from precipitation records and indirectly by assessment of the storm environment and of cumulus cloud colloidal instability.

1. The precipitation regime.

The most direct measure of convective storm variability is precipitation. The amount of rainfall produced indicates the efficiency with which the cumuli, whether seeded or unseeded, are processing the available atmospheric moisture. The manner in which the moisture is being processed is reflected in rainfall intensity and the extent and severity of hail events. It is clearly important that the categories defined by any classification scheme should have significantly different precipitation regimes.

2. The storm environment.

The main limitation in using precipitation variables to test the effective-

ness of a classification scheme is that rainfall and hailfall can only be ascertained after the event. It is essential that procedures for classification of convective storms be able to stratify precipitation events effectively in a predictive sense. Consequently, a procedure should show significant differences from one category to another with respect to variables that *determine* precipitation characteristics and which are measurable before cumulus storm development.

Moisture is an important variable, not only because it is an essential micro-physical ingredient in the process of precipitation formation, but also since the release of latent heat through condensation of water vapour constitutes the principal energy source for the dynamics of the convection mechanism. Efficient utilization of available moisture in cumuli by the ice-phase process, is dependent on cloud condensation nuclei (CCN) concentrations. Moist air deficient in aerosols will have vast quantities of water vapour competing for few condensation nuclei and precipitation formation is inhibited. Positive response to ice-nuclei seeding is maximized when low concentrations of natural CCN accompany an abundant supply of precipitable water, *ceteris paribus*.

Stability conditions of the storm environment will determine whether cumulus cloud development will be encouraged or inhibited after convection has been initiated. The introduction of warm, moist air at low levels and/or cooling and drying aloft will enhance atmospheric instability. In a generally stable environment convection will be impeded, even to the extent that ice-nuclei seeding will have no effect. If the atmosphere is unstable, convective development will be promoted and the storms naturally efficient. Under these conditions the introduction of artificial ice-nuclei will be superfluous or even detrimental. The situation where a

shallow stable layer or temperature inversion exists in the middle troposphere offers optimum seedability. Strong vertical wind velocity and/or direction shear will encourage severe storm development and hail formation. In this situation modification objectives are restricted to reduction of hailfall.

Cumulus storm characteristics also depend on the *manner in which the convection is initiated* or triggered. Two mechanisms are principally responsible for convective storm initiation and are determined by the nature of the low-level windfield. They are, surface convergence, which occurs in association with well-defined, low-level streamline confluence and surface heating, which triggers convection when the surface winds are light and non-convergent. Surface convergence occurs when confluent air streams meet producing vertical air movement. Providing sufficient moisture is available, this vertical movement will trigger convection through latent heat release. Suitable environmental instability will support and encourage convection. Frequently the synoptic system generating the surface convergence also gives rise to an unstable atmospheric stratification. Abundant low-level moisture in addition to these conditions favours severe storm development and hail formation. If the air is relatively dry, excessively turbulent, pulsating storms which produce little precipitation will result. Under conditions of well-defined, low-level convergence, storm seedability is minimized. Surface heating is the primary cause of local scale triggering of convection. On clear days intense heating of the surface by solar radiation warms air in the boundary layer. If the buoyant energy derived in this way and atmospheric moisture are sufficient, convection will be triggered. This situation is often attended by a mid-tropospheric stable layer or subsidence inversion and weak cumulus cloud dynamics. It therefore offers maximum seedability.

Energy profiles have been used to analyse the role of penetrative convection in the energy budget of the tropics (Riehl and Malkus, 1958; Darkow, 1968). Immediately above the surface in a shallow boundary layer total energy rises due to heating of the air by conduction from the surface. Above this layer mixing by means of microscale convection and mechanical turbulence produces a constant value for total energy up to approximately 500 m, above which level total energy decreases with height to a minimum in the mid-troposphere (500 - 600 mb). Above the mid-tropospheric minimum the total energy increases with height reaching values similar to those in the surface layer in the upper troposphere (Fig. 2.1).

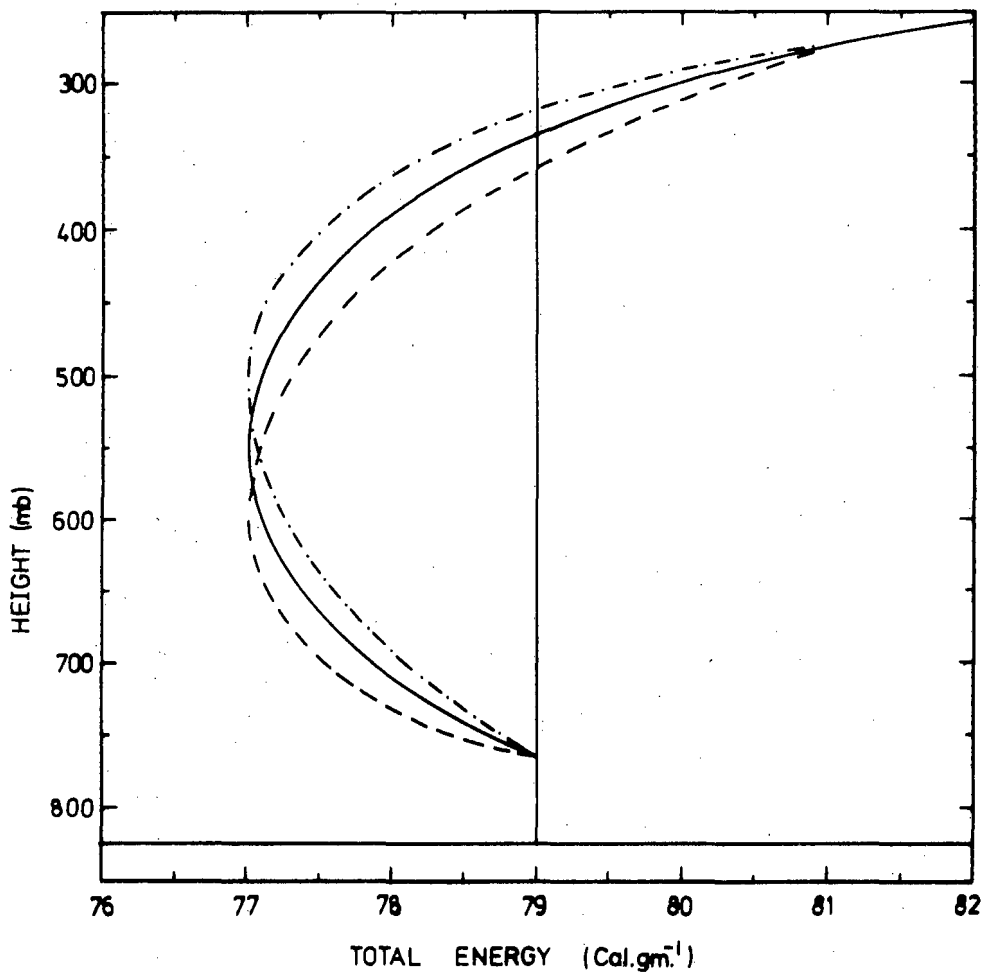


Fig. 2.1 Vertical profiles of total energy that are associated with:
 i) ----- vigorous convection,
 ii) ----- weak convective development,
 iii) ----- neutral convection-potential.

Since convective storms serve to transfer energy from regions of energy surplus (the lower layers) to regions of energy deficit (the middle and upper layers), the entire layer from the surface to the mid-tropospheric minimum is potentially-convectively unstable. The intensity of convection is directly related to the vertical energy gradient. The greater the deficiency in total energy in the upper layers relative to the layer of potential-convective instability, the more vigorous cumulus dynamics and hence storm development will be. Under these conditions rainfall intensity and hail potential are maximized and seedability minimized. Convective activity is suppressed and stratiform cloud formation encouraged where lower tropospheric energy deficiencies prevail. Consequently ice-nuclei seeding will have no effect. Days with a symmetric vertical distribution of total energy about the mid-tropospheric minimum provide maximum seedability. Since neither upper or lower tropospheric energy deficiencies exist on these days convection is neither promoted nor suppressed by the storm environment and the probability of altering the dynamics of individual cumuli by ice-nuclei seeding is optimized.

3. Cloud base temperature: an indicator of convective storm seedability.

The response of individual convective clouds to treatment by ice-nuclei seeding is related to the stability characteristics of the clouds. Maritime air masses have lower concentrations of CCN than continental air masses and cumulus clouds which form in these air masses possess broad cloud droplet spectra with an abundance of large drops. These clouds, said to be colloidally unstable, are efficient precipitation producers and cannot be modified by ice-nuclei seeding. Droplet spectra in continental cumulus clouds indicate high concentrations of small drops within a narrow range. These clouds are colloidally stable and generally inefficient in

the production of precipitation. Continental clouds may therefore respond positively to treatment with artificial ice-nuclei. Should these clouds, which are colloidally stable, extend to sub-freezing temperatures, (particularly to about -10°C) the ice-phase process will dominate precipitation formation and silver iodide or dry ice seeding may produce positive results. † The introduction of these artificial freezing nuclei to convective clouds can be carried out with two different objectives in mind. In both cases, the parameter cloud base temperature serves as the most important indicator of the response of super-cooled, colloidally stable cumulus clouds to ice-phase seeding.

MICROPHYSICAL ENHANCEMENT

When cumulus towers extend above the freezing level, much of their liquid water remains super-cooled. If silver iodide (AgI) is introduced into the super-cooled region of the cloud, the crystals act as precipitation embryos and may grow at the expense of the water droplets. In this way the efficiency of the ice-phase process is improved and increased precipitation results. However, the introduction of artificial ice-nuclei may alternatively cause the formation of large quantities of liquid drops which, along with the pre-existing super-cooled drops are transformed into ice crystals. Thus the number of ice-nuclei competing for the diminishing supply of liquid water is drastically increased and the efficiency of the ice-phase precipitation producing mechanism declines, resulting in reduced rainfall. Gagin (1975) has shown that summer continental clouds with cloud base temperatures above 10°C usually experience natural ice crystal

† Silver Iodide (AgI) and dry ice are the most commonly used artificial freezing nuclei.

enhancement. This is because such clouds have the ability to produce drops larger than $25 \mu m$ in large numbers at low altitudes (about $-5^{\circ}C$) and will therefore have copulent supplies of natural ice nuclei. Thus if the bases are warm the introduction of additional ice crystals (AgI) will cause the lower level of the cloud to glaciare prematurely thereby preventing the natural processes from exploiting efficiently the available liquid water content of the cloud. Cumulus clouds with cold bases which are continental in nature are unable to produce any precipitation sized particles if their tops are warmer than about $-10^{\circ}C$ since in such clouds the ice-phase process is naturally inefficient. Because graupel originally forms on ice, graupel contents in clouds with cold bases can be increased through artificial ice-nuclei treatment by microphysical (static) seeding on condition that moisture available for precipitation is reasonably abundant and the cloud tops are colder than about $-10^{\circ}C$.

DYNAMIC ENHANCEMENT.

The dynamic approach to seeding is based on the contention that the strength, size and duration of the vertical air currents, namely the cumulus dynamics has a stronger control on cumulus precipitation than the microphysics does. Table 2.1 shows clearly that a big cumulus cloud (about 13 km deep) with only 10% precipitation efficiency produces six times more precipitation than a medium sized cloud operating at 100% precipitation efficiency. (Precipitation efficiency is defined as the proportion of water vapour entering the cloud through its base that eventually falls to the ground as rain).

	Big Cloud	Middle-sized Cloud	Small Cloud
Air density (gcm^{-3})	$\sim 10^{-3}$	$\sim 10^{-3}$	$\sim 10^{-3}$
Specific humidity (gg^{-1})	18×10^{-3}	18×10^{-3}	18×10^{-3}
Cloud base area (cm^2)	$12,6 \times 10^{10}$	$0,78 \times 10^{10}$	$0,2 \times 10^{10}$
Updraft velocity (cm sec^{-1})	200	100	50
Duration of precipitation (sec)	3600	1800	600
Rainfall at 100% PE(kton)	1633	25,3	1,1
Rainfall at 50% PE(kton)	816	12,6	0,5
Rainfall at 10% PE(kton)	163	2,5	0,1

Dynamic seeding has as its main objective the invigoration of cumulus updrafts through glaciation of the available liquid water content of a super-cooled cloud, releasing the latent heat of fusion and thereby increasing cloud buoyancy. The nature of atmospheric instability and liquid water contents of the clouds determine to a large extent the suitability of this technique in the treatment of convective clouds. On humid days with a deep unstable layer cumulus clouds of all radii will grow naturally (i.e. seedability is a minimum). Condensation of water vapour into liquid drops releases sufficient energy to drive the cloud motions effectively. On days when the atmosphere is relatively dry and stable the latent heat liberated by condensation may be limited and cloud dynamics therefore restricted. Under these conditions cloud droplets will grow by the condensation process to 5 to 20 μm . Following

vertical transport of these droplets in the cloud to the super-cooled state, the rate of freezing is dependent on the number of active CCN. If natural CCN are deficient then further cumulus growth is prevented. The introduction of artificial ice-nuclei in the updraft region will increase the freezing rate, the rate of latent heat release and cloud buoyancy which is translated into greater updraft velocity and organization. The enhanced updrafts ensure maintenance of super saturation in the condensation region in the face of removal of water vapour by the growing drops. In this way the condensation process is improved and cloud buoyancy further increased by the augmented supply of latent heat. Communication of the added buoyancy aloft to the sub-cloud layer so as to increase the strength of the updrafts is dependent on the vertical distance through which the buoyant energy has to be translated. The colder the cloud base, the smaller the distance between the region of ice particle formation and buoyancy increase aloft and cloud base, the more efficient the translation of that energy increase to the sub-cloud layer and the greater the effect on the cumulus dynamics (Cotton, 1979).

Thus with respect to both microphysical and dynamic seeding with artificial ice-nuclei, warm-based clouds tend to produce less precipitation when seeded since they are naturally efficient. On the other hand cold-based clouds are naturally less efficient and show greater probability of positive response when seeded.

In summary, the following can be said regarding classification procedure and cumulus cloud modification. Categories defined by a scheme which classifies convective events should not only possess significantly different environmental moisture, instability, energy and windfield characteristics but should also be attended by varioform precipitation regimes and cumulus cloud base temperature conditions.

CHAPTER 3

A CUMULUS CLOUD WEATHER MODIFICATION EXPERIMENT

A weather modification experiment presently being conducted in South Africa is the data source for the proposed study. The Bethlehem Weather Modification Experiment (BEWMEX) was initiated to "test the feasibility of increasing rainfall and decreasing hailfall through silver iodide seeding of super-cooled cumulus clouds (Harrison, 1974, p.1)." The project is based at Bethlehem, a town in the north-eastern Orange Free State in the Republic of South Africa. The experimental area is that encompassed by a circle of 100 km radius centred at Bethlehem with the exception of those parts lying in the province of Natal and the Kingdom of Lesotho (Fig.3.1). The plan of BEWMEX as originally envisaged involves an initial eight-year period of experimentation which may be followed by an operational project if the experiment should prove that such a project would increase rainfall at an economic rate. Over most of the project area the average annual precipitation is between 600 and 800 mm. The winter months (April-September) are characterized by little rain, warm clear days and cold clear nights. More than 80% of annual rainfall occurs in the summer months from October to March.

1. Equipment and Data.

Real-time monitoring of the experimental area is being done by means of two weather radars; a Mitsubishi (5 cm) radar (Figs.3.2 and 3.3) operating in volume scan, plan position indicator (PPI) mode and a Selenia (3 cm) radar (Figs 3.4 and 3.5) operating in range height indicator (RHI) or constant elevation PPI mode. An IFF (identify friend or foe) radar (Fig. 3.5) for aircraft locating is slaved to the Mitsubishi radar. The

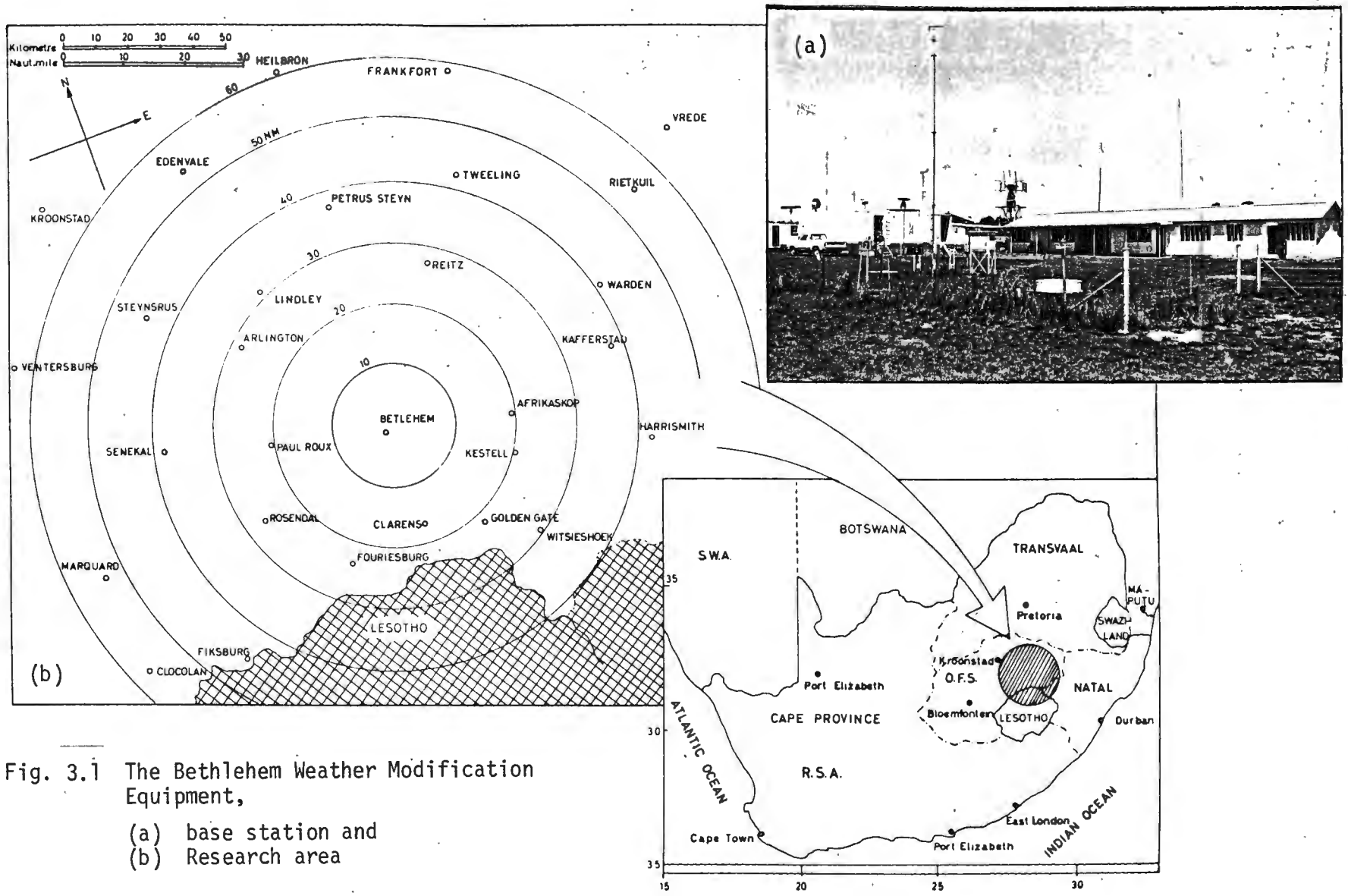


Fig. 3.1 The Bethlehem Weather Modification Equipment,
 (a) base station and
 (b) Research area

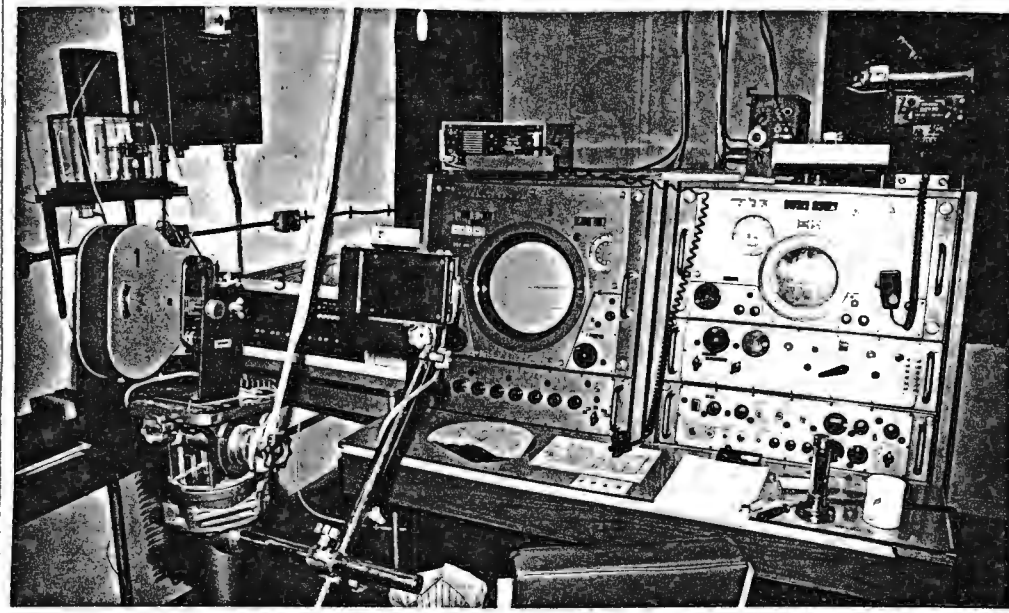


Fig. 3.2 (above) Control console of the Mitsubishi (5cm) weather radar with;

- 1) 35 mm camera,
- 2) polaroid camera,
- 3) Digital Video Integrating Processor (D.V.I.P.),
- 4) very high frequency (VHF) transmitter-receivers
- 5) IFF control panel



Fig. 3.3 (left) Antenna of the 5 cm Mitsubishi radar.



Fig. 3.4 (above) Control console of the Selenia 3 cm weather radar.

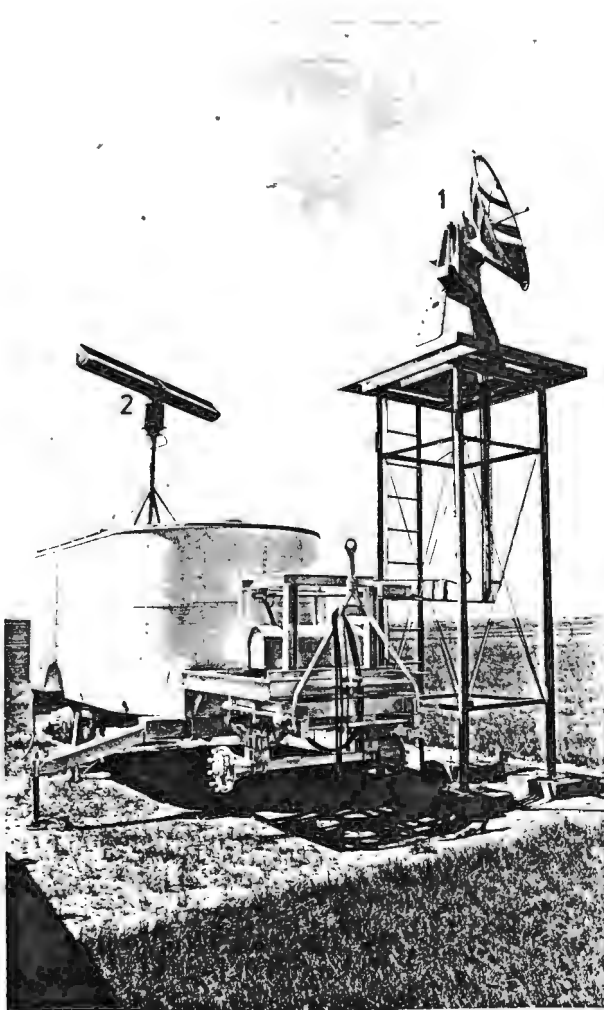


Fig. 3.5 (left) Antennae of the Selenia 3 cm weather radar (1) and the IFF radar (2) for aircraft locating which is slaved to the Mitsubishi radar.

Mitsubishi radar scope is being monitored by a motor-driven 35 mm camera which takes exposures of each elevation scan and Polaroid photographs are also being taken of both radar scopes at regular intervals.

Four aircraft including two Twin-Comanches (CA0 and CAN)(Fig 3.6) and two Aztecs (CAM and CAP) (Fig. 3.7) are being used to make in-cloud observations of cumulus dynamics and microphysics. All aircraft are equipped with instrument packages which record time, air pressure, indicated air speed, temperature, dew-point temperature and liquid water contents. A Mee Model 101 ice particle replicator (Fig.3.7) is fitted to the Aztec, CAM. However, no reliable data have been collected during the 1978/79 season. The same Aztec is also fitted with a Particle Measuring Systems (PMS) one dimensional optical array cloud droplet spectrometer and CAP has a PMS forward scattering spectrometer probe (FSSP) installed. Some data on cloud base droplet spectra have been obtained from these probes. Estimates of cloud base heights, temperatures and updraft velocities as well as cloud top heights and temperatures in convective conditions are recorded by the aircraft observers on a routine basis.

A mesoscale automatic weather station network is being interrogated from Bethlehem by telex. The stations, which record time, pressure, temperature, humidity, rainfall, wind speed and wind direction, provide data daily at 0600 GMT, 0800 GMT, 1100 GMT and 1400 GMT. Rainfall data are obtained from a network of gauges comprising about 65 autographic and 200 non-recording raingauges. Details of hailfall are being supplied by voluntary observers. On BEWMEX, days on which at least two reports of hail are received from observers in the project area have been defined as hail days. Hail days have been sub-divided further into extensive hail days and isolated hail

(a)



(b)



Fig. 3.6 The Twin-Comanche observation aircraft,

- (a) CAN and
- (b) CAO



Fig. 3.7 The Aztec observation aircraft,
 (a) CAM, which is equipped with a
 1) Mee Model 101 ice particle replicator,
 2) PMS one dimensional optical array cloud
 droplet spectrometer, and
 (b) CAP, which is fitted with
 1) PMS forward scattering spectrometer
 probe.

days. An extensive hail day is one on which hail reports are received from at least five different localities (towns or villages) in the experimental area, otherwise, it is an isolated hail day. Both rainfall and hailfall data are processed and disseminated by the Weather Bureau in Pretoria. Upper-air data are being acquired from radiosonde soundings made twice daily (0700 GMT and 1100 GMT) at Bethlehem. The corrected data are stored on magnetic disc at the University of South Africa computer centre. METEOSAT geostationary satellite visible (VIS) and thermal infra-red (TIR) photographs received at Hartebeeshoek tracking station are being made available for the 0600 GMT, 1200 GMT and 1700 GMT transmissions on a daily basis. Surface synoptic charts for 0000 GMT, 0600 GMT, 1200 GMT and 1800 GMT are archived at the Weather Bureau in Pretoria.

2. Classification of convective events.

Analysis of summer-time precipitation in the BEWMEX area for the period 1961 - 1975 indicates that of 1955 rainfall days, general or stratiform rains prevailed 8,9% of the time, scattered rainfall was evident on 59,9% of the days and on 31,2% of the days isolated showers occurred (Court, 1979). General rain days have been defined as days on which two-thirds of the rainfall stations record more than 5 mm while on isolated rain days less than 15% of the stations report rainfall. All other rain days are defined as having scattered rainfall. Since scattered and isolated rainfall is deposited in the form of local, intense convective showers, it can be seen that cumulus storms are responsible for rainfall on more than 90% of summer-time rain days.

Aircraft observations that have been made on 75 unseeded cumuli during the 1977/78 and 1978/79 seasons indicate that cumulus clouds possess diverse microphysical and dynamical characteristics. Mean cloud base

droplet distributions show narrow ranges (2 - 24 μm) of droplet diameters with modal concentrations associated with drops of size 15 μm . These spectra are typical of colloidally stable clouds. Shaw *et al* (1979) found that, of the clouds observed, which satisfied test cloud seeding criteria (Appendix A), 76% contained precipitation sized hydrometeors and substantial liquid water.[†] In most of these clouds the ice-phase process is naturally efficient and microphysical enhancement is unnecessary. However, since liquid water contents are high, dynamic enhancement may be possible under suitable atmospheric instability conditions. Of the clouds which did not meet the seeding criteria about one half had no snow pellets or graupel above the -5°C level, but nevertheless have abundant supplies of liquid water. These clouds, which appear to be colloidally stable, may therefore show positive response to both static (microphysical) and dynamic ice-nuclei seeding. These findings reveal that cumulus storms in the BEWMEX area manifest a wide variety of microphysical and dynamic characteristics. To reduce this variability and identify weather situations of greatest seeding potential the Bethlehem Weather Modification Experiment is presently employing a classification scheme which defines six categories describing the general weather expected or observed on a particular day in the experimental area. The classification scheme is presented in Table 3.1.

[†] Cumulus clouds which satisfy the criteria in Appendix A are termed 'test clouds' and being seeded on a random basis during aircraft operations. All other cumuli on which in-cloud observations are being made are termed 'observation clouds'.

Table 3.1 Outline of classification scheme currently being employed by BEWMEX to stratify experimental units (after Hudak and Steyn, 1980 p.66,)

WEATHER CODE	WEATHER CONDITIONS
I	Days with clear skies, cumulohumilis or stratus.
II	Days with very weak convection; cumulus tops warmer than -5°C .
III	Organized squall line moves into BEWMEX area overnight (this type is not used in the daily forecast or observed classification).
IV	General or stratiform rains situation. <ul style="list-style-type: none"> A. overcast, stratus or stratocumulus; little or no rain. B. overcast with prolonged periods of widespread rain. C. broken to overcast low and middle clouds producing some rain with convective elements producing heavier showers.
V	Days with significant convective activity; cumulus clouds have tops colder than -5°C and satisfy the test cell criteria <ul style="list-style-type: none"> S. Days with cumulus cloud tops colder than -5°C but the test cell criteria are not met.
VI	<ul style="list-style-type: none"> A. Days with cumulus cloud tops colder than -5°C and many of the clouds produce hail (moderate risk of hail) B. Days with cumulus cloud tops colder than -5°C and most of the clouds produce hail (high risk of hail).

Forecasts are made subjectively on the basis of raw and processed data from the 0700 GMT ascent made at Bethlehem, and information from the forecasting office of the South African Weather Bureau in Pretoria. The appropriate weather type is used to describe expected weather conditions. After the event, the code representing the actual weather situation for that day is being ascertained from radar and aircraft observations as well as rainfall and hailfall data. The scheme stratifies firstly between convective rainfall events and stratiform rainfall events (type IV days

are days of general or stratiform rains) and secondly between significant and inconsequent convective activity (types I and II are situations of insignificant cumulus development). Days with significant convective storm formation are divided further into three categories representative essentially of weak, (Vs) moderate (V) and strong (VI) convection. The potential of the weather type scheme to reduce natural variability in the required manner and to identify situations of differing response to ice-nuclei seeding will be assessed and evaluated in this study, the methodological and analytical approach of which is discussed in the next chapter.

CHAPTER 4

THE STUDY: METHODOLOGICAL AND ANALYTICAL APPROACH

In this study the effectiveness with which two different classification schemes reduce convective storm variability and identify situations of diverse seeding potential will be evaluated and compared. The weather type scheme, defined in chapter three, is the first of these. The second, to be formulated as part of the study, will be referred to as the synoptic systems classification scheme. This scheme is based on the premise that convective event variability and the response of cumulus clouds attending these events to ice-nuclei seeding are determined by physical processes associated with the concomitant synoptic situation. Visible and infra-red imagery from the METEOSAT synchronous meteorological satellite is used in conjunction with surface synoptic charts to identify summer-time synoptic situations defined by the criteria of the classification scheme. By means of physical case-studies, methods of representing the prevailing synoptic situation which may improve the identification process, are considered. Evaluation of the schemes will involve statistical analyses on a set of carefully chosen physical parameters. A series of statistical techniques are employed to test whether the categories defined by the schemes have significantly different precipitation regimes, storm environment characteristics and convective storm colloidal stability conditions. Following this examination the schemes are integrated to form a procedure whereby the most effective classification of convective events can be performed.

1. Statistical Analysis

Various statistical methods have been employed in an attempt to differentiate between hailfall and less significant classes of convective activity (Endlich and Mancuso, 1968; Modahl, 1979). Parameters and computed indices based on surface measurements and radiosonde data from fairly dense surface and upper-air networks were used in these analyses. Statistical evaluation of the weather type and synoptic systems schemes is accomplished by examination of a set of parameters which reflect the precipitation regimes, storm environment characteristics and cumulus cloud seedability. The parameters selected for use in the analyses are discussed below.

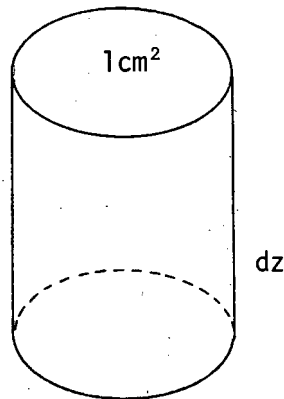
a) Precipitation variables

Mean daily rainfall has been chosen as an indicator of rainfall characteristics. This parameter is a measure of the efficiency with which convective storms process available environmental moisture. Discrete measurements of hailfall are not possible but differences in hailfall conditions can be assessed by distinguishing between extensive, isolated and non-hailfall events as discussed in chapter three. Hailfall is not considered for the weather type scheme since all hail days are classified into one category (VI).

b) Parameters representing storm environment characteristics.

The parameters Showalter index, total precipitable water and total static energy are derived from data obtained via radiosonde ascents. The Showalter index is a measure of the stability conditions of the atmosphere (Showalter, 1953). It indicates the likelihood of convective development

following initiation by surface heating or horizontal convergence. The index is defined as follows: a parcel with surface dewpoint and 800 mb temperature is lifted dry adiabatically to saturation and then moist pseudo-adiabatically to 500 mb. The temperature of the parcel subtracted from the environmental temperature gives the Showalter index. Total precipitable water is a measure of the amount of moisture in the troposphere, over a given area, available to the processes of precipitation formation. Total precipitable water is calculated as follows:



Consider a cylindrical column of air of height dz and cross-sectional area 1 cm^2 . Let,

PW = amount of precipitable water (g)

ρ = density of the air (g cm^{-3})

q = mixing ratio of the air (gg^{-1})

Then,

$$\text{PW} = \rho q dz$$

since the change in volume, $dv = 1 \cdot dz$.

Now, a column of cross-sectional area 1 cm^2 containing 1 g of water will have height 1 cm . Also $\frac{dp}{dz} = \rho g$

where, p = pressure

g = acceleration due to gravity.

Precipitable water can therefore be expressed in cm as follows:

$$\begin{aligned}
 PW &= \frac{-q}{g} dp \quad (\text{in cm}) \\
 &= \frac{-1}{g} \int_{P_s}^0 q dp \quad (\text{where } P_s = \text{surface pressure}) \\
 &= \frac{1}{g} \int_0^{P_s} q dp \\
 &\approx \frac{1}{g} \sum_i q_i \cdot \Delta p_i
 \end{aligned}$$

On BEWMEX Δp_i corresponds to height increments of 200 m and q_i is the average mixing ratio in the i th layer. Total specific energy combines the parameters of temperature, moisture, height (pressure) and velocity in a physically consistent manner in terms of energy units. The total specific energy (E_T) of a unit mass of air is given by the equation:

$$E_T = C_p T + gZ + Lq + v^2/2$$

the sum of thermal enthalpy, potential energy, latent enthalpy and kinetic energy respectively, where:

- C_p = specific heat of air at constant pressure
- T = temperature
- gZ = geopotential
- L = latent heat
- q = specific humidity
- v = velocity.

The kinetic energy term ($v^2/2$) is two orders of magnitude smaller than the others and may be neglected in the calculations. The sum of the first

three terms ($C_pT + gZ + Lq$) is called the total static energy (E_S). For a given pressure level, P the total static energy, through a series of reductions can be expressed in terms of the temperature, geopotential height and relative humidity as follows:

$$E_S = 0,24T + 0,00234 Z + \left(\frac{0,62e}{P-e}\right)(752,5 - 0,568T)$$

where,

$$e = \frac{RH}{100} \exp\left(\frac{19,08T - 4782,9}{T-35,9}\right)$$

and,

P = pressure (mb)

T = temperature ($^{\circ}K$)

Z = geopotential height (gpm)

RH = relative humidity (%)

E_S = total static energy (cal. gm^{-1}).

Total static energy is computed for the standard pressure levels and the resultant energy profiles are used in the analysis.

c) A data set for multivariate analysis.

Discriminant analysis, a powerful multivariate statistical technique, is used as an overall test of the classification schemes' potential to define categories possessing significantly different physical and dynamical characteristics. A set of parameters obtained from raw and processed 0700 GMT surface and upper-air data from Bethlehem are used in the analysis. For each of the standard pressure levels 800 mb, 700 mb, 600 mb, 500 mb, 400 mb and 300 mb the following variables are used:

geopotential height

dry-bulb temperature

dew point temperature
relative humidity
wind direction
wind speed
potential temperature
dew point depression
latent enthalpy (Lq)
total static energy ($CpT + gZ + Lq$).

The following parameters are also incorporated:

Showlater index
precipitable water (surface to 1,4 km AGL)
precipitable water (1,4 km to 4,0 km AGL)
total precipitable water
height of the freezing level
height of the -5°C level
height of the -10°C level
convective temperature
maximum temperature predicted
maximum temperature observed.

At cloud base the following are measured:

height
temperature
relative humidity
wind direction
wind speed.

Surface measurements include:

pressure

pressure tendency
temperature
dew point temperature
relative humidity
wind direction
wind speed
mixing ratio

The following indices, representing differences between variable at selected levels, are used in the analysis:

dew point depression difference between 600 mb and 500 mb
dew point depression difference between 800 mb and 600 mb
wind speed shear between 700 mb and 800 mb
potential temperature difference between 800 mb and 300 mb
difference in total static energy between 800 mb and 500 mb
difference in total static energy between 800 mb and 600 mb
difference in total static energy between 800 mb and 300 mb
difference in total static energy between 500 mb and 300 mb
difference in total static energy between 700 mb and 500 mb
relative humidity difference between 800 mb and 300 mb
relative humidity difference between 800 mb and 700 mb
relative humidity difference between 600 mb and 300 mb
relative humidity difference between 800 mb and 500 mb.

The following indicators of convective potential are computed;

- i) Difference between the convective temperature and the 800 mb dry-bulb temperature: For deep convection the surface layers must be warmer relative to the layers aloft for stable, dry conditions than for moist unstable conditions. This index removes the temp-

erature dependency upon season and air mass associated with the convective temperature.

- ii) The K-index is given by: (temperature at 800 mb - temperature at 500 mb) - (temperature at 700 mb - dew point at 700 mb) + dew point at 800 mb. It combines a measure of the 800 mb to 500 mb stability with the 800 mb moisture and depth of the moist layer given by the 700 mb dew point depression. Larger values of the K-index indicate greater thunderstorm potential.
- iii) The D-index, defined by: (height at 600 mb - height at 800 mb) - (height at 300 mb - height at 500 mb) gives atmospheric stability by the thickness difference between two layers. It therefore rests primarily on thermal considerations. Larger D-values are found where a warm layer is overlain by a cold layer, a condition favourable for vigorous convection.
- iv) The Total Totals Index is given by: (dew point at 800 mb - temperature at 500 mb) + (temperature at 800 mb - temperature at 500 mb). The index is an indicator of severe weather (hail and tornadoes).
- v) The SWEAT index is defined by: $12(\text{dew point at 800 mb}) + 20(\text{Total Totals index} - 49) + 4(\text{wind speed at 800 mb}) + 0,2(\text{wind speed at 500 mb}) + 125(0,2 + \sin(\text{wind direction at 500 mb} - \text{wind direction at 800 mb}))$.

These parameters and computed indices constitute a comprehensive data set on which multivariate analyses can be performed using the discriminant technique.

- d) Cumulus cloud seedability.

The parameter cloud base temperature has been selected as an indicator of cumulus cloud seedability on convective days. The manner in which this parameter aids in the identification of seedable situations has been

discussed in chapter two.

e) Statistical techniques

PARAMETRIC TESTS

Parametric statistical tests are carried out on the distribution of the parameters mentioned in sections a) and b) and d) within the categories defined by the classification schemes. The analysis of variance test, using the F -statistic, is performed on the data to determine whether the variance between the sample groups or categories is significantly different from the variance within the samples. If the test indicates that between-sample variance is significantly greater than within-sample variance, then random variability in the observation set of the parameter under examination is significantly reduced by the particular classification scheme. The larger the value of the F -statistic, the greater the differences between categories and the more effective the scheme decreases variance with regard to the parameter in question. The Student's t -statistic is employed to test differences between the sample means and is most useful as a compliment to the F -test. Should analysis of variance indicate that differences between the samples are truly significant, the Student's t -test can be applied to any combination of two samples to investigate which categories show greatest differences between each other.

THE DISCRIMINANT ANALYSIS TECHNIQUE

A sub-program of the Statistical Package for the Social Sciences (SPSS) called 'DISCRIMINANT' (Klecka, 1975) facilitates discriminant analysis of a series of cases (experimental units) with which are associated a

number of discriminating variables. The analysis can be performed either by entering all the variables directly or through a variety of *stepwise* methods selecting the best set of discriminating variables. Criteria available for controlling the *stepwise* selection are: minimum Wilk's - lambda, minimum Mahalanobis distance between groups, largest minimum between-groups F and the largest increase in Rao's V . Discriminant analysis therefore provides a method to statistically distinguish between two or more groups of cases. The groups are defined by the particular research situation. Thus in the present study the groups may be the synoptic categories 1A, 1B, 2A, 2B and 3 determined from the METEOSAT imagery and synoptic charts. A set of variables (in this case Showalter index, precipitable water etc.) that measure characteristics on which groups are expected to differ is then selected. The discriminant analysis then weighs and linearly combines the discriminating variables in some fashion so that the groups are forced to be as statistically distinct as possible. The technique provides a test of the success with which the discriminating variables actually discriminate the cases into the specified groups by assigning a probability that a particular case belongs to one of the groups. Once a set of variables is found which discriminates satisfactorily for cases with known group membership, a set of classification functions can be derived which will permit the classification of new cases with unknown membership.

Frequently there may be more discriminating variables than necessary to achieve satisfactory discrimination. In this event the *stepwise* procedure can be used. The objective of the *stepwise* method is to identify the set of variables which "best" discriminates between a given set of K populations. If the F -statistic is used as the criterion to choose variables then selection is based on a one-way analysis of variance test. The logic behind the *stepwise* discrimination procedure is as follows: The variable for which the mean values in the K populations are "most different" is

identified. For each variable this difference is measured by a one-way analysis of variance F -statistic and the variable with the largest F is chosen (or entered). On successive steps the conditional distribution of each variable not entered given the variable(s) entered is considered. Of the variables not entered, the variable for which the mean values of the conditional distribution in the K populations is "most different" is determined. This difference is also measured by a one-way analysis of variance F -statistic. The *stepwise* process is terminated when no additional variables contribute significantly to discrimination between the K populations. The point at which the *stepwise* process is stopped is decided by a prescribed inclusion level for F , called the F to include. This inclusion value is specified by the degrees of freedom at any particular step and the desired level of statistical significance, (α) .

2. Physical Analysis.

Analysis of the physical processes associated with the categories of the classification scheme is best achieved by the case-study method. The case studies are conducted to investigate whether significant improvement can be made to the identification processes, which employs surface synoptic charts and satellite imagery, by the inclusion of additional methods of representing the prevailing synoptic situation. Micro-physical characteristics of the convective storms are determined from data that has been collected on 418 radar echoes and obtained by aircraft while penetrating cumulus clouds. Radar echo data includes information on first echo and maximum top heights and temperatures. Observations that have been made of cloud base droplet spectra, cloud base temperature, updraft and downdraft velocities, liquid water content and hydrometeors are also

available. Radar photographs are used to deduce the areal organization pattern of the storms. On the synoptic scale, analysis involves consideration of moisture, temperature and wind fields for the 700 mb, 500 mb and 300 mb pressure surfaces, surface synoptic charts and METEOSAT imagery.

The formulation of the synoptic systems classification scheme, which constitutes the first phase of the study, is performed in chapter five.

CHAPTER 5

FORMULATION OF THE SYNOPTIC SYSTEMS CLASSIFICATION SCHEME

The southern African sub-continent, by virtue of its geographical location between low and middle latitudes is influenced by weather systems of both tropical and temperate origin. Fluctuations in the intensity and latitudinal position of the sub-tropical high pressure zone determines to a large degree the observed sequence of weather in this region. Stable atmospheric conditions and fair weather accompany intensification of the sub-tropical high pressure belt which is dissociated into two anticyclones located over the south Indian and south Atlantic oceans respectively. Subsidence in this region of high pressure gives rise to a mid-tropospheric temperature inversion over the interior which strengthens as the pressure increases. Periodical weakening of the sub-tropical anticyclones and upper-air subsidence inversion promotes instability and permits migratory synoptic depressions to influence southern Africa. These low pressure systems may have their source in either low or middle latitudes and are associated with disturbed weather and unstable conditions. Situations conducive to convective storm development occur in summer when the high pressure cells migrate southwards and the intensity of the subsidence inversion over the interior decreases.

In this section a classification scheme is formulated which facilitates stratification of summer-time convective events on the basis of the synoptic situations which give rise to and maintain the convection. METEOSAT imagery and surface synoptic charts are employed to identify the situations defined by the classification scheme.

1. Situations involving tropical disturbances.

In summer, the zone of converging air known as the Inter-Tropical Convergence Zone (ITCZ) is deflected southwards over central Africa with northern Zimbabwe as its southern-most limit (Fig. 5.1). A secondary belt of convergence coincides with the confluence of warm moist tropical air over Zaïre and the easterly trades. This convergence zone (which will be referred to as the Zaïre Air Boundary - ZAB), extends south-westwards from northern Zambia, through Zaïre to southern Angola. The ZAB is associated with a trough extending south-westwards from a tripple point located at about 15°S , 34°E . The low pressure system over western *Botswana* and north-eastern *Namibia* (henceforth referred to as the BOTNAM low) is located at the south-western extremity of the ZAB. Under certain circumstances the BOTNAM low intensifies and deepens and when this occurs a trough generates south-south-eastwards over the interior of southern Africa. This trough, which will be referred to as the sub-tropical trough, is attended by an outflow of warm, moist air from tropical latitudes. Vertically, this southward flux of thermal and latent energy extends to middle levels and anomalously high moisture contents have been detected between 200 and 300 mb in association with the trough (Harrison, 1979). Low-level convergence due to interaction between the windfields of the sub-tropical trough and the south Indian ocean anticyclone (SIA) initiates convection. Unstable conditions and an abundant supply of moisture promote the generation and development of convective storms in the convergence zone. A situation worthy of special consideration is that where strong mid-tropospheric streamline convergence accompanies the sub-tropical trough. Confluence between air flowing around a high pressure system in the upper air over the central interior and the windfield in association with a longwave trough is responsible for the convergence. Because of the copulent supplies of moisture in the mid-troposphere, horizontal convergence at these levels encourages formation of stratiform rains. Occasionally, convective cells, which develop as a result of low-level convergence are

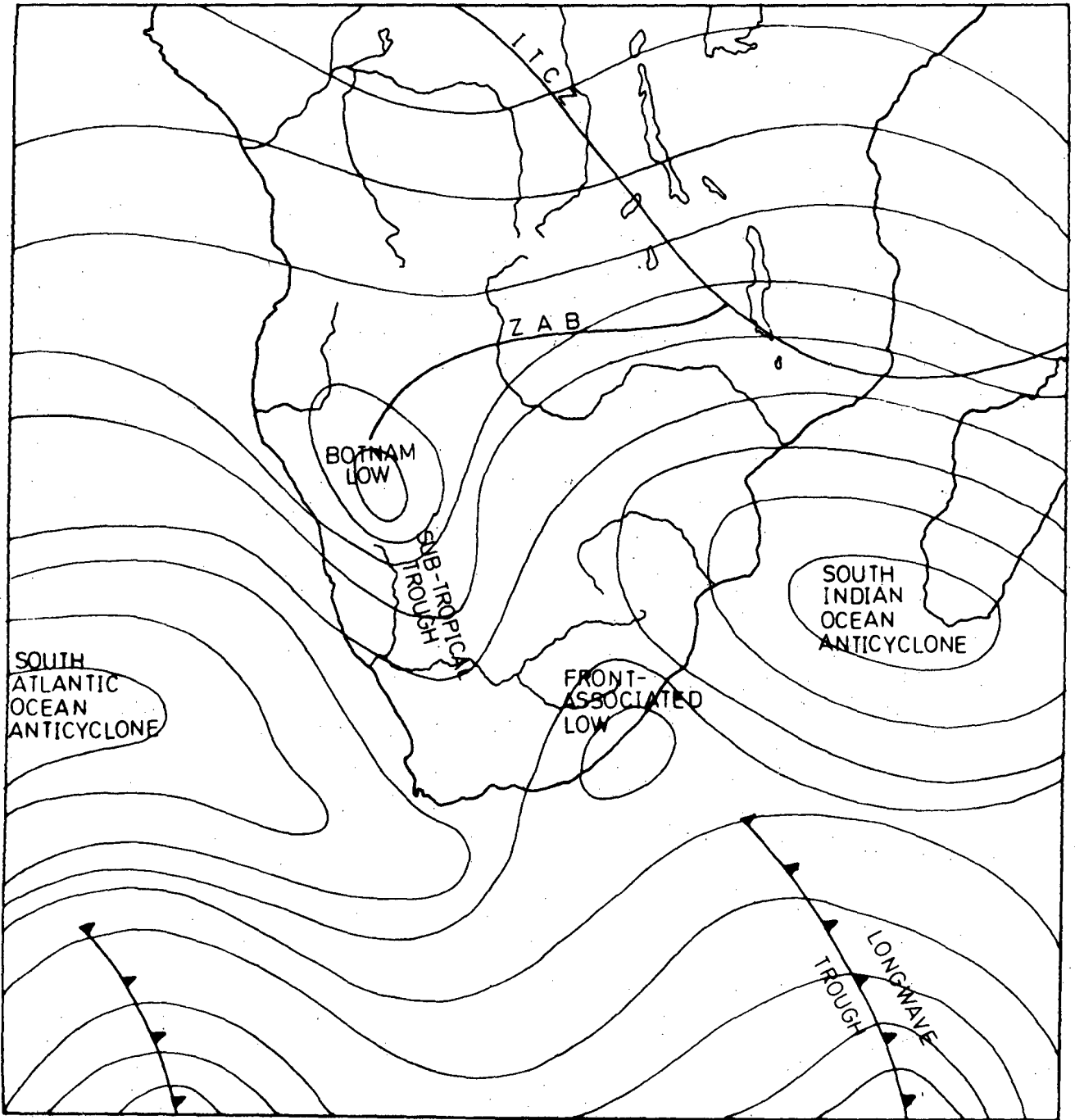


FIG. 5.1 SCHEMATIC REPRESENTATION OF THE PRIMARY METEOROLOGICAL FEATURES WHICH INFLUENCE WEATHER CONDITIONS OVER SOUTHERN AFRICA.

observed embedded in the stratiform cloud deck. The cloud deck is readily identifiable on satellite images as a well-defined cloud band which develops southwards with the sub-tropical trough (Johnson, 1970). Almost invariably this cloud band (henceforth referred to as the sub-tropical cloud band) is found to be connected to a frontal cloud band. The connection results when the band of cloud associated with the southward propagating sub-tropical trough coincides positionally with the frontal cloud band. The connection between low and middle latitudes thus established is not merely a visual phenomenon but is in fact, a distinct synoptic system whereby momentum sensible heat and latent enthalpy are transferred from the tropics to higher latitudes. Harrison (1979) has found that measurable poleward fluxes of momentum, thermal enthalpy and latent energy occur in apposition to the cloud band. The system may persist for several days, the southern extremity being carried eastwards by the baroclinic disturbance while the northern extremity appears to be anchored in the BOTNAM low.

Since both these situations involve disturbances of tropical origin, the convective events that they give rise to will manifest concordant micro-physical and dynamical characteristics. Because the troughs are warm-cored and hence not as deep as those of temperate origin, the resultant low-level convergence and atmospheric instability are such that the storms are not as dynamically vigorous as those associated with cold-cored, mid-latitude low pressure systems. However, the convective storms are nevertheless naturally efficient producers of precipitation since they occur in warm, moist tropical air masses and hence tend to be colloidally unstable. These factors ensure that the cumuli will utilize the abundant supplies of precipitable water to produce heavy rainfall rather than hail, since the latter will only form in cumulus clouds that are vehemently active dynamically. The likelihood of hail is therefore minimized when disturbances

of tropical origin are responsible for convective events. The potential for increasing rainfall by ice-nuclei seeding is also minimal under these conditions since the cumuli have warm bases and are inclined to be colloidally unstable. Although absolute energy values are high in both situations, differences exist in the vertical distribution of total energy. In addition, variations are evident in the relative strength of horizontal convergence at low and middle levels. Convection is encouraged by upper tropospheric energy deficiencies and greater low-level convergence while stratiform events will dominate with strong middle level streamline convergence and lower tropospheric energy deficiencies. Herein lies the basis for distinguishing two synoptic situations that involve low pressure systems of tropical origin. The criteria by which these situations are defined and the manner in which they are identified by use of surface synoptic charts and satellite imagery are given below.

Synoptic Situation 1A

IDENTIFICATION

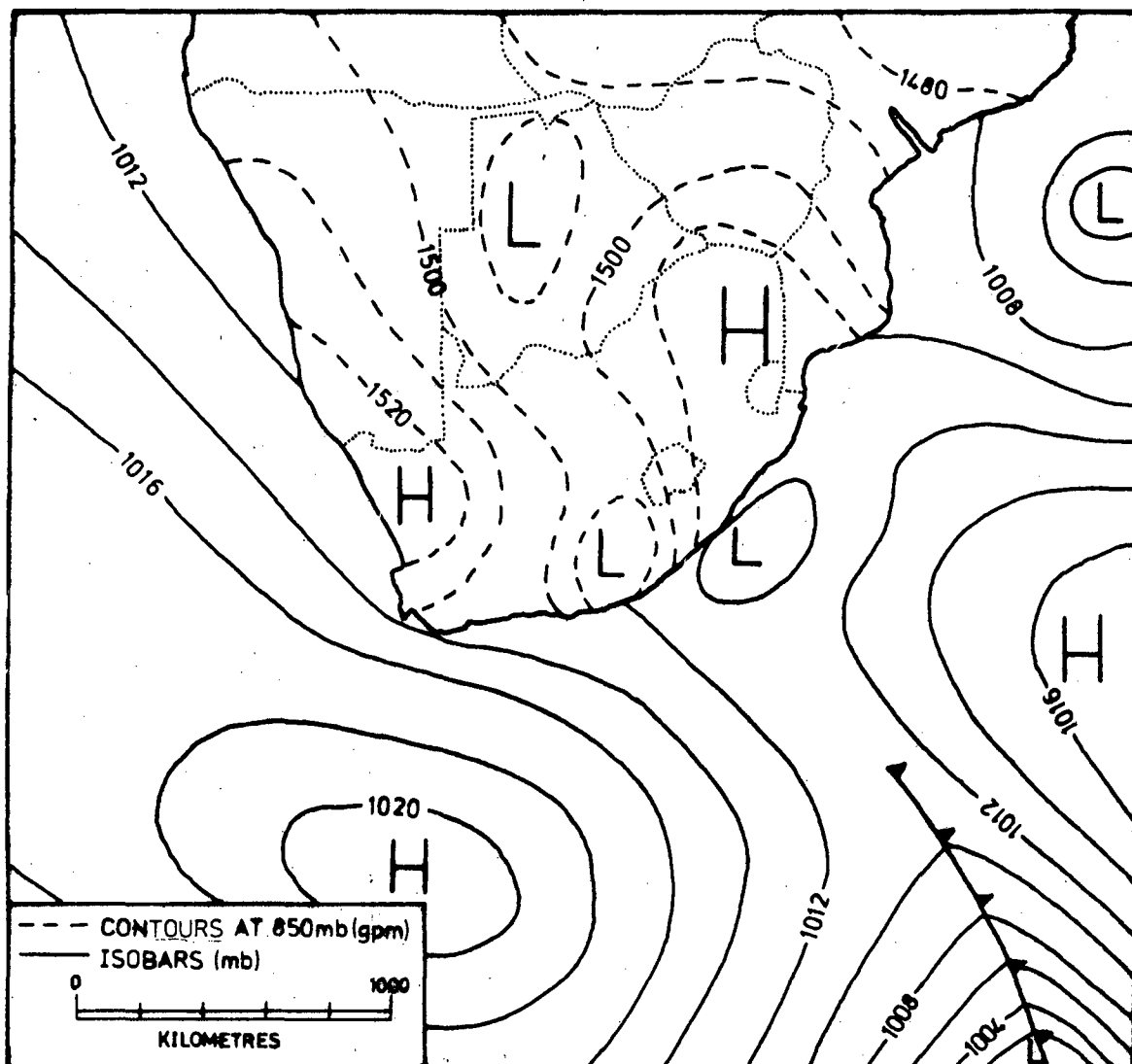
- a) Synoptic Chart
 - i) a trough extending southwards from the BOTNAM low.
 - ii) confluence between windflows attending the SIA and sub-tropical trough.
- b) Satellite imagery
 - i) the Zaïre Air Boundary is present.
 - ii) cloud configuration indicates a southward flow of tropical air from the BOTNAM low.
 - iii) cumulus cloud development is most prominent in the confluence region.

EXPECTED CUMULUS CLOUD AND STORM ENVIRONMENT CHARACTERISTICS

- a) Precipitation: heavy rainfall but low probability of hail.
- b) Storm environment: abundant moisture, moderate instability, upper-tropospheric energy deficiencies and moderate low-level convergence.
- c) Colloidal stability: cumuli are colloidally unstable and have warm bases.

EXAMPLE: 5 FEBRUARY 1979

Below are presented the surface chart and METEOSAT images for 790205 a typical type 1A day from the 1978/79 summer season.



790205 1200 GMT

Synoptic Situation 1B

IDENTIFICATION

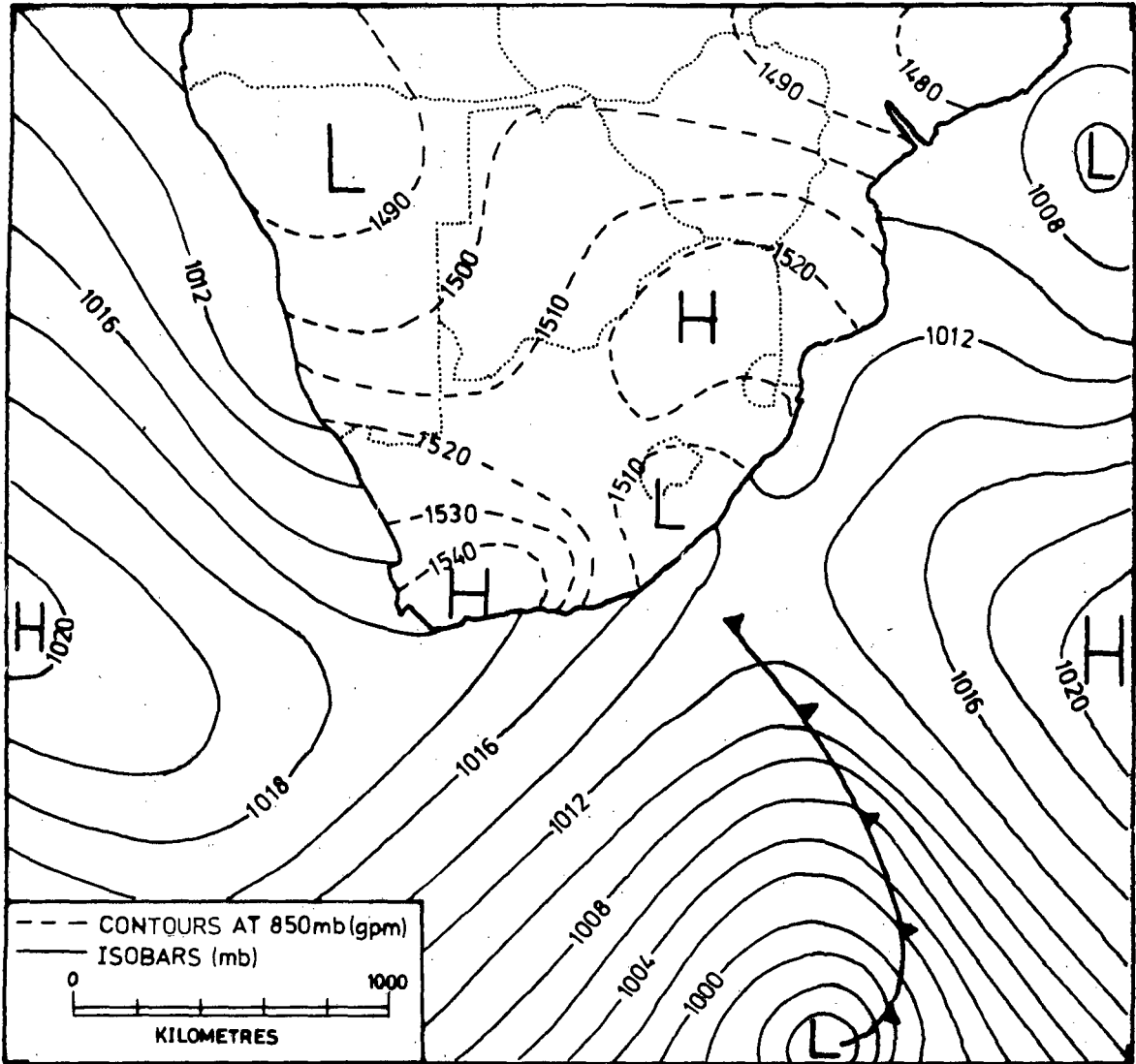
- a) Synoptic Chart
 - i) a trough extending southwards from the BOTNAM low.
 - ii) little or no confluence between the windflows of the sub-tropical trough and the SIA.
- b) Satellite imagery
 - i) historically: a band of cloud develops southwards from the BOTNAM low and merges with a passing frontal cloud band.
 - ii) the cloud band forms a continuous, well-defined connection between tropical and temperate latitudes.
 - iii) the cloud band constitutes principally stratiform cloud.

EXPECTED CUMULUS CLOUD AND STORM ENVIRONMENT CHARACTERISTICS

- a) Precipitation: steady rainfall of long duration, little or no risk of hail.
- b) Storm environment: very moist, moderate instability, lower-tropospheric energy deficiencies and strong middle-level stream-line convergence.
- c) Colloidal stability: convective cells if present in the stratiform deck are colloiddally unstable and have very warm bases.

EXAMPLE: 22 FEBRUARY 1979

METEOSAT imagery and surface synoptic chart for 790222 a typical type 1B day are presented below. The system was already well developed by 1200GMT on 22nd, having formed the previous day.



790222 1200 GMT

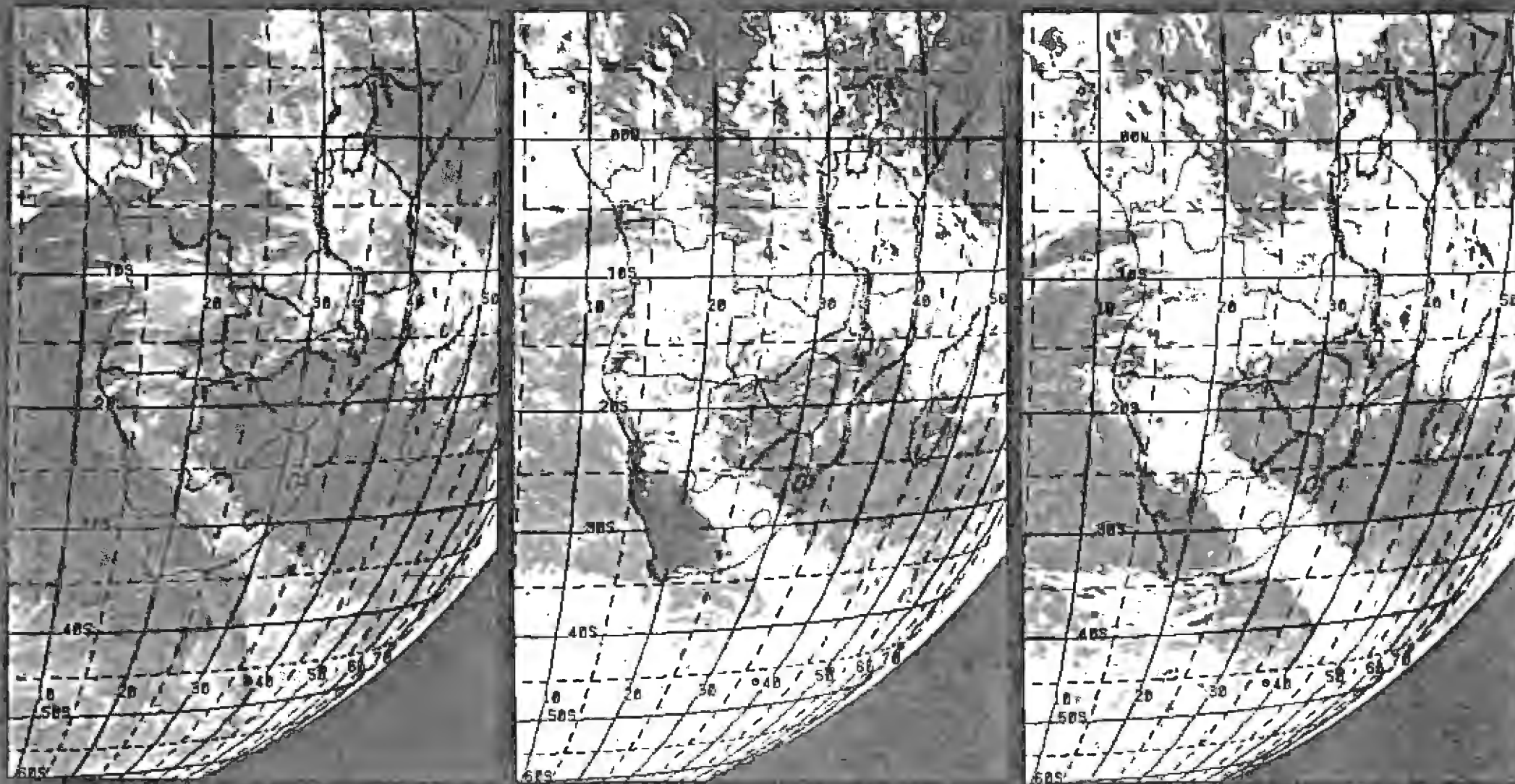


Plate 2. METEOSAT TIR images for 0600 GMT, 1200 GMT and 1700 GMT on 790222, a typical type 1B day from the 1978/79 summer season.

2. Situations involving temperate disturbances

South of the sub-tropical anticyclones, in middle latitudes, is the zone of the temperate westerlies in which baroclinic disturbances and their attendant troughs and frontal systems originate and travel eastward.

Southward migration of the pressure belts in summer limits the influence temperate disturbances have on weather over southern Africa in these months. However, especially in early and late summer, low pressure systems of temperate origin may nevertheless affect the weather of this region to a significant degree. In this regard, Taljaard (1972, p.158) observed:

It is common experience that when lows move eastward with their centres at 45-55° and when their associated fronts do not extend into sub-tropical latitudes (25-35°S), deep sympathetic troughs are nevertheless found at these low latitudes in positions N or NNW of the lows.

These mid-latitude troughs are well-developed and cold-cored. Interaction of the windfields attending the trough and the SIA gives rise to strong low-level convergence. In addition, the advancing sector of the trough is a region of positive vorticity advection where surface convergence is supported by strong divergence aloft. This windfield is ideal for the triggering and maintenance of severe convective storms.

Cumulus storms which form under these synoptic conditions will therefore be dynamically vigorous. Because environmental instability is high and prominent upper-tropospheric energy deficiencies exist cumulus development will be rapid, the mature stage being reached soon after initiation. Dissipation will occur equally suddenly if atmospheric moisture, which is the energy source for the convection mechanism, is deficient. Under these conditions little precipitation will result, but successful modification is not possible since it is precipitable water that is lacking and the cumuli are dynamically efficient anyway. However, if atmospheric moisture,

particularly at low-levels is relatively high, severe storm potential is maximized. Intense showers and hailfall accompany these storms. Because temperate air is involved, cloud base temperatures will be low, but the factors mentioned above indicate that these convective storms are naturally efficient processors of available precipitable water and ice-nuclei seeding will have no effect. (Modification of severe convective storms to reduce hailfall, is not considered in this study.)

Differences in atmospheric moisture conditions are responsible for variations observed within the set of convective events that are associated with disturbances of temperate origin. The presence of a weak sub-tropical trough on certain days serves to augment atmospheric moisture by its attendant flow of warm, moist air from tropical latitudes. The sub-tropical trough does not, however, influence cumulus development in any other way. The front-associated trough alone, is responsible for the generation of low-level convergence and environmental instability. Synoptic situations involving low pressure systems of mid-latitude origin maybe classified into one of two categories as follows:

Synoptic Situation 2A

IDENTIFICATION

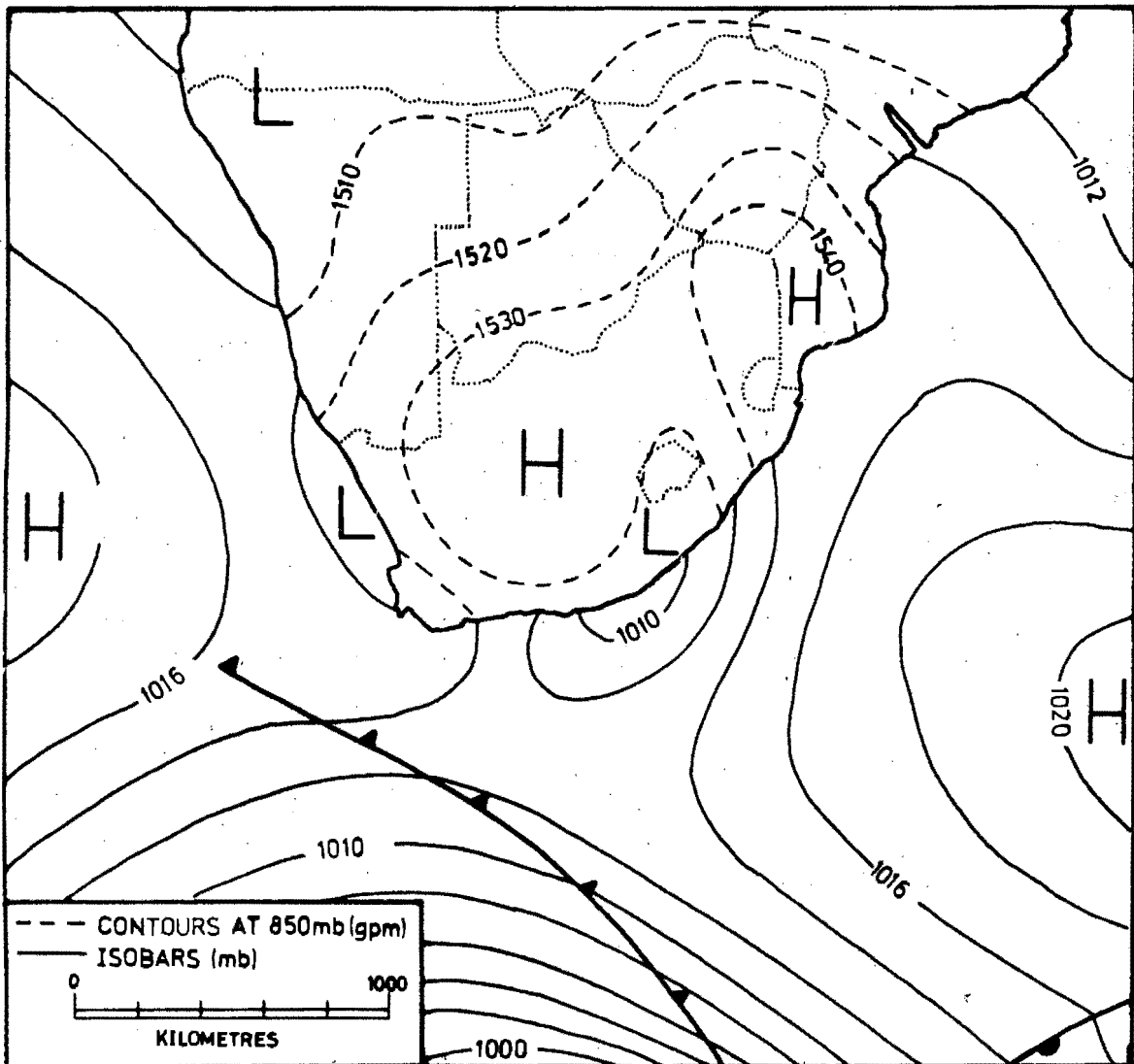
- a) Synoptic chart.
 - i) confluence between the windfields of a front-associated trough and the SIA.
- b) Satellite imagery
 - i) the presence of a baroclinic disturbance and frontal cloud band south of the sub-continent.
 - ii) the existence of extensive cumulus cloud cover in the region of surface convergence.

EXPECTED CUMULUS CLOUD AND STORM ENVIRONMENT CHARACTERISTICS

- a) Precipitation: intense showers of short duration with moderate to high likelihood of hail.
- b) Storm environment: variable moisture but tending to be low, very unstable, prominent upper-tropospheric energy deficiencies with lower absolute values than 2B and very strong low-level convergence.
- c) Colloidal stability considerations are unimportant in this category.

EXAMPLE: 15 MARCH 1979

A typical type 2A day occurred on 15 March 1979. The surface synoptic chart and METEOSAT imagery for that day are presented below.



790315 1200 GMT

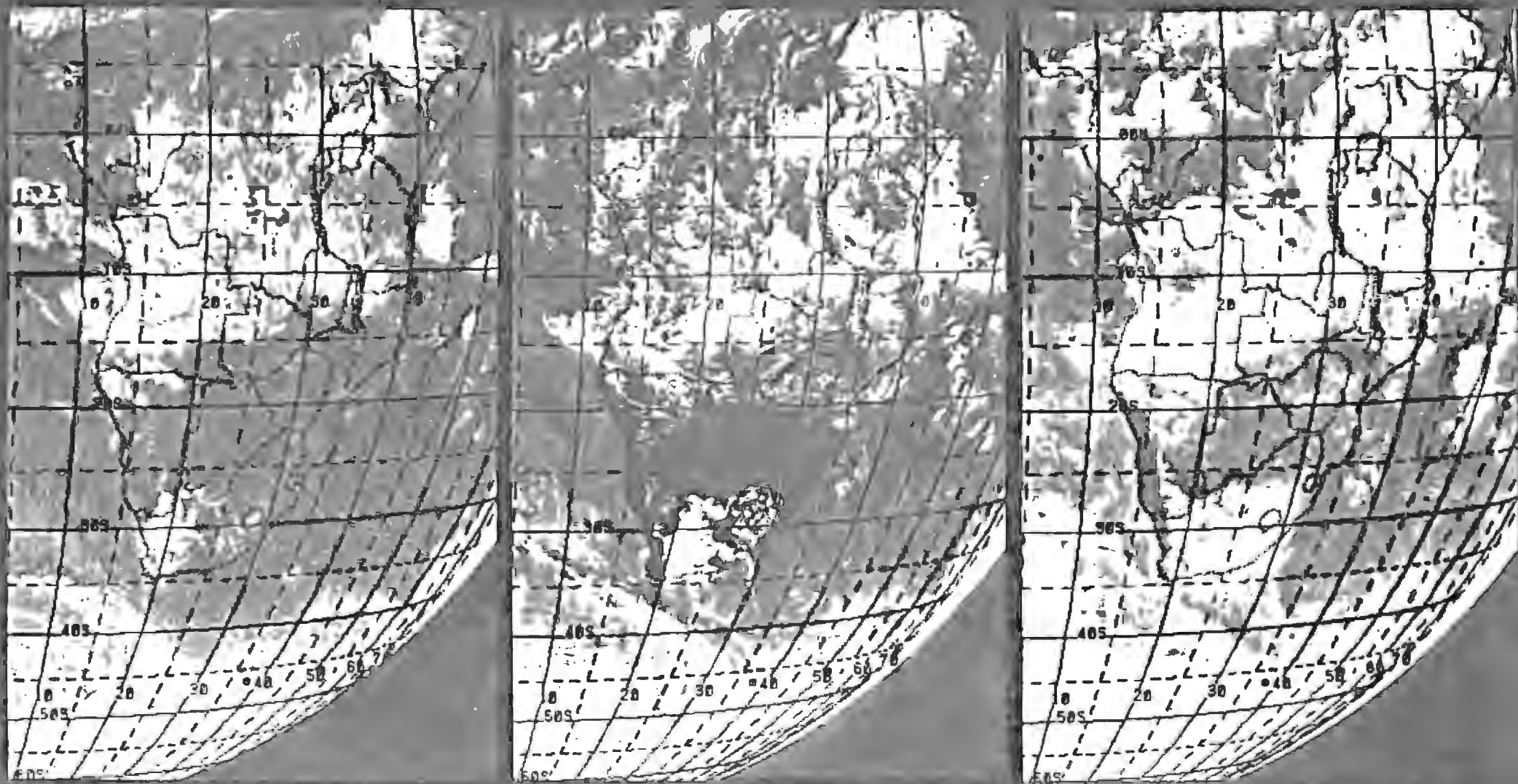


Plate 3. METEOSAT TIR images for 0600 GMT, 1200 GMT and 1700 GMT on 790315, a typical type 2A day from the 1978/79 summer season.

Synoptic Situation 2B

IDENTIFICATION

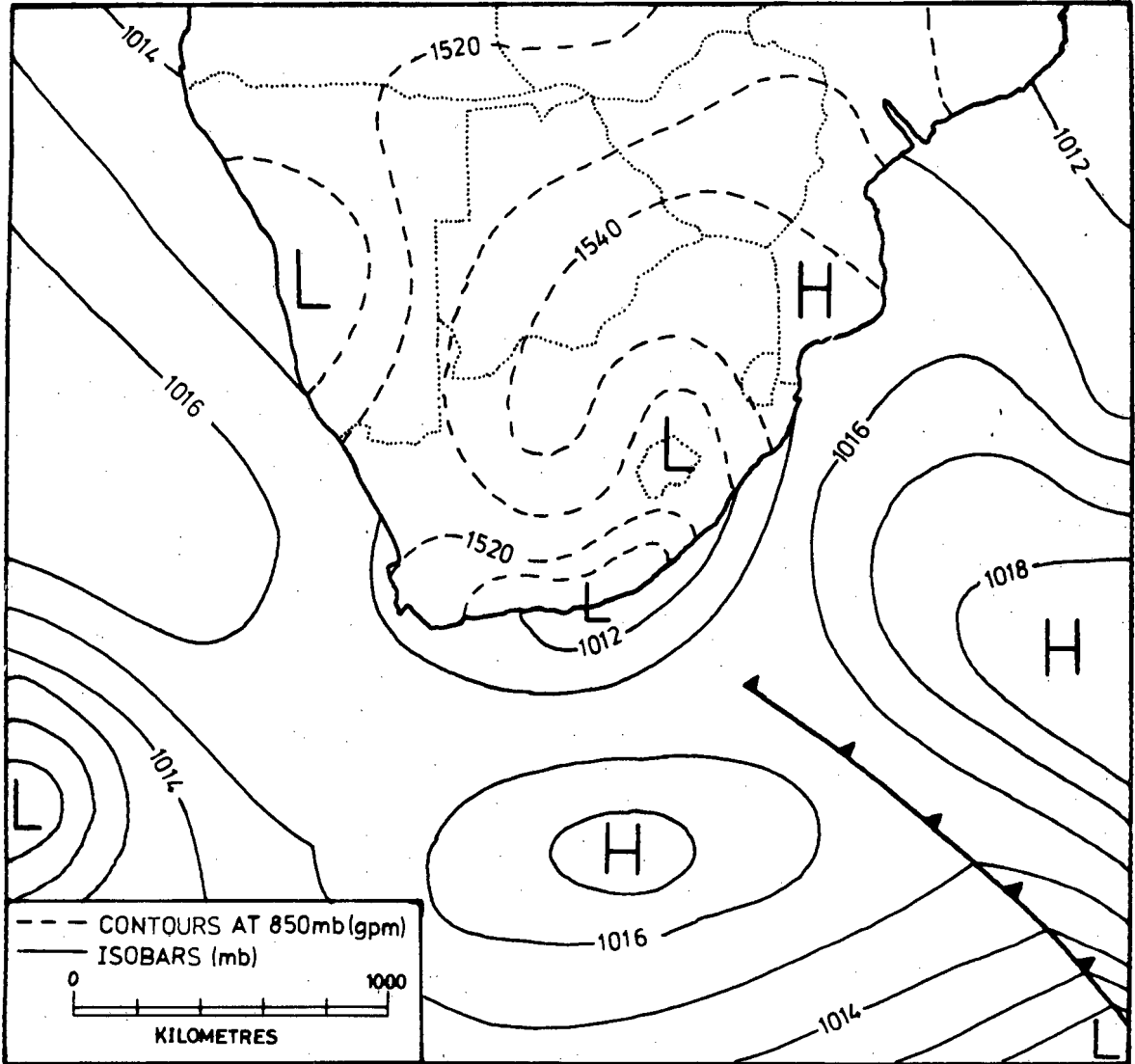
- a) Synoptic chart
 - i) confluence between the windfields of a front-associated trough and the SIA.
 - ii) the presence of a weak sub-tropical trough.
- b) Satellite imagery
 - i) the presence of a baroclinic disturbance and frontal cloud band south of the sub-continent.
 - ii) the existence of cumulus cloud cover in the region of surface convergence.
 - iii) the ZAB is present and broken cloud cover occurs in association with the sub-tropical trough.

EXPECTED CUMULUS CLOUD AND STORM ENVIRONMENT CHARACTERISTICS

- a) Precipitation: heavy showers with a very high probability of hail.
- b) Storm environment: abundant moisture, very unstable, upper tropospheric energy deficiencies with higher absolute values than 2A and very strong low-level convergence.
- c) Colloidal stability considerations are unimportant in this category.

EXAMPLE: 16 MARCH 1979

Surface synoptic chart and METEOSAT imagery for 16 March 1979, a typical type 2B day are given below.



790316 1200 GMT

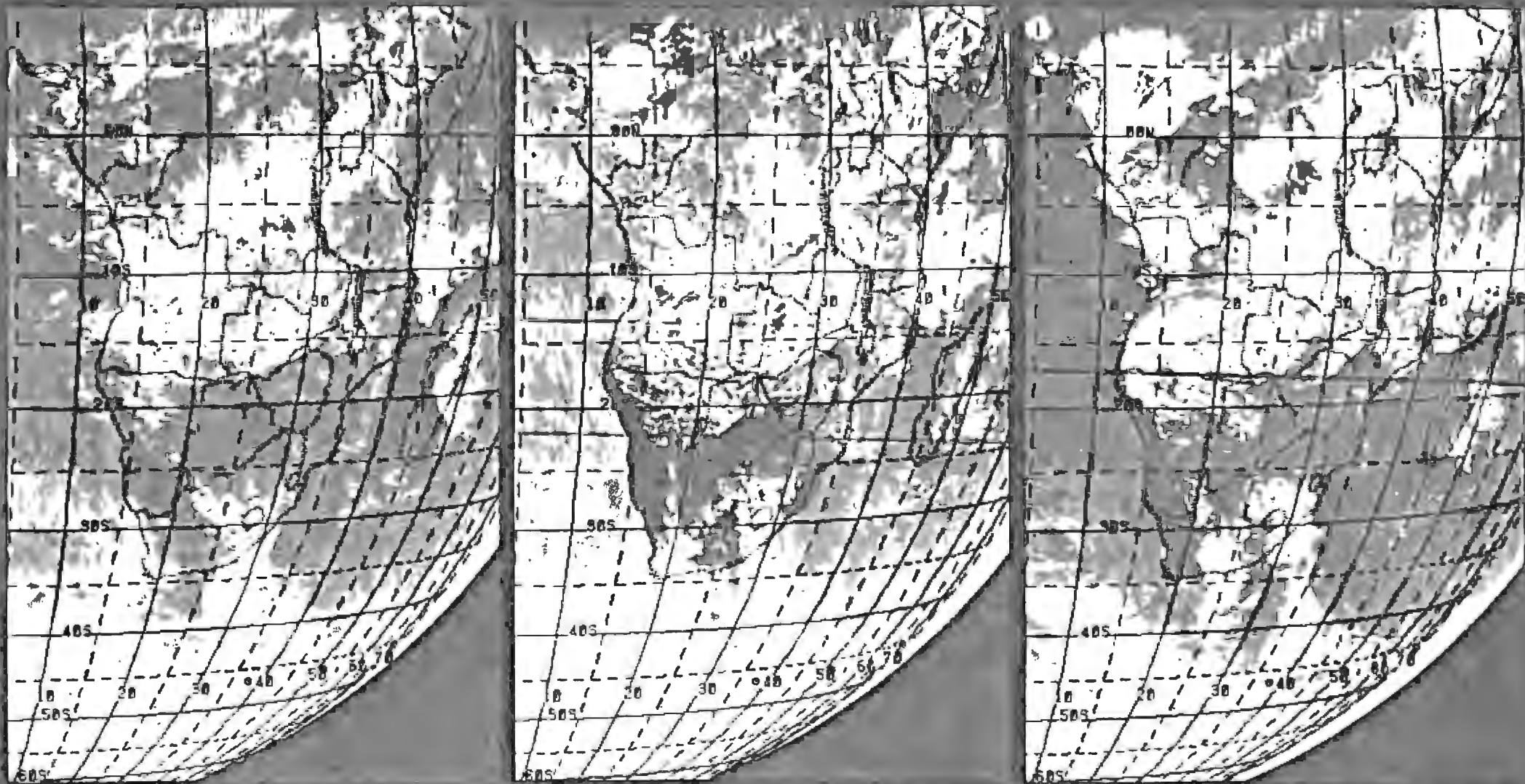


Plate 4. METEOSAT TIR images for 0600 GMT, 1200 GMT and 1700 GMT on 790316, a typical type 2B day from the 1978/79 summer season.

3. A situation involving local-scale convective storm generation.

When the sub-tropical high pressure region over southern Africa intensifies and prohibits tropical or temperate disturbances from influencing weather conditions, convection may nevertheless be triggered by localized surface heating and sustained by the release of latent energy through condensation and sublimation. A common feature on mid-day, summer-time synoptic charts is a shallow low pressure cell over the central interior which is, in fact, a consequence of surface heating. Above this thermal low, which is not attended by a cyclonic windfield but is rather characterized by light and variable winds, the flow becomes anticyclonic at about 700 mb. In the anticyclonic circulation aloft the air is subsiding. This subsidence gives rise to a generally stable atmospheric stratification with a mid-tropospheric temperature inversion. Convective development under these conditions is therefore entirely dependent on surface heating for initiation and liberated latent heat for support.

Characteristics of the convective storm environment associated with this situation determine that the cumuli will have a weak dynamic structure. For this reason the cumulus clouds, which are colloidally stable, will be inefficient producers of precipitation. The existence of a subsidence inversion at middle levels inhibits convection but provides maximum seedability since an artificially induced increase in buoyant energy may cause the cumulus clouds to penetrate the inversion. However, this effect can only be achieved if the energy, in the latent form of precipitable water, necessary for the increase in buoyancy, is available. If atmospheric moisture is low, cumulus tops may not even reach the -5°C level, in which case seeding will have no effect because artificial seeding agents only become active at approximately this temperature. Convective storms which originate in the absence of both tropical and temperate disturbances are grouped into one category defined as follows:

Synoptic Situation 3

IDENTIFICATION

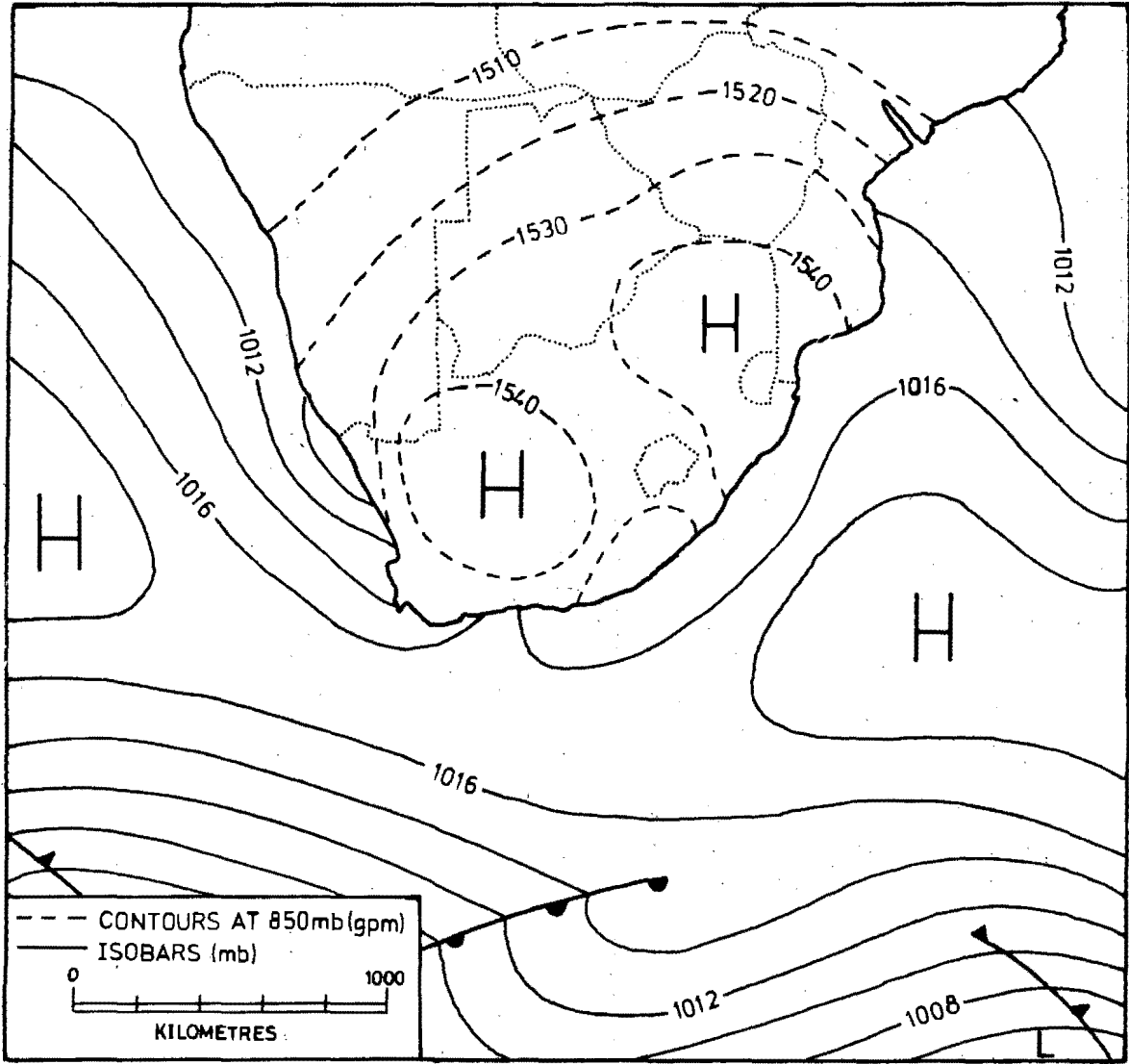
- a) Synoptic chart
 - i) a low pressure cell of thermal origin over the central interior.
 - ii) light and variable surface winds.
 - iii) no evidence of a sub-tropical trough or front-related trough.
- b) Satellite imagery
 - i) the presence of a nearly cloudless region of high surface temperature coincident with the heat low.
 - ii) there is no evidence of a frontal cloud band or sub-tropical cloud band over the sub-continent.

EXPECTED CUMULUS CLOUD AND STORM ENVIRONMENT CHARACTERISTICS

- a) Precipitation: low rainfall with little likelihood of hail.
- b) Storm environment: highly variable moisture, generally stable with a mid-tropospheric inversion, very low absolute values of total energy and light and variable surface winds.
- c) Colloidal stability: cumuli are colloiddally stable.

EXAMPLE: 14 MARCH 1979

On 14 March 1979 the synoptic situation defined above was responsible for convective storm formation. The surface synoptic chart and METEOSAT imagery for this day are given below.



790314 1200 GMT

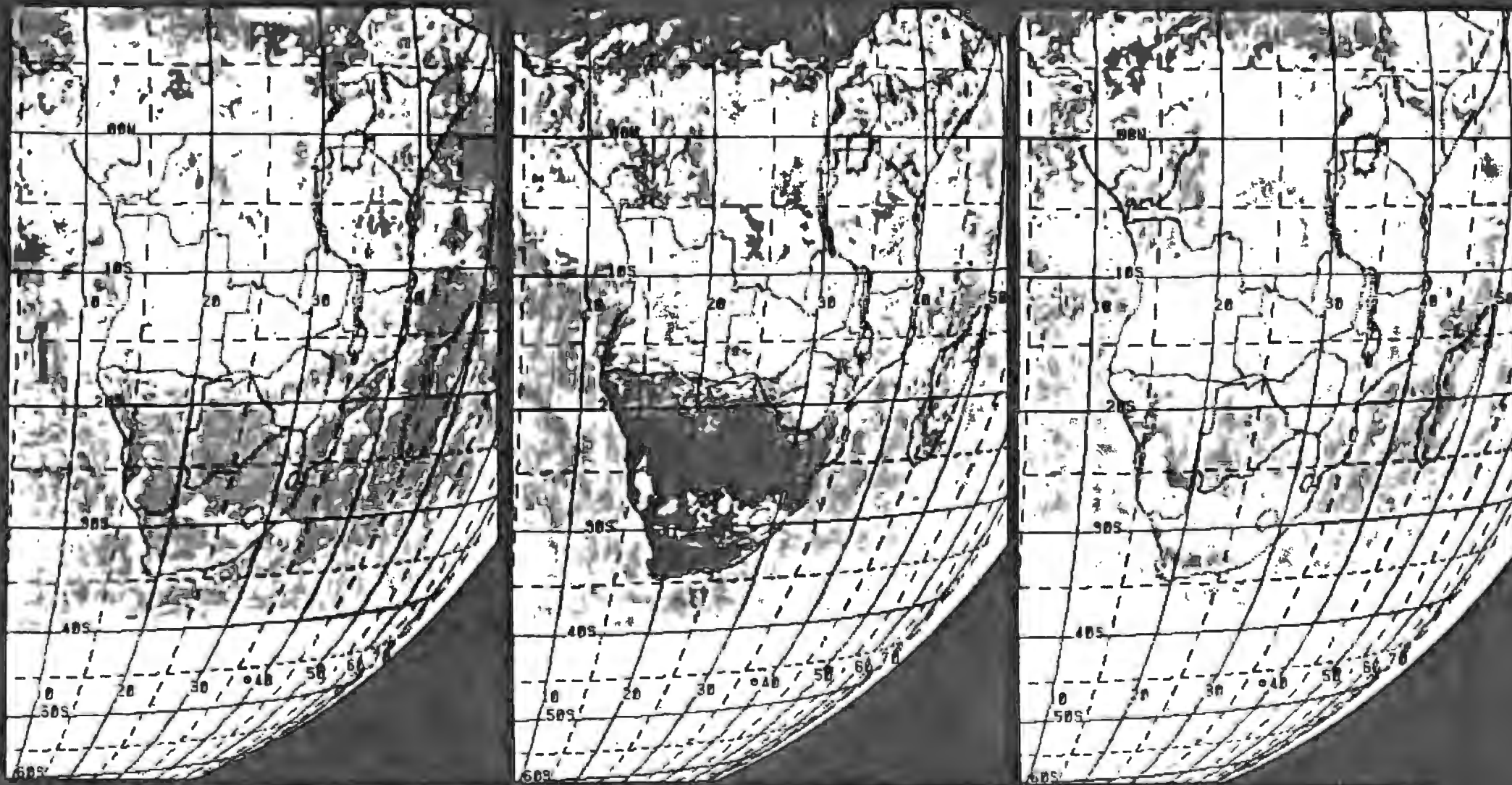


Plate 5. METEOSAT TIR images for 0600 GMT, 1200 GMT and 1700 GMT on 790314, a typical type 3 day from the 1978/79 summer season.

TABLE 5.1 THE SYNOPTIC SYSTEMS CLASSIFICATION SCHEME

- | | | | |
|-----------------------|---------------------------|-------------------------------------|-----------------------|
| 1) BOTNAM low | 3) Subtropical cloud band | 5) South Indian Ocean Anticyclone | 7) Zaïre Air Boundary |
| 2) Subtropical trough | 4) Frontal cloud band | 6) South Atlantic Ocean Anticyclone | 8) Heat Low |

Tropical Systems

Temperate Systems

Local System

1A

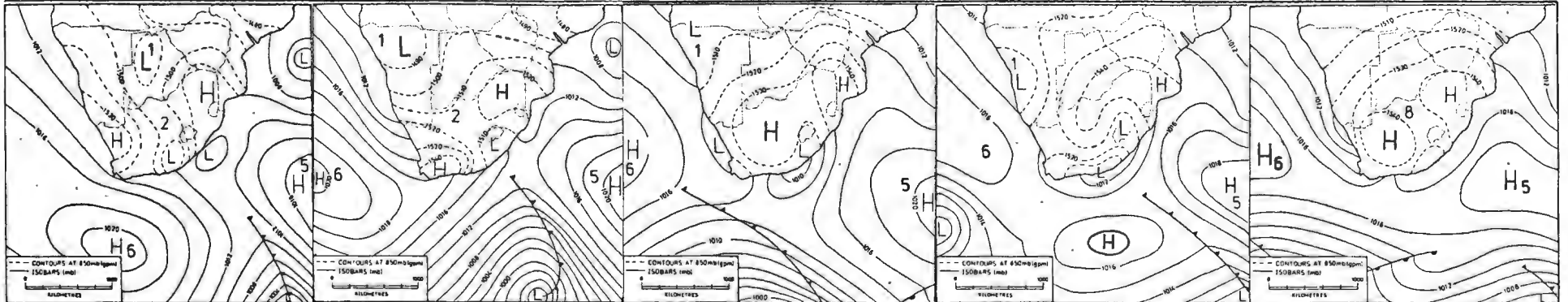
1B

2A

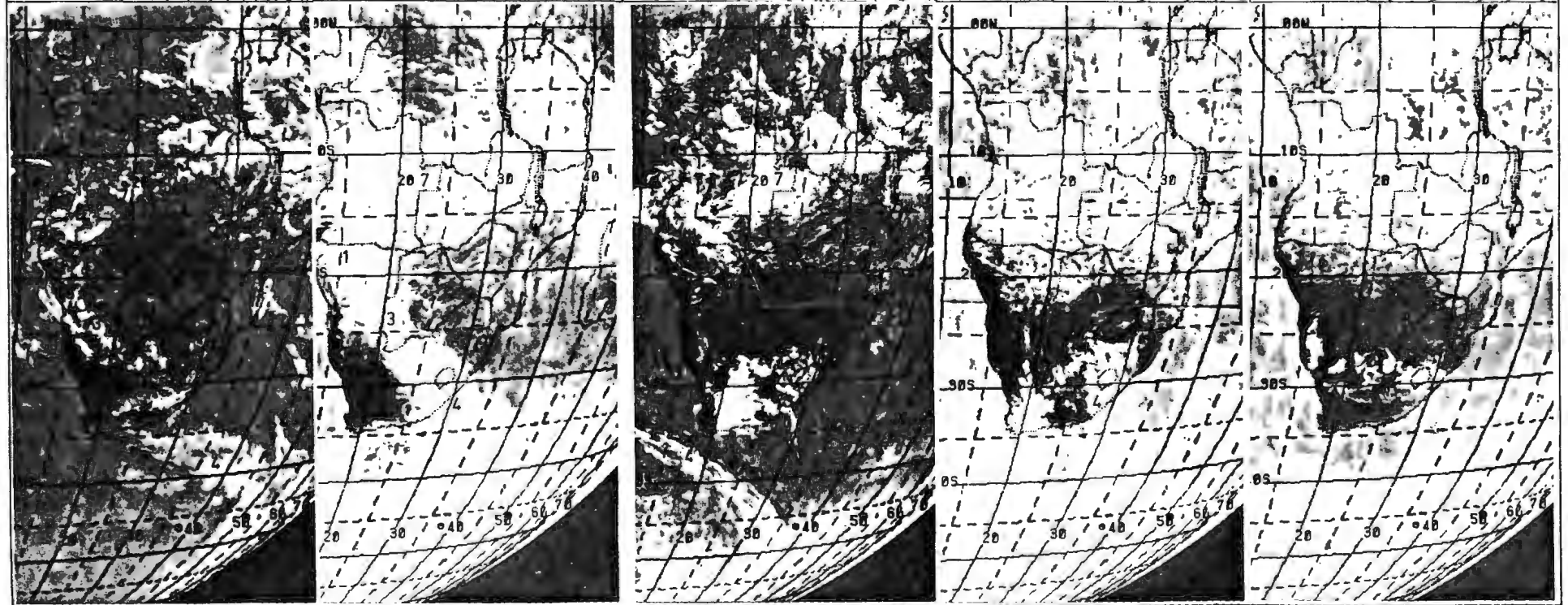
2B

3

Synoptic Charts 1200 GMT



METEOSAT TIR 1200 GMT



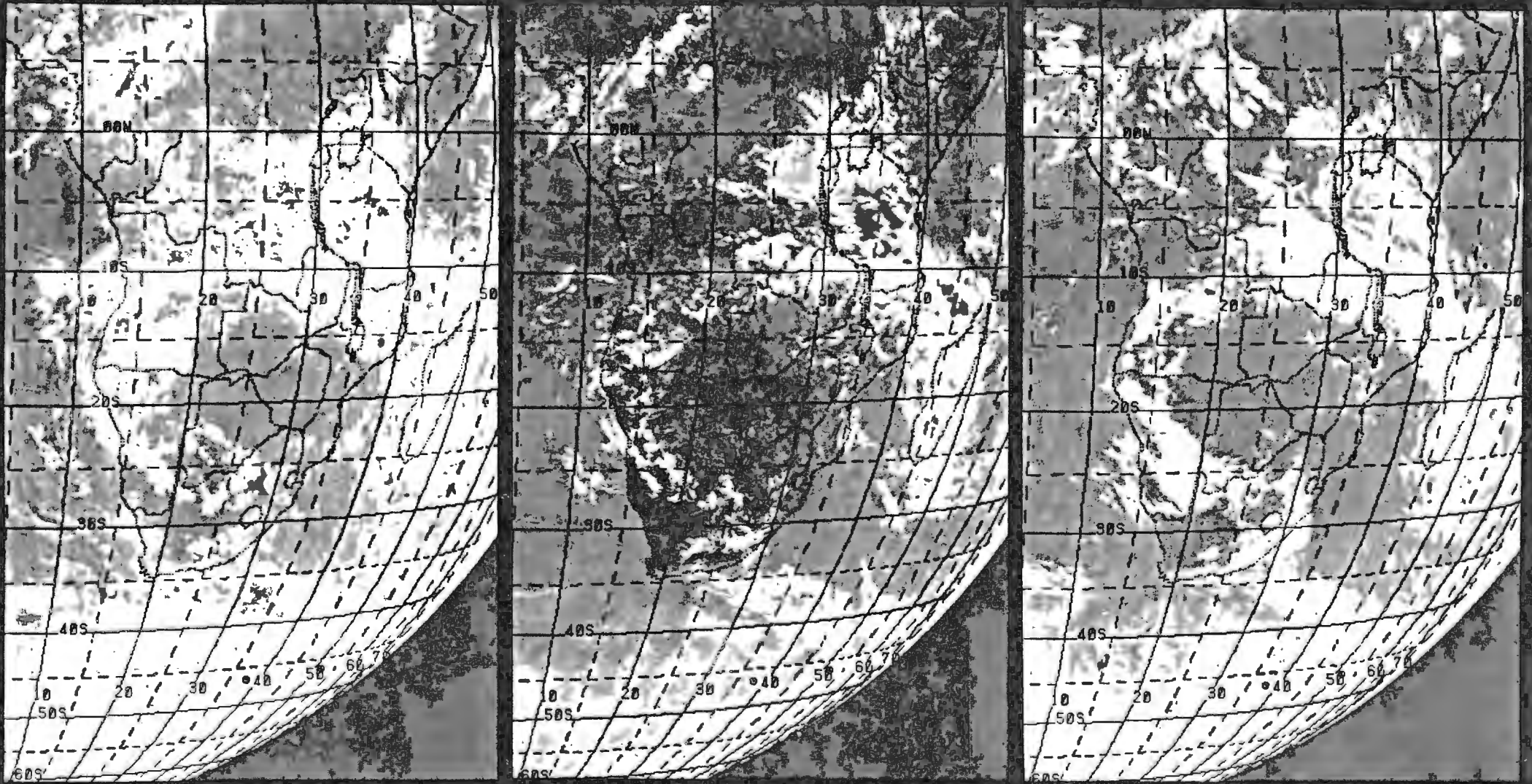


Plate 1. METEOSAT TIR images for 0600 GMT, 1200 GMT and 1700 GMT on 790205, a typical type 1A day from the 1978/79 summer season.

The synoptic systems scheme is presented in summarized form in Table 5.1. In addition to satellite imagery and surface synoptic charts other methods may be used to identify characteristic synoptic situations. The advantages to be gained from incorporation of these methods in the identification process of the synoptic systems classification scheme are given consideration in the next chapter.

CHAPTER 6

THE IDENTIFICATION PROCESS OF THE SYNOPTIC SYSTEMS CLASSIFICATION SCHEME

The classification criteria of the synoptic systems scheme are based on knowledge of the manner in which synoptic scale physical processes influence the storm environment and hence the microphysical and dynamical characteristics of the cumulus cloud population. It is clear that the constraints which large-scale systems impose on cumulus cloud characteristics will be consistent with physical processes attending these systems. Thus tropical disturbances will give rise to convective storms that are different dynamically and microphysically to those storms accompanying disturbances of temperate origin. With regard to the classification of synoptic situations, once suitable criteria have been formulated to differentiate between the situations to be stratified, the main problem remaining is deciding on the best means for identification of these situations. Classification procedure must avoid the dangers of oversimplification on the one hand, and of making the criteria for classification too complicated on the other. Likewise with regard to the methods to be used in the identification process, a balance must be maintained between methods that are too subjective and techniques that are overly involved. Since the aim in classification is quick, easy and effective identification of characteristic situations, it is vital that such balance be achieved. The synoptic systems scheme employs satellite imagery and surface synoptic charts to identify the situations defined by the scheme. However, other methods of depicting the prevailing synoptic situation may be utilized in the identification process. Inclusion of these methods, although enabling more objective identification to be

accomplished, will also serve to complicate the process of identification. In this section the benefits to be accrued by incorporating additional ways of representing the synoptic situation in the identification process are weighed against the disadvantages that may result from this action.

1. Physical case study analysis.

Investigation of methods used to depict the synoptic situation, that may be employed in the identification process, is carried out by the case-study approach. The five days cited as typical examples of the synoptic categories and for which the surface synoptic charts and METEOSAT imagery are presented in the previous chapter have been selected for study. The days chosen and the categories into which they are classified according to the weather type and synoptic systems schemes are given in Table 6.1.

Table 6.1 Case-study dates and classifications according to the weather type and synoptic systems schemes.					
	790205	790222	790314	790315	790316
Weather type forecast	V	VIA	V	-	I
Weather type observed	VIA	IVc	V	V	V
Synoptic category	1A	1B	3	2A	2B

TABLE 6.2 SUMMARY OF THE WEATHER SITUATION ON THE DAYS FOR WHICH CASE STUDIES ARE BEING CONDUCTED.

SYNOPTIC CATEGORY	1A			1B	2A		2B	3		
Date	5 February 1979			22 February 1979	15 March 1979		16 March 1979	14 March 1979		
Mean Rainfall	3,451			9,093	1,418		1,487	0,757		
Hailfall	Isolated			none	none		none	none		
Cloud Base Temperature ($^{\circ}\text{C}$)	9,0			10,9	5,7		4,1	2,0		
Cloud Base Height (m)	3900			3150	3800		3400	4300		
First Echo Temperature: mean ($^{\circ}\text{C}$)	-10,6			0,3	-15,5		-17,1	-11,8		
mode ($^{\circ}\text{C}$)	-15,9			-1,4	-15,9		-18,0	-9,6		
First Echo Height: mean (m)	6613			4847	6728		6910	6190		
mode (m)	7500			5177	6723		6822	5750		
Maximum Cloud Top: mean ($^{\circ}\text{C}$)	-33,5			-10,3	-27,1		-30,5	-29,6		
mode ($^{\circ}\text{C}$)	-21,7 and -36,1			-3,1	-26,4		-24,5	-20,9		
Maximum Cloud Top: mean Height (m):mode	9691 10126			6630 5834	8415 8201		8938 8667	8673 7300		
Test Cloud Data										
First Echo Temp. ($^{\circ}\text{C}$)	-19,5			No Data	-10,7		No Data	-15,6		
First Echo Height (m)	7800			Data	5900		Data	6900		
Maximum Top Temp. ($^{\circ}\text{C}$)	-40,5				-31,2			-49,5		
Maximum Top Hgt. (m)	10600				9000			11400		
Aircraft Penetration levels ($^{\circ}\text{C}$)	8,0	-7,0	-13,0		1,0	-14,5		2,0	-5,0	-13,0
Maximum LWC (gm^{-3})	-	2,2	3,0	No Data	-	2,1	No Data	-	0,7	1,4
Max.Updraft (mS^{-1})	5,0	17,5	15,0	Data	-	5,0	Data	5,0	3,0	7,5
Max.Downdraft (mS^{-1})	2,5	10,0	7,5		-	7,5		5,0	6,0	7,5
Hydrometeors	Rain	Rain, Snow	Snow		Graupel, Rain	Soft Hail, Rain		Snow, Rain	Snow, Rain,	Snow, Rain.
Mean Droplet Spectrum at Cloud Base.	No Data			No Data						
Temporal Considerations of Cumulus Development.										

a) The weather situation.

The observed weather situations for the days being examined are presented in summarized form in Table 6.2. Characteristics of the cumulus cloud population as determined from in-cloud, aircraft observations and radar data collected on echo-producing cumuli are presented in the table (Fleischer, 1980).

b) Representation of the synoptic situation.

Besides satellite imagery and surface synoptic charts, differences in meso- and large-scale physical processes can be discerned from radar photographs, by direct measurement of storm environment characteristics and from upper-air synoptic charts.

i) Radar imagery.

The areal organization patterns of cumulus clouds as deduced from PPI scope radar photographs, reflects the scale at which the horizontal dynamics of the storms are being determined. Lines of storms, particularly lines of storm complexes tend to occur in a zone of well-defined surface convergence resulting from the interaction of synoptic scale windfields. Cumulus cloud distribution is usually scattered on days where the surface winds are light and variable and development is thermally initiated. On days with a weak synoptic scale windfield and exceptionally high atmospheric moisture, the circulation systems of convective storms which form first are enhanced rapidly by latent energy release. Moisture, containing energy in the latent form, is drawn into these storms and they will therefore tend to develop further, doing so at the expense of the other cumuli with weaker dynamics. Since horizontal

convergence is a principal criterion of the synoptic systems classification scheme, the areal organization pattern of cumulus clouds can be used to identify differences in the synoptic situations defined by the scheme. For the days being considered the areal organization patterns are presented in Fig. 6.1.

ii) Physical condition of the storm environment.

The criteria for classification can be quantified if discrete measurements are made of the temperature, moisture and windflow characteristics of the storm environment. Such measurement is made by means of radiosonde ascents at a location above which the tropospheric conditions are representative of the meso-scale storm environment. However, quantification tends to make the identification process too involved and time consuming. Subjectively deduced changes in the moisture, temperature, energy and windfield conditions between successive upper-air ascents at various tropospheric levels may nevertheless provide useful means for identification. The 0700 GMT and 1100 GMT radiosonde ascents made at Bethlehem provide data on changes in storm environment conditions for the days being studied. The data are presented in Table 6.3 in the form of tephigrams and vertical profiles of total energy, wind speed and wind direction.

iii) Upper-air synoptic charts.

Physical conditions in the upper-air are best represented by charts depicting the wind, temperature and moisture fields for selected pressure surfaces. For the purposes of the case-studies, 1200 GMT upper-air data from South Africa's network of radiosonde stations are used to construct these fields for the 700 mb, 500 mb and 300 mb pressure surfaces. Streamlines and isotachs are used to represent the windfield while depression to dewpoint ($T-T_d$) is

FIG. 6.1 SELECTED MITSUBISHI RADAR SCOPE IMAGES FOR THE CASE STUDY DAYS (ALL AT 2nd SCAN ELEVATION). RING MARKS ARE 10 NMI APART. (All times GMT).

790205

790222

790315

790316

790314

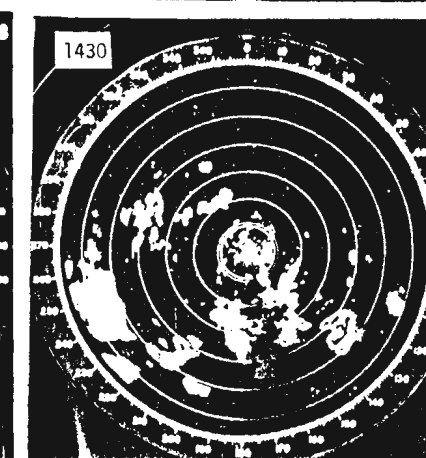
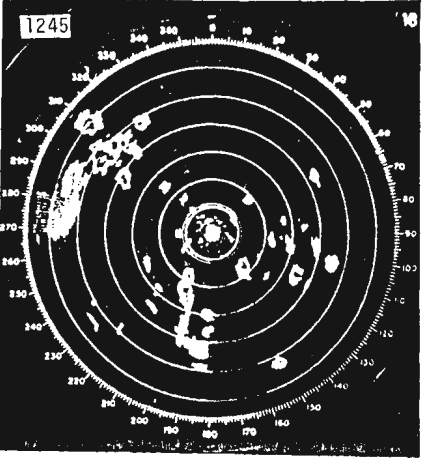
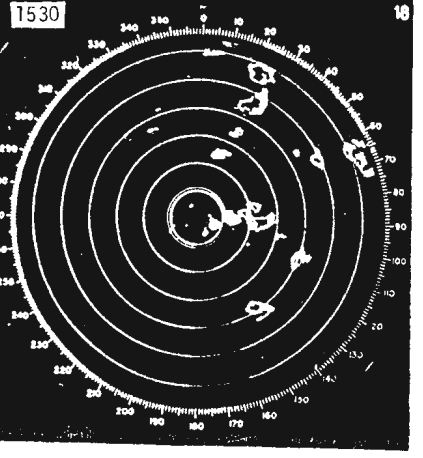
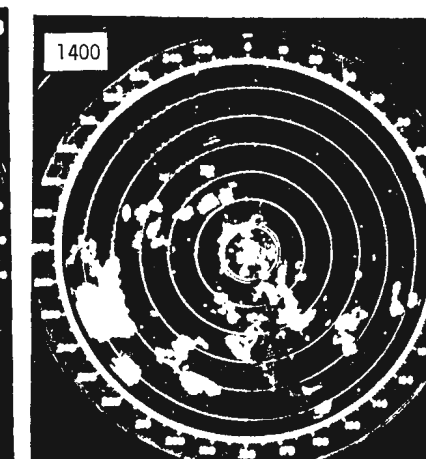
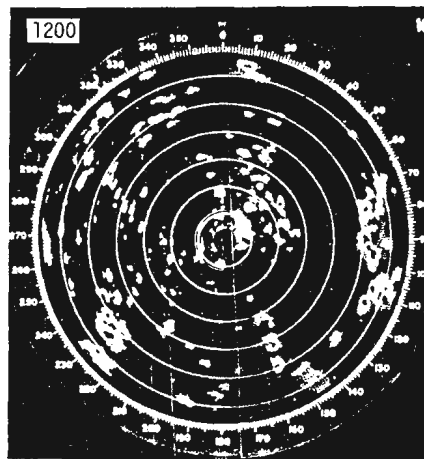
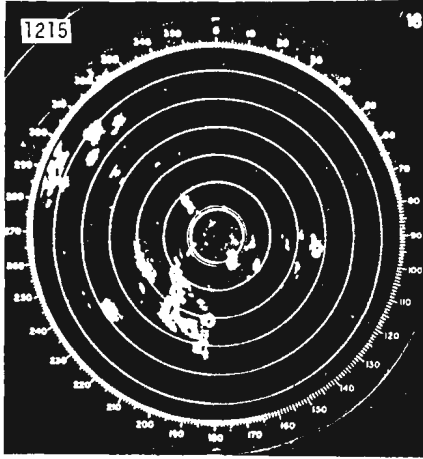
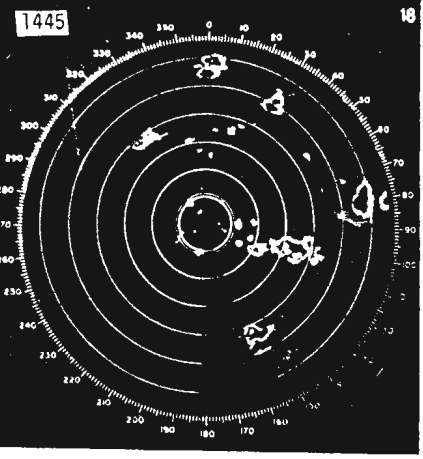
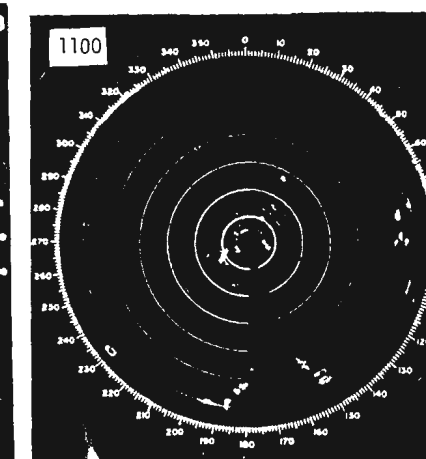
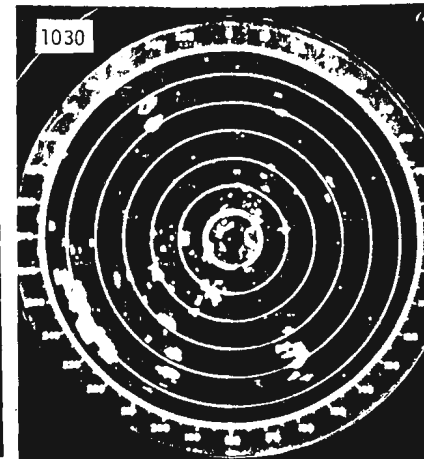
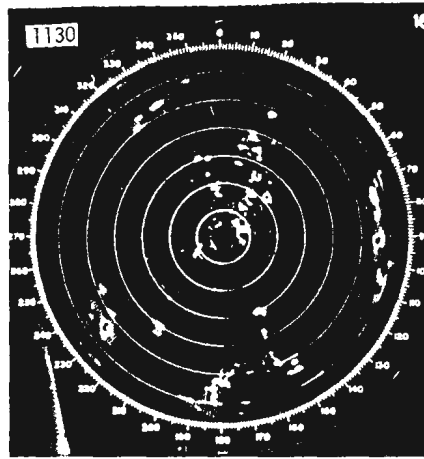
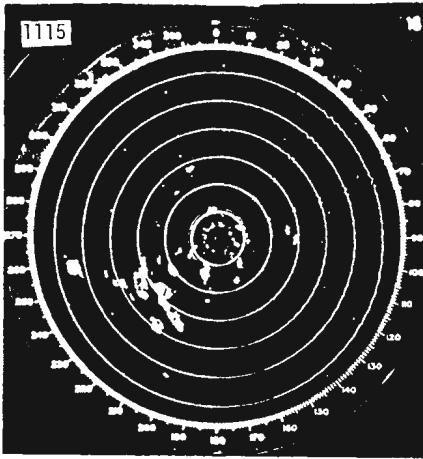
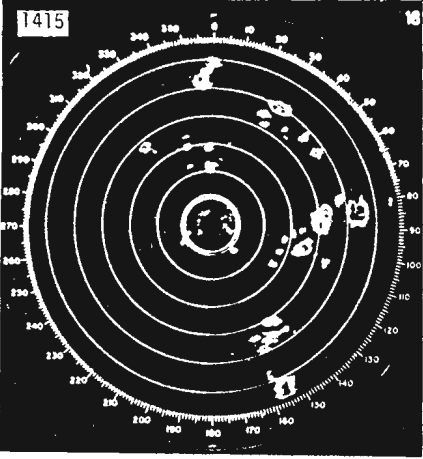


TABLE 6.3 PHYSICAL CONDITION OF THE STORM ENVIRONMENT

Synoptic Category	1A	1B	2A	2B	3
Date	5 February 1979	22 February 1979	15 March 1979	16 March 1979	14 March 1979
Showalter Index	-2,6	-0,9	-3,5	-4,2	-2,4
Total Precipitable Water (mm)	18,9	25,8	17,4	20,0	16,6
Vertical Profiles of:					
Total Energy (cal.gm ⁻¹)					
Wind Direction (degrees)					
Wind Speed (knots)					
Upper-Air temperature and moisture sounding for Bethlehem					
0700 GMT: T					
0700 GMT: Td					
1100 GMT: T					
1100 GMT: Td					

employed as a measure of moisture conditions. The temperature field is expressed in terms of the potential temperature. The analyses are presented in Fig. 6.2.

2. Improving the identification process.

The areal organization pattern of cumulus storms provide useful means for identification of the presence and intensity of low-level streamline convergence, an important criterion of the synoptic systems classification scheme. However, the fact that convective storm organization patterns can only be deduced by monitoring of the radar PPI scope in real-time and are not determinable in a predictive sense, limits the usefulness of this identification method. Information from the radar may be used to verify classifications during and after events without causing significant complication of the classification procedure.

Unless the criteria for classification are to be quantified, measurements of the physical condition of the storm environment is not a suitable means for improving the identification process. Since quantification complicates the classification procedure such action is not desirable. In addition, the relatively short time period between successive radiosonde ascents (4 hours) does not allow for detection of significant changes in the storm environment. Because of the static nature of this identification method it will be of little use to the synoptic systems classification scheme which is dynamically oriented. No advantages accrue to the classification scheme by inclusion of this method in the identification process.

The currently employed methods of identification, utilizing satellite imagery and surface synoptic charts, give limited consideration to large-scale upper-air physical processes in the classification of synoptic situations. This failing arises because analyses of lower (700 mb), middle (500 mb) and upper (300 mb) tropospheric wind, moisture and temperature fields are not available in real-time and cannot, therefore, be utilized in the identification process. However, examination of these data for the case-study days indicates that these upper-air charts will assist in the identification of the synoptic categories. Features of these synoptic situations which can be distinguished particularly well by this identification method are:

Synoptic category 1A: i) a flow of warm, moist air from tropical latitudes.

- B: i) a flow of warm and very moist air in association with the cloud band connection.
ii) when compared to 1A, the greater strength of horizontal convergence at middle and upper levels.

Synoptic category 2A: i) the presence of well-defined, intense, low-level convergence and upper-tropospheric divergence.

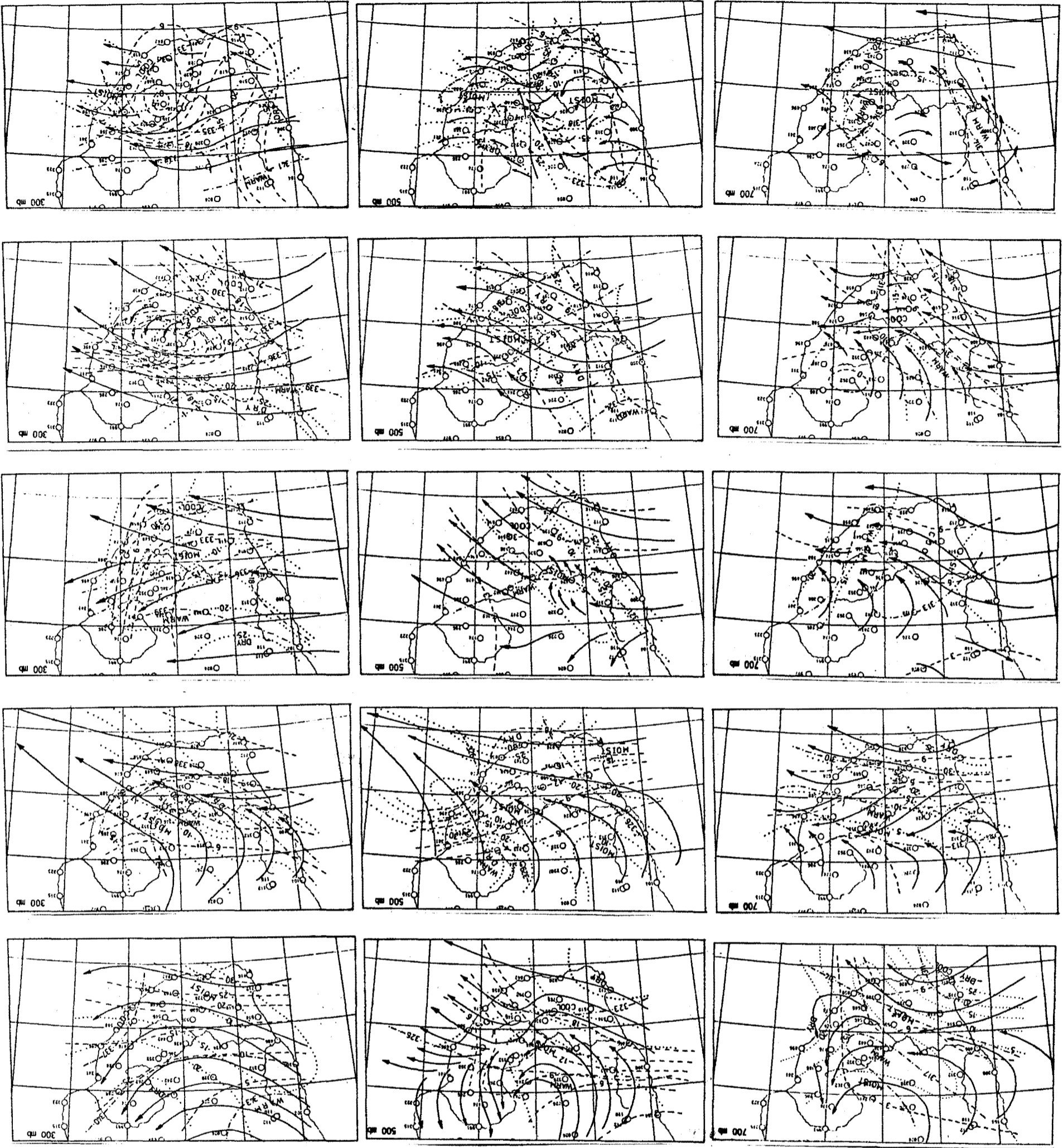
- B: i) when compared to 2A, the existence of a tropical component.

Synoptic category 3: i) the existence of light and variable winds at low and middle-levels.

- ii) a characteristic configuration of the moisture field in relation to the isotachs at low-levels.

Fig. 6.2 UPPER-AIR MOISTURE, TEMPERATURE AND WIND FIELD ANALYSES AT 700 MB, 500 MB AND 300 MB FOR THE CASE STUDY DAYS. THE FIELDS ARE REPRESENTED BY:

- I DEPRESSION TO DEWPOINT (T-D),
- II - - - - - POTENTIAL TEMPERATURE ISOTHERMS (°K),
- III ———— STREAMLINES, AND
- IV - - - - - ISOTACHS (KNOTS).



790205

1A

790222

1B

790315

2A

790316

2B

790314

3

Access to upper-air temperature, moisture and windfield analyses in the identification process will reduce misclassification by the synoptic systems scheme to a significant degree. Availability of these analyses in real-time, for inclusion in the classification procedure, will necessitate computerized construction of the synoptic fields. This is not yet being undertaken in southern Africa and it is unlikely that such will be accomplished within the foreseeable future.

Analyses of large-scale physical processes on five days, each of which are typical examples of the synoptic categories defined by the synoptic systems scheme, indicate that limited improvements can be made to the identification process by including additional methods of depicting the prevailing synoptic situation. Radar imagery can only be used as a means to verify classification decisions that have already been made. If upper-air moisture, temperature and wind field analyses can be made available in real-time, incorporation of these analyses in the identification process will improve the accuracy of classification. Thus, at the present time, satellite imagery and surface synoptic charts constitute the best means of identifying summer-time synoptic situations over southern Africa.

The synoptic systems classification scheme is based on the premise that cumulus cloud variability and their response to ice-nuclei seeding are determined by differences in the moisture, stability energy and wind field characteristics of the storm environment, which differences are caused by synoptic scale physical processes. The scheme therefore attempts to reduce natural variability within the set of convective events

by classification of the synoptic situations giving rise to and supporting the convection. In the following chapter the extent to which and the manner in which the synoptic systems classification scheme accomplishes this objective are examined statistically.

CHAPTER 7

STATISTICAL EXAMINATION AND EVALUATION OF THE SYNOPTIC SYSTEMS CLASSIFICATION SCHEME

Because the synoptic systems classification scheme stratifies convective events on the basis of physical processes associated with the attendant synoptic situation, it is reasonable to expect that the categories thus defined will possess significantly different precipitation regimes, storm environment characteristics and cloud base temperature conditions. In order to test, statistically, whether this is the case the synoptic systems classification scheme is employed to categorize days for the 1978/79 summer season (1 October 1978 to 31 March 1979). Thereafter the distributions of the parameters mean daily rainfall, hailfall, Show-alter index total precipital water, total static energy and cloud base temperature are examined by parametric statistical techniques to determine the level at which differences between the categories are significant. The monthly distribution of synoptic categories during the summer of 1978/79 is also considered. Discriminant analysis, is applied to the set of synoptic variables defined in chapter four as an overall test of the scheme's ability to stratify convective events.

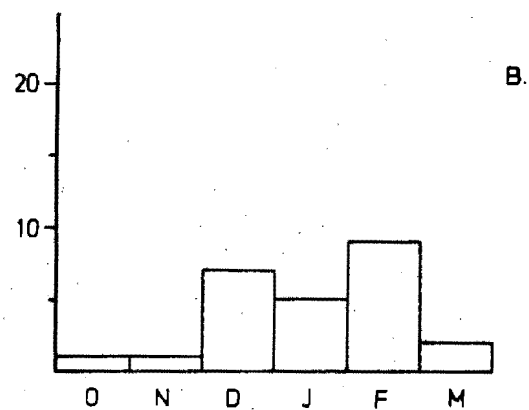
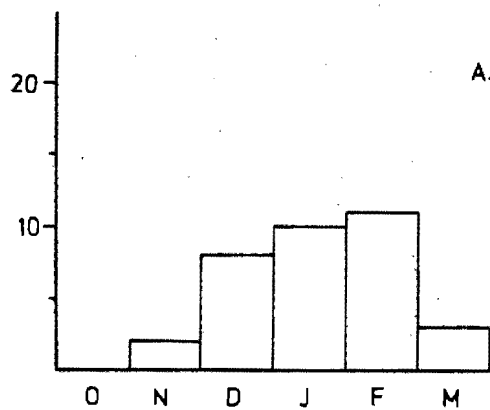
A. STATISTICAL EXAMINATION

1. Distribution of days for the summer of 1978/79.

Of the 182 days during the 1978/79 summer season, the absence of data made classification impossible on 13 days. Of the remaining 169 days, the synoptic situations on 10 days were such that they could not satisfy

the criteria of any one of the five categories defined by the synoptic systems scheme. The distribution of each synoptic category by months for the 1978/79 summer are given in Table 7.1 and Fig. 7.1.

CATEGORY	OCT	NOV	DEC	JAN	FEB	MAR	TOTAL
1A	0	2	7	10	11	3	33
1B	1	1	7	5	9	2	25
2A	20	4	0	2	0	6	32
2B	0	2	6	1	2	3	14
3	8	16	8	7	4	14	52
No Data	0	1	3	3	4	2	13
Not Classify-able	2	4	0	3	0	1	10
	31	30	31	31	28	31	182



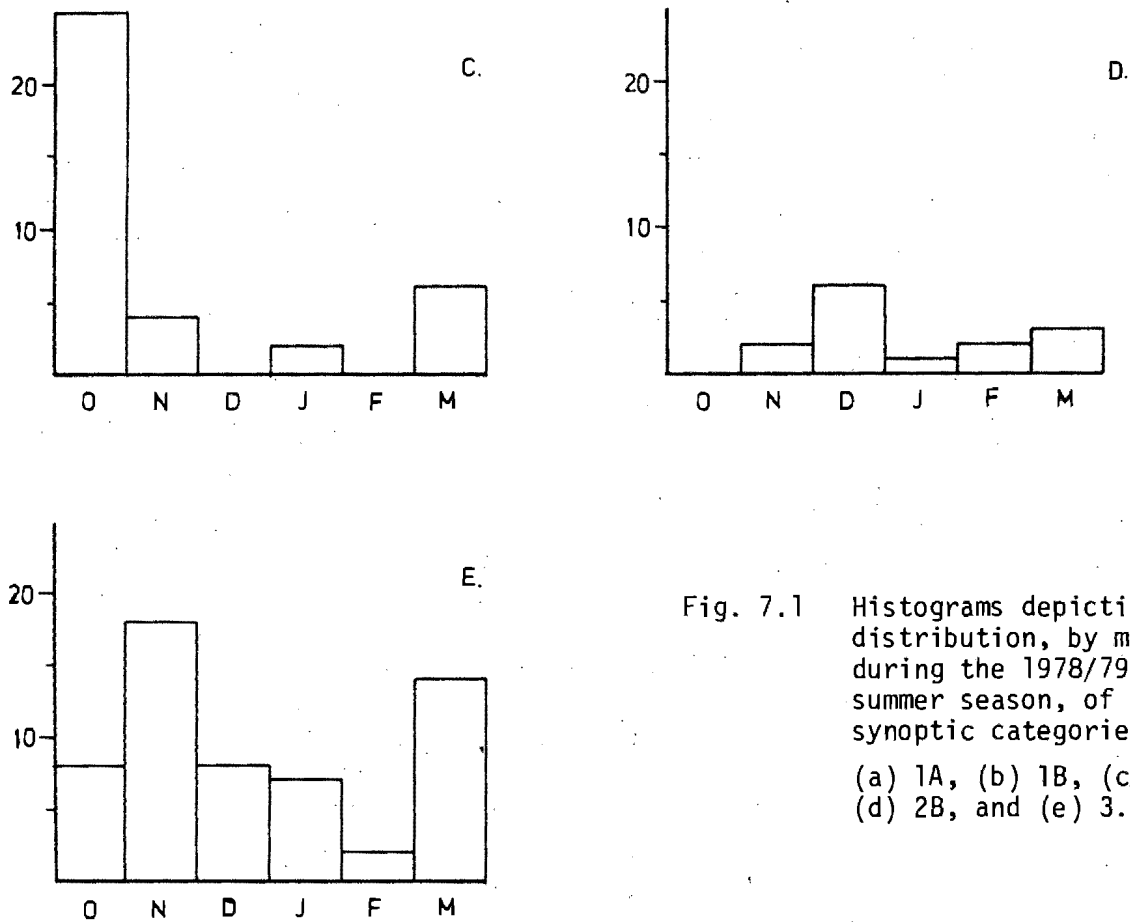


Fig. 7.1 Histograms depicting the distribution, by months during the 1978/79 summer season, of the synoptic categories: (a) 1A, (b) 1B, (c) 2A, (d) 2B, and (e) 3.

As expected, tropical systems (1A and 1B) dominate during the mid-summer months (December-February) when the pressure belts are at their southern-most extremity. Type 2A occurs most frequently in early (October) and late (March) summer since mid-latitude depressions extend their influence further north in these months than in mid-summer. Synoptic situation 3 prevails most often in November and early March when surface heating is sufficient to induce convection and when tropical disturbances have not yet commenced or have ceased their influence on weather conditions.

2. The precipitation regime.

a) Mean daily rainfall.

Average daily precipitation for the BEWMEX area is derived from a dense raingauge network. For analytical purposes the data have been stratified into a series of classes. The distribution of precipitation by classes for each synoptic category is presented in Table 7.2 and graphically in Fig. 7.2. Days for which no data are available and those not classifiable under the synoptic systems scheme are omitted.

Table 7.2 Distribution of mean daily rainfall (x) by classes and by months during the 1978/79 summer for each synoptic category.						
	OCTOBER	NOVEMBER	DECEMBER	JANUARY	FEBRUARY	MARCH
	1A1B2A2B3	1A1B2A2B3	1A1B2A2B3	1A1B2A2B3	1A1B2A2B3	1A1B2A2B3
$x < 1$	0 0 8 0 8	1 0 3 0 14	2 1 0 1 8	2 2 1 0 7	3 1 0 0 2	3 0 5 0 14
$2 > x \geq 1$	0 1 5 0 0	1 0 0 1 1	1 2 0 2 0	2 2 0 0 0	5 2 0 0 0	0 0 1 2 0
$4 > x \geq 2$	0 0 2 0 0	0 1 1 0 1	1 1 0 2 0	2 1 1 0 0	1 2 0 1 0	0 1 0 1 0
$6 > x \geq 4$	0 0 4 0 0	0 0 0 0 0	2 0 0 0 0	2 0 0 0 0	1 0 0 1 0	0 0 0 0 0
$8 > x \geq 6$	0 0 0 0 0	0 0 0 0 0	1 0 0 1 0	1 0 0 0 0	1 2 0 0 0	0 0 0 0 0
$10 > x \geq 8$	0 0 0 0 0	0 0 0 1 0	0 0 0 0 0	1 0 0 1 0	0 2 0 0 0	0 0 0 0 0
$x > 10$	0 0 1 0 0	0 0 0 0 0	0 3 0 0 0	0 0 0 0 0	0 0 0 0 0	0 1 0 0 0

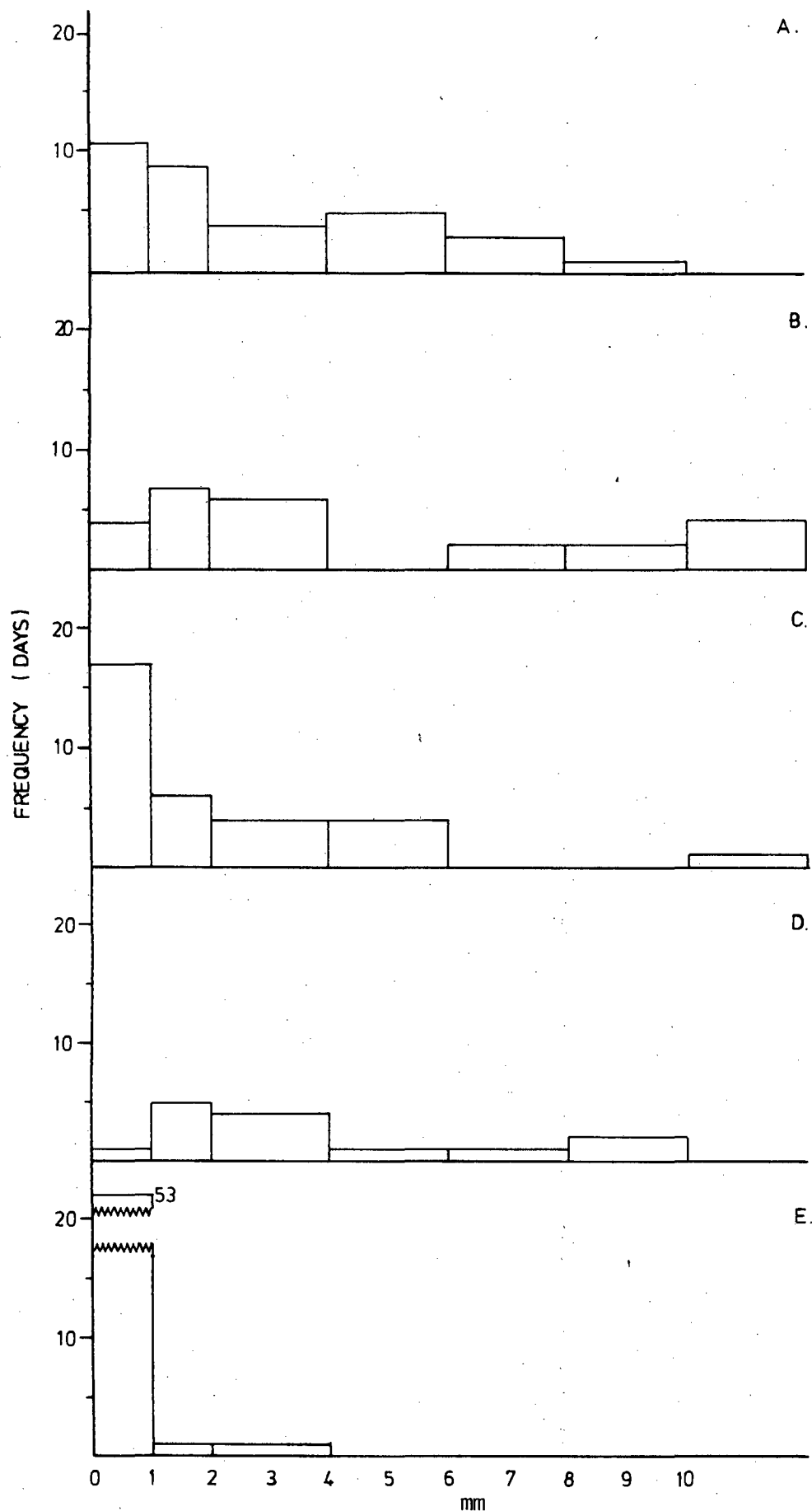


Fig. 7.2 Histograms depicting the distribution of the parameter mean daily rainfall (mm) during the 1978/79 summer season for the synoptic categories: (a) 1A, (b) 1B, (c) 2A, (d) 2B and (e) 3.

It is noteworthy that highest mean daily rainfalls under type 1 conditions occur in February when tropical systems are at their strongest. Temperate disturbances cause high rainfall in October when the intensity and northward extent of these troughs are a maximum. Of the 55 days in category 3, 53 have an average rainfall of less than 1 mm.

STATISTICAL TESTS

Differences in the rainfall characteristics of each category are investigated statistically by the F and Student's t parametric tests. Overall differences are examined by an analysis of variance on all five groups and the category means (Table 7.3) are compared using the null hypothesis that no significant differences exist between the means of the groups. The results are presented in Table 7.4. SD denotes that a significant difference exists between the means of the two categories being compared. The figure in parenthesis is the level (%) at which the differences are significant. The cut-off significance level is taken at 5%. NSD denotes that no significant difference exists between the means of the groups concerned, i.e. the null hypothesis is accepted.

CATEGORY	1A	1B	2A	2B	3
MEAN AVERAGE DAILY RAINFALL	2,535	4,830	1,853	3,502	0,316
CONTRIBUTION	83,66	120,76	59,30	49,03	17,40
% CONTRIBUTION	24,1	34,8	17,1	14,1	5,0

Table 7.4 Summary of parametric (F and t) test results for the parameter mean daily rainfall					
Analysis of Variance					
CATEGORIES INCLUDED	calculated F	$F_{0,05}$	$F_{0,01}$	$F_{0,005}$	RESULT
ALL	15,327	2,45	3,51	3,98	SD (> 0,5%)
Student's t -test					
CATEGORY	1B	2A	2B	3	
1A	SD(5,0)	NSD	NSD	SD(0,1)	
1B		SD(0,1)	NSD	SD(0,1)	
2A			NSD	SD(0,1)	
2B				SD(0,1)	

DISCUSSION

Analysis of variance, using the F -statistic, applied to all categories indicates that differences between the categories are significant at >0,5% level. The Student's t -test results show that category 3 has a significantly lower mean than all the other synoptic types. The two synoptic situations involving tropical systems have significantly different means, type 1B having a larger mean than 1A. Although type 2B does have a higher mean than its counterpart, category 2A, due to the tropical component in the former, the difference is not statistically significant. Where no significant differences exist between the means of categories representing unrelated synoptic situations (viz. 1A and 2A, 1A and 1B, 1B and 2B), it is apparent that processes operating are

almost equally efficient in the production of rainfall. The classification scheme therefore reduces natural variability as measured by mean daily rainfall most significantly with respect to category 3.

b) Hailfall.

Hail formation is maximized in an environment of strong, well-organized low-level convergence and excessive energy deficiencies in the upper troposphere. These shortages of energy in the upper-air are created by an influx of cool, dry air at high levels and/or an inflow of warm, moist air at low levels, which processes also promote storm environment instability. The synoptic situations which produce an environment ideal for hail formation are types 2A and 2B and prominent hail events can therefore be expected to accompany these situations. Of the 54 days classified as hail days for the 1978/79 season, 20 were extensive hail days and 34 isolated hail days. The distributions of extensive hail days, isolated hail days and non-hail days by synoptic category are given in Table 7.5 and presented graphically in Fig. 7.3.

CATEGORY	1A	1B	2A	2B	3	UNCLASSIFIABLE DAYS	TOTAL
EXTENSIVE HAIL DAYS	1	2	8	6	1	2	20
ISOLATED HAIL DAYS	9	7	5	3	10	0	34
NON-HAIL DAYS	15	24	19	5	44	8	115

DISCUSSION

When tropical systems prevail and hailfalls result, these falls are usually isolated. There is a distinct preference for hailfalls, especially extensive hailfalls to occur when mid-latitude systems involving temperate air masses influence the BEWMEX area. In fact on over 60% of type 2B days and

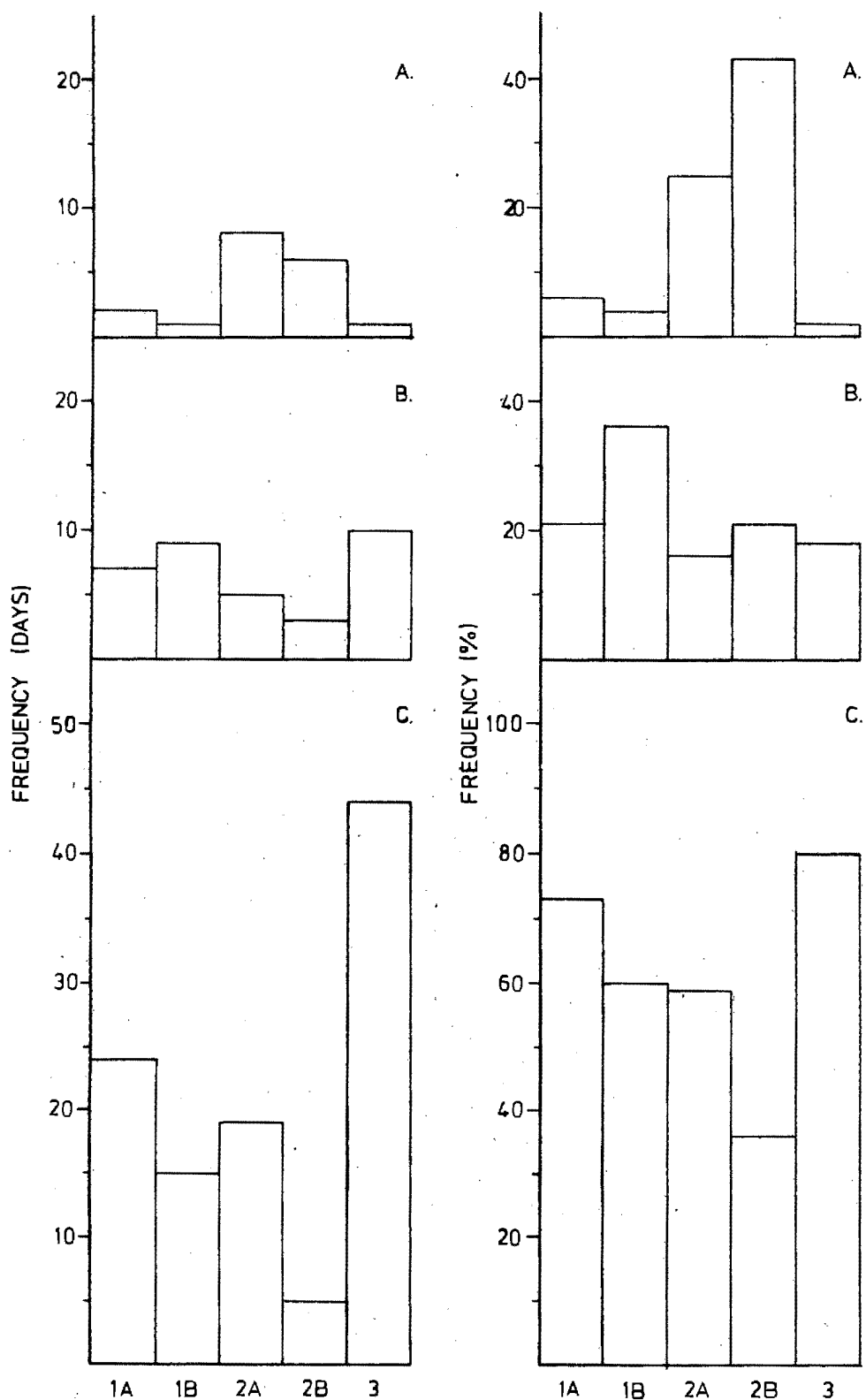


Fig. 7.3 Histograms depicting the frequency and percentage frequency of occurrence of (a) extensive hail days, (b) isolated hail days, and (c) non-hail days during the 1978/79 summer season for each synoptic category.

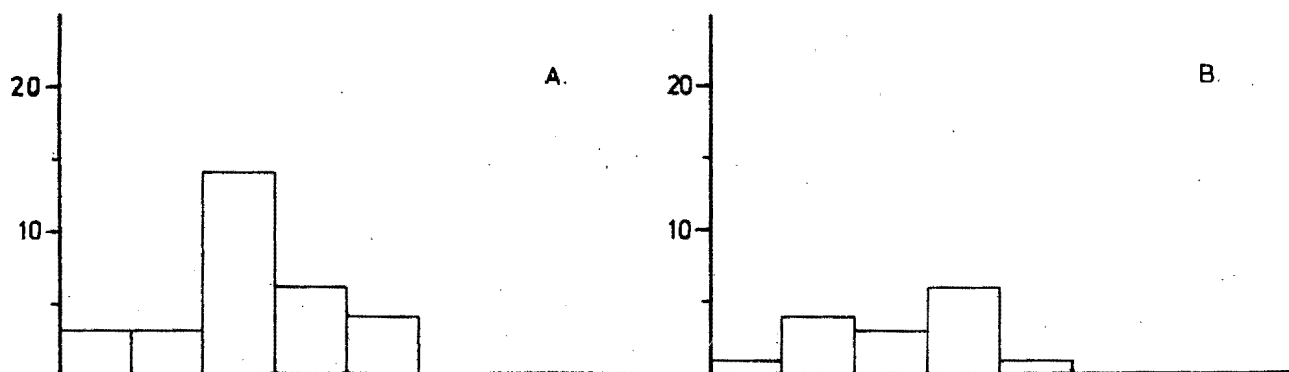
on nearly 40% of type 2A days hail was reported for the 1978/79 season. Because discrete measurements of hailfall are not possible, differences between categories cannot be tested statistically. Nevertheless, it is clear that noteworthy differences do exist between the categories particularly between situations involving systems of different latitudinal origin.

3. Storm Environment Characteristics.

The parameters Showalter index, total precipitable water and total static energy are used as indicators of the stability, moisture and energy characteristics of the storm environment. These parameters are derived from the 0700 GMT radiosonde ascent made daily at Bethlehem and therefore reflect the condition of the atmosphere in the BEWMEX area prior to storm development. These data are available for 112 days during the summer of 1978/79.

a) Showalter index.

Negative values of Showalter index denote unstable atmospheric conditions and positive values greater stability. The distribution of Showalter index by classes is given in Table 7.6 and the corresponding histograms in Fig. 7.4.



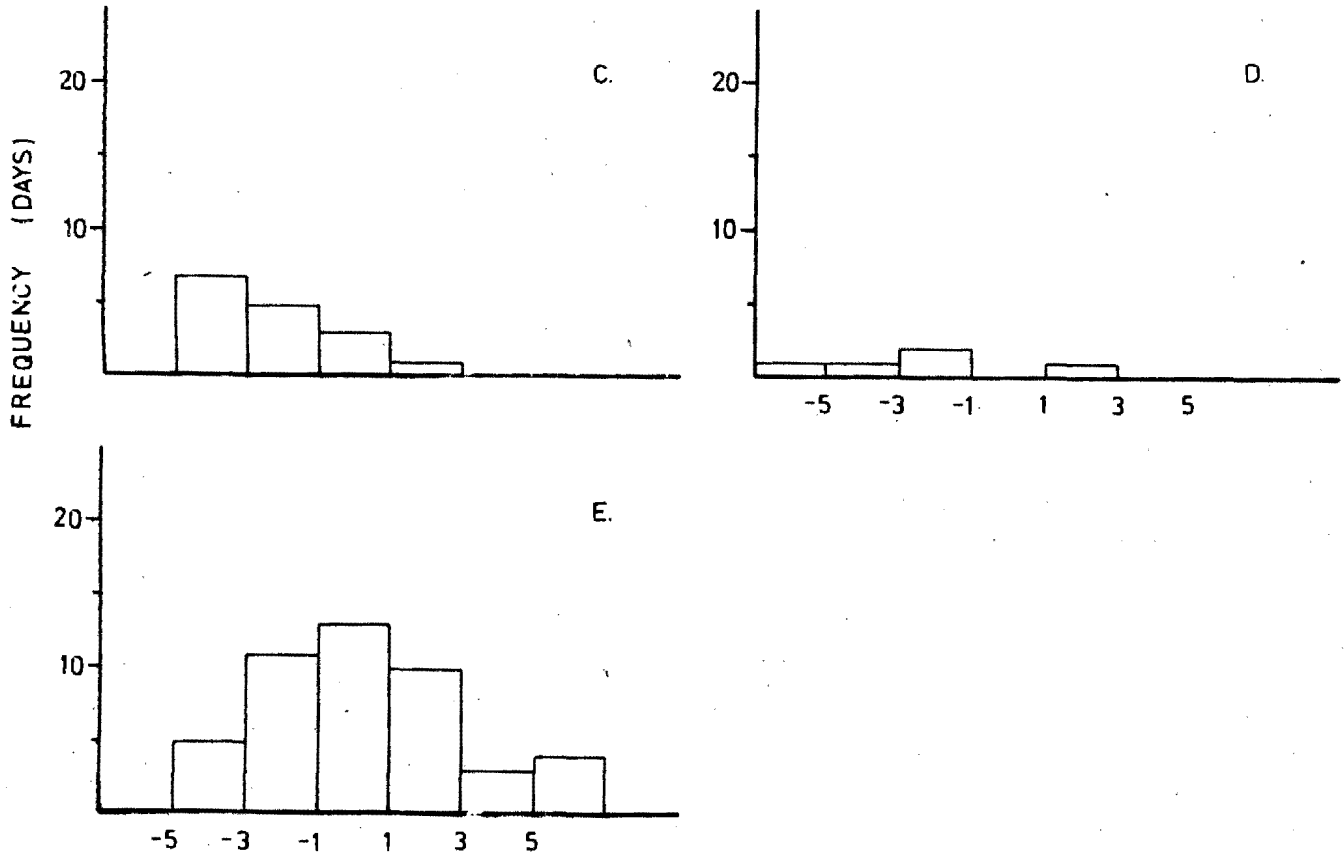


Fig. 7.4 Histograms depicting the distribution of the parameter Showalter index during the 1978/79 summer season for the synoptic categories (a) 1A, (b) 1B, (c) 2A, (d) 2B and (e) 3.

CATEGORY	SHOWALTER INDEX (x)							TOTAL	MEAN
	$x \leq -5$	$-5 < x \leq -3$	$3 < x \leq -1$	$1 < x \leq 1$	$1 < x \leq 3$	$3 < x \leq 5$	$x > 5$		
1A	3	3	14	6	4	0	0	30	-1,7667
1B	1	4	3	6	1	0	0	15	-2,2000
2A	0	7	5	3	1	0	0	16	-2,2125
2B	1	1	2	0	1	0	0	5	-1,750
3	0	5	11	13	10	3	4	46	0,3565
TOTAL	5	20	35	28	17	3	4	112	-

STATISTICAL TESTS

The results of statistical tests using the variance ratio F -statistic and the Student's t -statistic are presented in Table 7.7.

Table 7.7 Summary of parametric (F and t) test results for the parameter Showalter index					
Analysis of Variance					
CATEGORIES INCLUDED	F calculated	$F_{0,05}$	$F_{0,01}$	$F_{0,005}$	RESULT
ALL	5,860	2,46	3,51	3,95	SD(>0,5%)
2A, 2B	0,011	4,38	8,18	10,07	NSD
2A, 2B, 3	6,606	3,15	4,95	5,79	SD(>0,5%)
1A, 1B	0,190	3,19	5,08	5,95	NSD
Student's t -test					
CATEGORY	1B	2A	2A	3	
1A	NSD	NSD	NSD	SD(0,1)	
1B		NSD	NSD	SD(0,1)	
2A			NSD	SD(0,1)	
2B				NSD	

DISCUSSION

Analysis of variance tests on a series of combinations of categories indicates that, although differences are significant at >0,5% level if all categories are considered, the stability characteristics of type 3 are responsible for this significance. When the F -test is applied to 2A and 2B alone and to 1A and 1B without category 3, no significant differences are discernible. As soon as type 3 is included with 2A and

2B the value for F increases dramatically. Tests on category means substantiate this fact. The mean of group 3 is significantly greater than those of all other categories (except 2B, which is probably due to insufficient observations in this category). Since no significant differences are evident between the means of categories 1A, 1B, 2A and 2B, similar values of Showalter index may occur under totally different synoptic situations. Similarities in the stability conditions accompanying these categories may be real. However, consideration of the energy profiles of these synoptic types (see later) suggests that the Showalter index, a rather primitive indicator of environmental instability, may not be a suitable indicator of stability characteristics in the BEWMEX area. The Showalter index is related basically to the likelihood of instability resulting from convergence. It is not surprising therefore that the categories 1A, 1B, 2A and 2B display similar values of Showalter index since in all these synoptic situations surface convergence is responsible for the initiation of convection. It is noteworthy too, that category 3, the only synoptic type devoid of low level convergence, has significantly different Showalter index values. A more appropriate indicator of environmental instability should be sought for application in the BEWMEX area. Analysis of the parameter Showalter index nevertheless indicates that the synoptic systems classification procedure does reduce natural variation in environmental stability characteristics in that it differentiates between category 3 (significantly more stable) and the categories 1A, 1B, 2A and 2B (significantly more unstable).

b) Total precipitable water.

Total precipitable water, expressed in millimetres is a measure of the amount of moisture in the atmosphere that can be utilized by the processes of precipitation formation. The distribution of the parameter total precipitable water by classes for each synoptic category is given in Table 7.8 and Fig. 7.5.

Table 7.8		Distribution of the parameter, total precipitable water by classes for each synoptic category								
CATEGORY	Total Precipitable Water (x) in mm.							TOTAL	MEAN	
	x<10	10≤x<13	13≤x<16	16≤x<19	19≤x<22	22≤x<25	x≥25			
1A	0	0	1	9	7	9	4	30	21,0933	
1B	0	0	0	0	4	3	8	15	24,8800	
2A	0	1	1	6	6	2	0	16	18,6175	
2B	0	0	1	0	0	4	0	5	20,1620	
3	6	7	14	17	2	0	0	46	14,7152	
TOTAL	6	8	17	30	19	18	12	112	-	

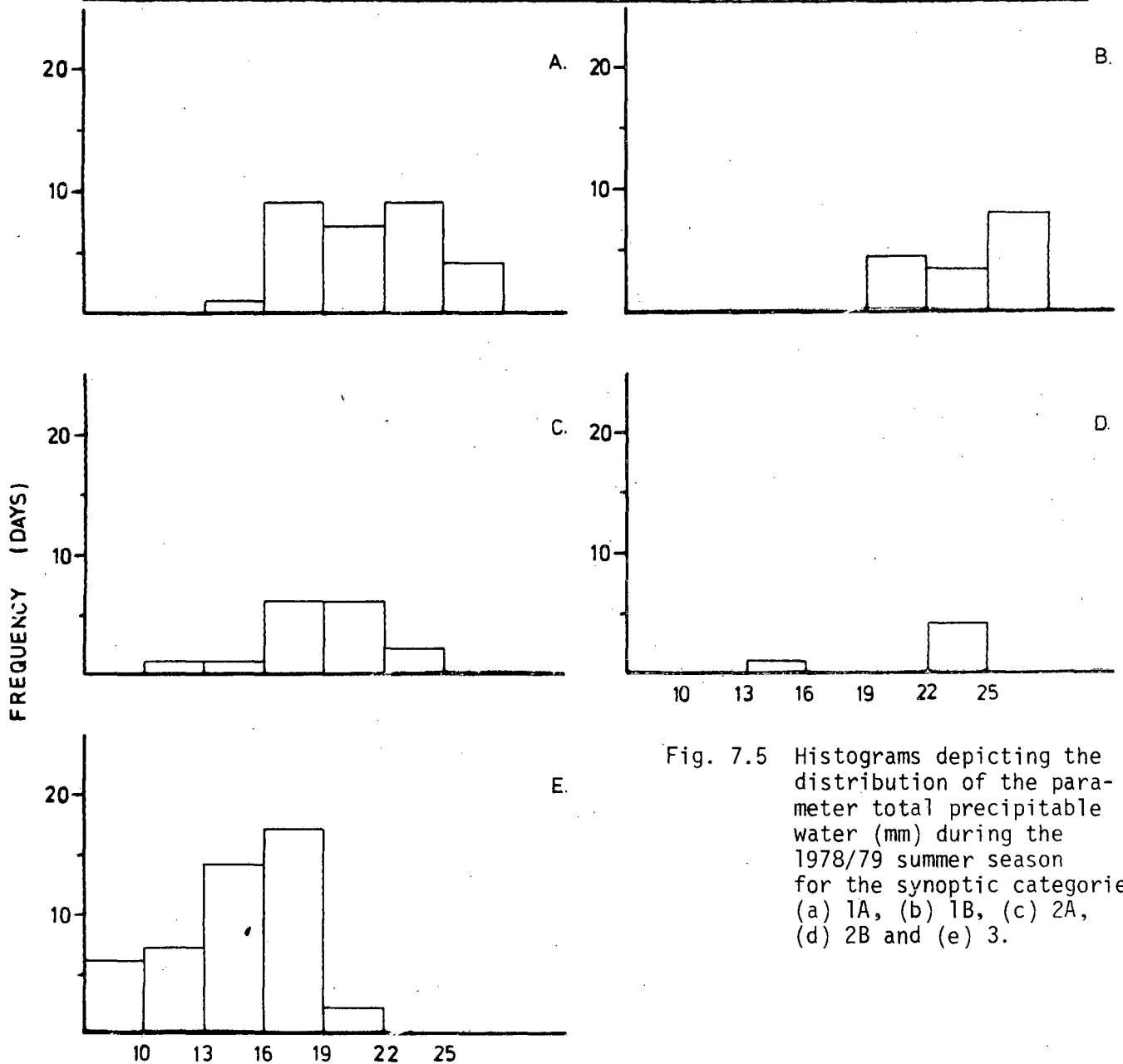


Fig. 7.5 Histograms depicting the distribution of the parameter total precipitable water (mm) during the 1978/79 summer season for the synoptic categories: (a) 1A, (b) 1B, (c) 2A, (d) 2B and (e) 3.

STATISTICAL TESTS

The analysis of variance *F*-test and Student's *t*-test are used to establish the statistical significance of differences and similarities between the categories. The results are presented in Table 7.9 below.

Table 7.9 Summary of parametric (<i>F</i> and <i>t</i>) test results for the parameter total precipitable water					
Analysis of variance					
CATEGORIES INCLUDED	<i>F</i> calculated	<i>F</i> _{0,05}	<i>F</i> _{0,01}	<i>F</i> _{0,005}	RESULT
ALL	35,096	2,46	3,51	3,95	SD(>0,05%)
Student's <i>t</i> -test					
CATEGORY	1B	2A	2B	3	
1A	SD(0,1)	SD(2,5)	NSD	SD(0,1)	
1B		SD(0,1)	SD(2,5)	SD(0,1)	
2A			NSD	SD(0,1)	
2B				SD(0,1)	

DISCUSSION

The variance ratio test shows that differences between all groups are highly significant with the calculated *F* value being exceptionally large. The Student's *t*-test indicates that these differences exist between nearly all possible combinations of categories. The categories, in general, have dissimilar atmospheric moisture characteristics. Type 3 has a significantly lower mean than all other categories at >0,1% level and category 1B has

a mean that is higher than the other synoptic types at $>2,5\%$ level of significance. As in the case with mean daily rainfall, although the differences between the means of 2A and 2B are not significant the mean of the latter is marginally higher which shows that the weak subtropical trough does serve to augment atmospheric moisture. These findings, with regard to the parameter total precipitable water, indicate that anomalies observed in the precipitation characteristics of the various categories are caused by atmospheric moisture and wind field peculiarities rather than differences in environmental instability as indicated by the Showalter index. In addition, the analyses show most conclusively that the categories defined by the synoptic systems classification scheme are associated with moisture regimes that are significantly different.

c) Total Static Energy.

The importance of using vertical profiles of total static energy rather than some absolute energy value when considering the energy characteristics of the storm environment was discussed in chapter four. Total static energy has been computed for the 800, 700, 600, 500, 400 and 300 mb pressure levels for each of the 112 days on which upper-air ascents were made at Bethlehem during the 1978/79 summer season. For each standard level the mean value of total static energy was computed for each of the categories defined by the synoptic systems classification scheme and the resulting energy profiles are shown in Fig. 7.6. In order to facilitate consideration of the relative importance of the moisture component (Lq) and the other terms ($CpT+gZ$), the profiles of latent enthalpy and thermo-geopotential energy are presented in Figs. 7.7 and 7.8.

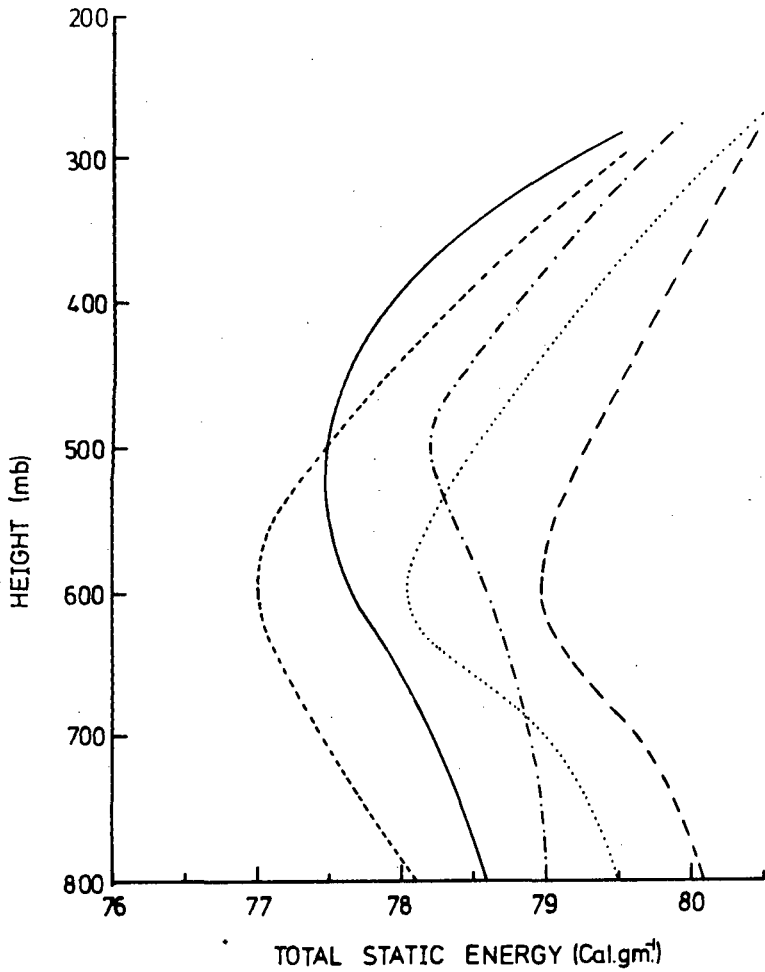


Fig. 7.6 Vertical profiles of total static energy, as derived from Bethlehem's upper-air data during the 1978/79 summer season, for the synoptic categories:

- (a) 1A,
- (b) - - - - 1B,
- (c) ———— 2A,
- (d) - · - · - 2B, and
- (e) - - - - 3.

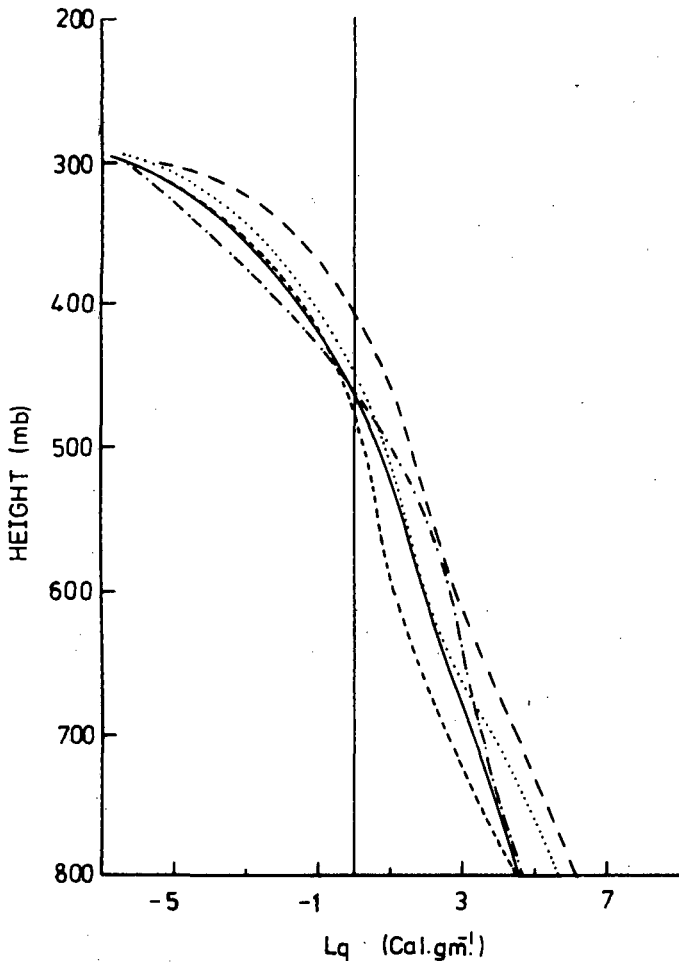


Fig. 7.7 Vertical profiles of latent enthalpy (Lq), as derived from Bethlehem's upper-air data during the 1978/79 summer season, for the synoptic categories:

- (a) 1A,
- (b) - - - - 1B,
- (c) ———— 2A,
- (d) - · - · - 2B, and
- (e) - - - - 3.

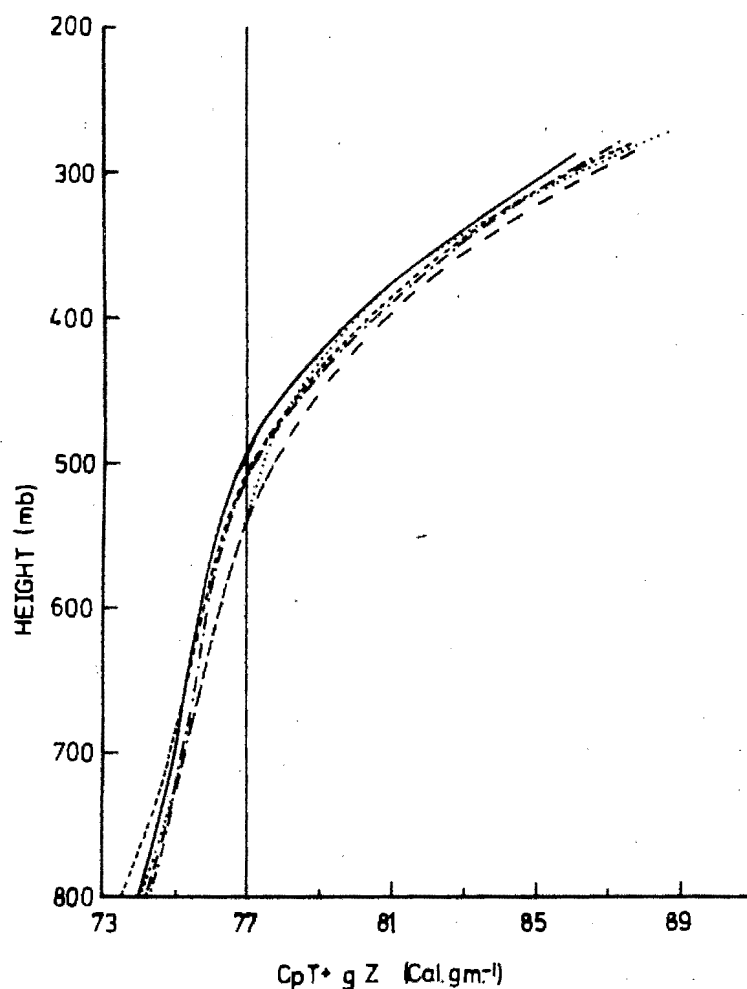


Fig. 7.8 Vertical profiles of thermo-geopotential energy (C_pT+gZ), as derived from Bethlehem's upper-air data during the 1978/79 summer season, for the synoptic categories:

- (a) 1A,
- (b) - - - - 1B,
- (c) _____ 2A,
- (d) - · - · - 2B, and
- (e) - - - - - 3.

DISCUSSION

Differences in the shape and location of the static energy profiles are visually spectacular. Comparison of Figs. 7.7 and 7.8 reveal that these differences are caused primarily by moisture anomalies. It would be desirable to conduct some multivariate analysis on the data in order to verify these differences statistically. However, such an examination, because of the intricacies involved, would constitute a study of its own and hence makes performing therefore impossible within logistical time constraints.

The relative importance of convective and cyclonic processes in weather phenomena is reflected in the vertical distribution of total static energy. The 550 mb level has been chosen arbitrarily to divide the upper and lower

troposphere. Profiles associated with types 2A and 2B have greatest energy deficits in the upper troposphere. Their minima are both at 500 mb, about 100 mb lower than both tropical-disturbance situations. The environmental energy conditions accompanying categories 2A and 2B favour severe storm development. Convective storms attending these situations will have strong updrafts and downdrafts, intense precipitation and high probability of hail. This finding harmonizes with results of previous analyses in connection with hail events. It is noteworthy that category 2B has higher absolute values of total energy than 2A. The latent enthalpy (Lq) curve and the graph of C_pT+gZ indicate that this difference is caused by a greater moisture component in the former. This observation correlates well with findings deduced from analyses of total precipitable water. The structures of the total energy profiles of the synoptic categories 1A and 1B are similar, with type 1B having marginally higher absolute energy values. In both categories energy deficits are concentrated in the region below 550 mb. Convection will therefore be less vigorous than that associated with temperate disturbances but rainfall will nevertheless be high because moisture is abundant. Type 1B is considerably warmer and more moist at middle levels (500 - 600 mb) than 1A which is significant since stratiform rain decks, which require warm, moist air at those levels to form, tend to occur under 1B conditions. Although the energy profile of category 3 resembles those of types 1A and 1B, consideration of the latent enthalpy and thermo-geopotential energy graphs show clearly that the factors giving rise to the energy profiles are vastly different. In the first instance, absolute energy values are much lower in the case of category 3. In addition, Fig. 7.7 indicates that the energy deficit below 500 mb is due to excessive drying in this region. Also, the energy curve intersects a line extending vertically from the 800 mb value at 450 mb, a level much lower than in the other categories. This energy surplus in the upper-troposphere is caused by adiabatic warming of these layers through subsidence, thereby promoting stability and

inhibiting convection. Therefore, to have cumulus cloud development under type 3 conditions, warming aloft must be compensated for by intense surface heating and the supply of atmospheric moisture must be adequate.

Analyses of the parameters Showalter index, total precipitable water and total static energy indicate that natural variability within the set of convective events as reflected in the storm environment can be significantly reduced by application of the synoptic systems classification scheme.

4. Discriminant analysis.

Following several computer runs using the *direct* method, the *stepwise* procedure employing, largest minimum between-groups F equivalent to minimum Wilks' λ) as the selection criterion is applied to the set of parameters and computed indices defined in chapter four and derived from the 0700 GMT radiosonde ascent made daily at Bethlehem. To ensure a 1% level of significance for the analysis an F to enter value of 2,4 is utilized. Firstly, the analysis determines the set of variables which discriminates most effectively between the categories defined by the synoptic systems classification scheme. The parameters and computed indices chosen, in order of entry and hence discriminating power, are:

- i) total precipitable water,
- ii) potential temperature difference between 800 mb and 300 mb,
- iii) wind speed at 600 mb,
- iv) surface mixing ratio,
- v) total static energy at 500 mb,

- vi) maximum temperature predicted,
- vii) relative humidity difference between 800 mb and 500 mb,
- viii) relative humidity at 500 mb,
- ix) wind direction at 700 mb, and
- x) temperature at 500 mb.

In addition to selecting the set of variables with greatest discriminating power the analysis also computes the multivariate F matrices associated with each entered variable. These matrices (Table 7.10) indicate the relative importance of the particular variable in discriminating between any two of the given categories. Larger F denotes greater discriminating power.

Table 7.10 Multivariate F matrices for the variables chosen by the discriminant analysis technique as those with the greatest discriminating power.					
VARIABLE	CATEGORY	1A	1B	2A	2B
TOTAL PRECIPITABLE WATER	1B	15,7			
	2A	8,4	35,7		
	2B	0,1	4,4	4,5	
	3	65,5	114,2	11,3	19,8
POTENTIAL TEMPERATURE DIFFERENCE BETWEEN 800 mb AND 300 mb.	1B	8,6			
	2A	16,4	32,3		
	2B	3,6	7,5	2,4	
	3	38,9	65,5	8,5	10,2
WIND SPEED AT 600mb	1B	5,9			
	2A	12,4	23,7		
	2B	2,7	5,7	1,6	
	3	38,7	54,9	8,0	8,3
SURFACE MIXING RATIO	1B	4,7			
	2A	10,4	17,8		
	2B	6,6	6,9	3,0	
	3	28,8	41,5	7,9	11,7
TOTAL STATIC ENERGY AT 500 mb	1B	4,2			
	2A	9,5	16,5		
	2B	5,6	6,4	2,4	
	3	22,9	33,0	8,5	9,8
MAXIMUM TEMPERATURE PREDICTED	1B	5,1			
	2A	9,3	13,6		
	2B	4,7	5,4	2,1	
	3	20,2	27,4	7,1	8,1

Table 7.10 (continued...)

VARIABLE	CATEGORY	1A	1B	2A	2B
RELATIVE HUMIDITY DIFFERENCE BETWEEN 800 mb and 500 mb	1B	4,8			
	2A	9,5	11,8		
	2B	4,1	4,8	2,5	
	3	17,3	25,5	7,3	6,9
RELATIVE HUMUDITY at 500 mb	1B	5,8			
	2A	9,0	10,4		
	2B	3,5	5,0	2,5	
	3	15,6	20,9	6,4	6,2
WIND DIRECTION AT 700 mb	1B	6,6			
	2A	9,0	9,2		
	2B	3,3	4,5	2,3	
	3	14,6	18,7	5,8	5,5
TEMPERATURE AT 500mb	1B	6,3			
	2A	8,0	8,5		
	2B	4,0	5,9	3,0	
	3	12,0	17,2	5,1	6,0

DISCUSSION

Of the 10 discriminating variables, four are moisture parameters, three are temperature variables, two reflect wind variations and one is an energy parameter. Total precipitable water is the most powerful discriminator between most combinations of categories. Exceptions are 2A and 1A and 2B and 1B where potential temperature difference between 800 and 300 mb is most powerful and 2B and 1A, where the variable with the greatest discriminating power is surface mixing ratio. Moisture parameters are clearly of primary importance in distinguishing between the synoptic categories. Parameters reflecting middle level and low level tropospheric conditions rather than upper-air characteristics discriminate most effectively between the groups. This is noteworthy since variations in the tropospheric environment are most marked below the subsidence inversion located between 450 mb and 550 mb, whereas above this temperature inversion, environmental conditions remain fairly uniform through time.

The discriminant analysis technique also provides for testing the overall ability of the synoptic systems scheme to classify cases (days) into groups that are most distinct statistically. The probability that a particular case belongs to each of the five specified groups is calculated. Based on these probabilities the predicted group membership is computed and then compared to the actual group membership. The predicted group membership is that which will make the groups as statistically different as possible. The results of this analysis is presented in Table. 7.11.

	SYNOPTIC CATEGORY	NUMBER OF DAYS	PREDICTED GROUP MEMBERSHIP				
			1A	1B	2A	2B	3
ACTUAL GROUP MEMBERSHIP	1A	29	25 86,2%	1 3,4%	1 3,4%	2 6,9%	0 0%
	1B	15	3 20%	11 73,3%	1 6,7%	0 0%	0 0%
	2A	15	1 6,7%	0 0%	11 73,3%	0 0%	3 20%
	2B	5	0 0%	0 0%	1 20%	4 80%	0 0%
	3	45	3 6,7%	0 0%	3 6,7%	0 0%	39 86,7%
Percentage of grouped cases correctly classified = 82,57%							

The table shows that the groups most difficult to distinguish between are 2A and 3, 1A and 1B and, 2A and 2B. Types 1A and 1B are both synoptic categories associated with tropical disturbances while synoptic situations involving temperature disturbances are classified into categories 2A and 2B. It is encouraging to find that the greatest degree of 'misclassification' occurs between groups possessing similarities. Predicted group membership corresponds with actual group membership in 82,57% of the

cases. Thus the memberships of the categories, is defined by application of the synoptic systems classification scheme, will be the same as that membership which would make the categories most different from one another, statistically, 82,57% of the time. Discrimination analysis shows that naturally occurring variations in weather conditions in the BEWMEX area, as reflected by the set of parameters and indices measuring moisture, temperature, energy and wind flow overhead Bethlehem, can be reduced to a large degree through classification by means of the synoptic systems classification scheme.

5. Cloud base temperature: an indicator of cumulus cloud seedability.

In the BEWMEX area cumulus clouds have typically continental cloud condensation nuclei concentrations (Lyons, 1979). Analyses of droplet evolution spectra at 500 m above cloud base reveal a narrow distribution of droplet sizes and an abundance of small drops (Shaw *et al*, 1979). Cloud base temperature can therefore be used as an indicator of cumulus cloud colloidal instability and hence also of response to ice-nuclei seeding. The potential of the synoptic systems scheme to classify convective events into categories of significantly different cloud base temperature conditions will be investigated by statistical analysis of data from the summer of 1978/79. The distribution of cloud base temperature by classes for each synoptic category is given in Table 7.12 and depicted graphically in Fig. 7.9.

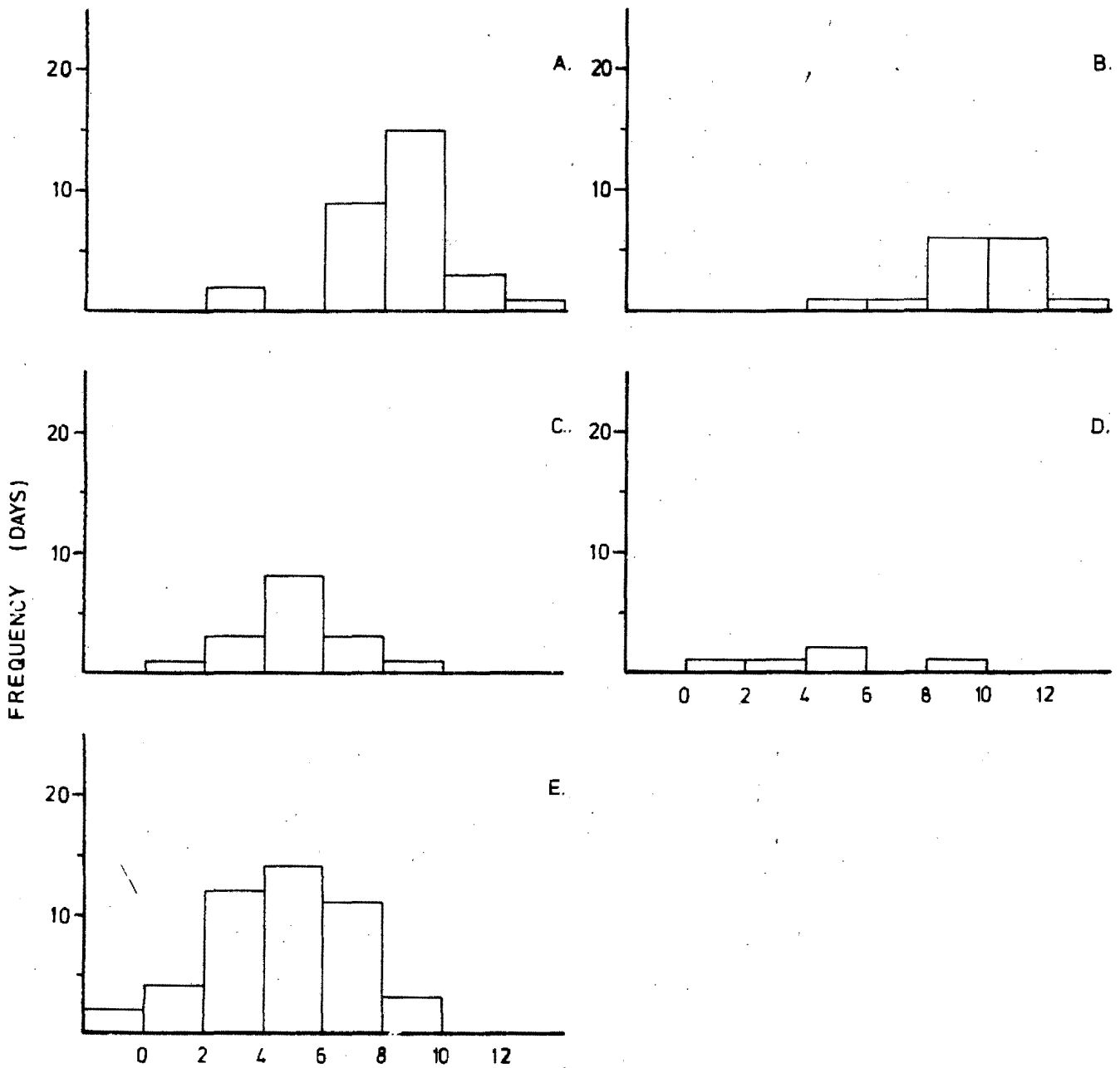


Fig. 7.9 Histograms depicting the distribution of the parameter cloud base temperature ($^{\circ}\text{C}$) during the 1978/79 summer season for the synoptic categories: (a) 1A, (b) 1B, (c) 2A, (d) 2B, and (e) 3.

CATEGORY	CLOUD BASE TEMPERATURE (x) in °C								TOTAL	MEAN.
	x ≤ 0	0 < x ≤ 2	2 < x ≤ 4	4 < x ≤ 6	6 < x ≤ 8	8 < x ≤ 10	10 < x ≤ 12	x > 12		
1A	0	0	2	0	9	15	3	1	30	8,3800
1B	0	0	0	1	1	6	6	1	15	9,7533
2A	0	1	3	8	3	1	0	0	16	5,2250
2B	0	1	1	2	0	1	0	0	5	3,8500
3	2	4	12	14	11	3	0	0	46	4,8870

STATISTICAL TESTS

Results of the variance ratio (F) test and Student's *t*-test are presented in Table 7.13. These tests determine the statistical significance of differences that exist between the categories of the synoptic systems classification scheme.

Analysis of variance					
CATEGORIES INCLUDED	F calculated	F _{0,05}	F _{0,01}	F _{0,005}	RESULT
ALL	21,619	2,46	3,51	3,95	SD(>0,5%)
2A,2B,	0,315	4,38	8,18	10,07	NSD
2A,2B,3	0,174	3,15	4,98	5,79	NSD
Student's <i>t</i> -test					
CATEGORY	1B	2A	2B	3	
1A	SD(5)	SD(0,1)	SD(0,1)	SD(0,1)	
1B		SD(0,1)	SD(0,1)	SD(0,1)	
2A			NSD	NSD	
2B				NSD	

DISCUSSION

The F-test when applied to all groups shows that differences between the groups are significant at $>0,5\%$ level but between the categories 2A, 2B and 3 there are no significant differences with respect to cloud base temperature. It is evident therefore that greatest differences occur between categories involving tropical temperate and local disturbances rather than within these major divisions. The Student's t -test results substantiate this view. No significant differences exist between the means of any combination of the categories 2A, 2B and 3. In addition the synoptic situations 1A and 1B have significantly warmer cloud base temperature conditions than the other categories. However this does not necessarily mean that cumulus storms occurring under conditions accompanying the synoptic categories 2A, 2B and 3 will provide more rainfall when seeded. Other considerations, regarding horizontal convergence, environmental instability and vertical energy gradients, show that the cumuli associated with categories 2A and 2B are not suitable candidates for treatment with artificial ice-nuclei. The synoptic situation generating cumulus clouds that may respond favourably to ice-nuclei seeding is therefore type 3.

B. EVALUATION

The synoptic systems scheme attempts to achieve the objectives of classification by stratifying the convective events into categories possessing significantly different physical and dynamical characteristics. Consideration of the meteorological processes associated with these categories suggests that differences in precipitation regimes, storm environment characteristics and cumulus cloud base temperature

Parameter	test	Category												F test results							
		1A		1B		2A		2B		3											
		G.T.	L.T.	G.T.	L.T.	G.T.	L.T.	G.T.	L.T.	G.T.	L.T.	G.T.	L.T.		1A	1B	2A	2B	3		
Precipitation Daily Rainfall	t	1A	-	-	1A	X		1A			1A			X	Differences Signif.	X	X	X	X	X	
		1B		X	1B	-	-	1B		X	1B			X							
		2A			2A	X		2A	-	-	2A			X	Differences not Signif.						
		2B			2B			2B			2B	-	-	X							
		3	X		3	X		3	X		3	X		3		-	-				
Storm Environment Showalter Index Total Precipitable Water Total Static Energy	t	1A	-	-	1A			1A			1A		X	Differences Signif.	X	X	X	X	X		
		1B			1B	-	-	1B			1B		X					X	X	X	
		2A			2A			2A	-	-	2A		X		Differences not Signif.			X	X		
		2B			2B			2B			2B	-	-								
		3			3			3			3			3		-	-	X	X		
	t	1A	-	-	1A	X		1A		X	1A			X	Differences Signif.	X	X	X	X	X	
		1B		X	1B	-	-	1B		X	1B		X	X							
		2A	X		2A	X		2A	-	-	2A			X	Differences not Signif.						
		2B			2B	X		2B			2B	-	-	X							
		3	X		3	X		3	X		3	X		3		-	-				
Profiles	Profiles																				
		t	1A	-	-	1A	X		1A		X	1A			X	Differences Signif.	X	X	X	X	X
			1B		X	1B	-	-	1B		X	1B		X	X						
			2A	X		2A	X		2A	-	-	2A			X	Differences not Signif.					
			2B			2B	X		2B			2B	-	-	X						
3	X		3	X		3	X		3	X		3	-	-							
Seedability Cloud Base Temperature	t	1A	-	-	1A	X		1A		X	1A		X	Differences Signif.	X	X	X	X	X		
		1B		X	1B	-	-	1B		X	1B		X		X						
		2A	X		2A	X		2A	-	-	2A			X	Differences not Signif.			X	X	X	
		2B	X		2B	X		2B			2B	-	-								
		3	X		3	X		3			3			3		-	-				

Fig. 7.14 Summary of statistically significant differences between the categories defined by the synoptic systems classification scheme. (G.T.≡ greater than, L.T.≡ less than.)

conditions can be expected to exist between the categories. In this chapter the existence of these differences and their statistical significance have been determined by a number of analytical techniques. Examination of the parameters mean daily rainfall, hailfall, Showalter index, total precipitable water, total static energy and cloud base temperature indicate that differences do, in fact, exist and are statistically significant in most cases. The results of these analyses are presented, in summarized form, in Table 7.14. Only those differences verified by statistical tests to be significant are noted in the table. The table indicates that the synoptic systems classification scheme is particularly effective in identifying situations of diverse moisture, energy, cloud base temperature and horizontal convergence conditions. All these factors directly affect cumulus cloud characteristics and their response to ice-nuclei seeding. Discriminant analysis confirms that the scheme classifies convective events into categories that are significantly different. Two shortcomings of the synoptic systems classification scheme are discernible. Firstly, the criteria of the scheme do not enable selection of individual cumuli for observation or seeding on a particular day. In this regard, the shape, vertical dimensions and stage of development of the clouds are of importance. It is therefore necessary that a set of selection criteria, such as that in Appendix A, be used in conjunction with the scheme so that cumuli suitable for observation and/or seeding can be identified. Secondly, the scheme does not eliminate days on which cumulus cloud tops do not extend vertically above the -5°C level and days with stratiform rains from the set of experimental units. This would be necessary if cumulus clouds are the only candidates for modification. This problem can be overcome by incorporation of certain features of the weather type classification scheme, which are established following the examination of this scheme in the next chapter.

CHAPTER 8

STATISTICAL EXAMINATION AND EVALUATION OF THE
WEATHER TYPE CLASSIFICATION SCHEME

The weather type classification scheme, defined in chapter three, is presently being used on the Bethlehem Weather Modification Experiment to categorize experimental days. The scheme endeavours to reduce natural variability by differentiating, firstly, between convective events and stratiform rain days and secondly, between significant and unsubstantial convective activity. Days with significant convection (cloud tops colder than -5°C) are sub-divided further into three categories corresponding to weak, moderate and strong cumulus development. The extent to which the scheme attains the principal objectives of classification (chapter 1) by defining categories possessing significantly different physical characteristics is examined statistically in this chapter. The distribution of the parameters mean daily rainfall, Showalter index, total precipitable water, total static energy and cloud base temperature for the 1978/79 summer season are analysed by the statistical techniques used to examine the synoptic systems scheme. It is important to note that the observed weather types and not the forecast weather types for each day are used in the analysis. According to Hudak and Steyn (1980), during the 1977/78 summer 80% of type I forecasts were correct, 17% of type II, 68% of type IV, 78% of type V and 62% of type VI, which represents an overall accuracy of 73%. Thus, findings of the statistical investigation will pertain specifically to the usefulness of the weather type scheme in post-event analysis. For the purposes of the examination the weather types are grouped into five categories as follows: I/II, IV, V, Vs and VI.

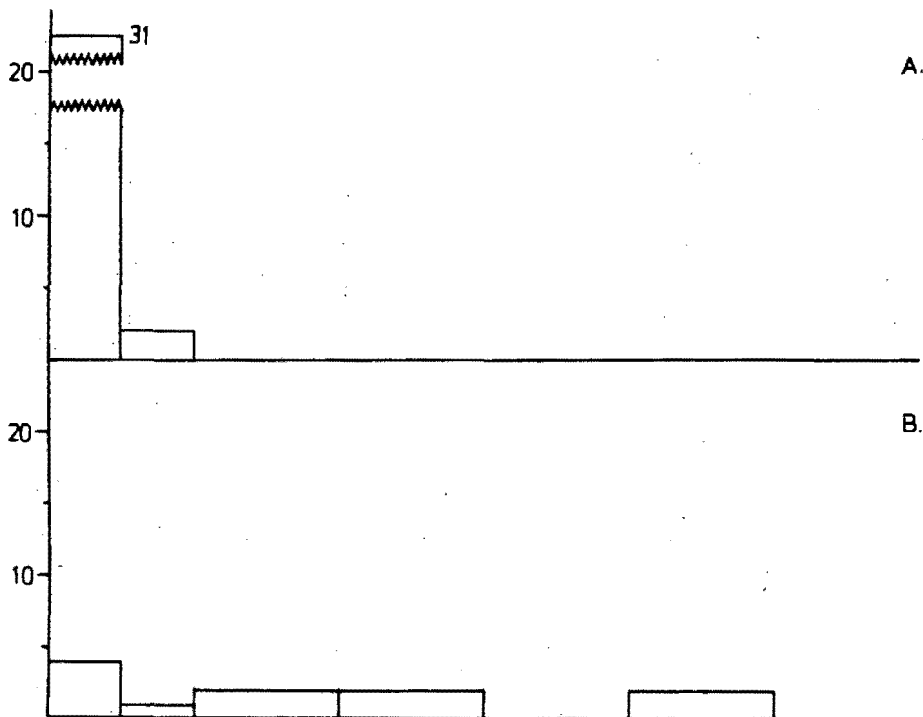
A. STATISTICAL EXAMINATION

1. The precipitation regime.

a) Mean daily rainfall.

Of the 182 days during the summer of 1978/79, 135 were experimental days. The distribution of mean daily rainfall by classes for each weather type is presented in Table 8.1 and the corresponding histograms are shown in Fig. 8.1.

WEATHER TYPE	MEAN DAILY RAINFALL (x) in mm							TOTAL	MEAN
	$x < 1$	$1 \leq x < 2$	$2 \leq x < 4$	$4 \leq x < 6$	$6 \leq x < 8$	$8 \leq x < 10$	$x \geq 10$		
I/II	31	2	0	0	0	0	0	33	0,2314
IV	4	1	2	2	0	2	0	11	3,5722
V	17	15	9	2	0	1	0	44	1,4630
Vs	13	2	1	1	0	0	0	17	0,8053
VI	1	4	7	5	5	3	5	30	6,3618



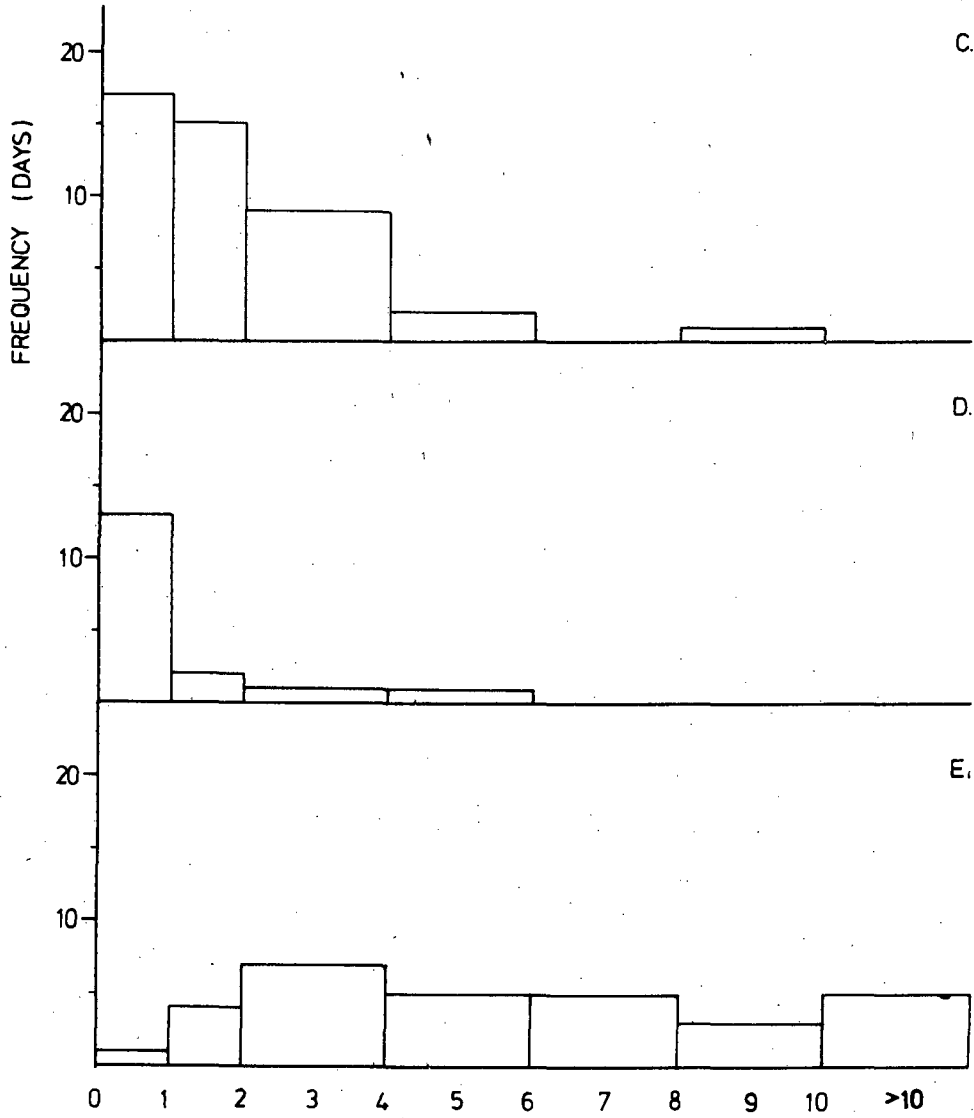


Fig. 8.1 Histograms depicting the distribution of the parameter mean daily rainfall (mm) during the 1978/79 summer season for the weather types: (a) I/II, (b) IV, (c) V, (d) Vs and (e) VI.

STATISTICAL TESTS

Results of the variance ratio (F) and Student's t -test on differences between the category means are presented in Table 8.2

Table 8.2 Summary of parametric (F and t) test results for the parameter mean daily rainfall.					
Analysis of variance					
WEATHER TYPES INCLUDED	F calculated	$F_{0,05}$	$F_{0,01}$	$F_{0,005}$	RESULT
ALL	26,72	2,44	3,15	3,92	SD (>0,5%)

	Student's t -test			
WEATHER TYPE	I/II	IV	V	Vs
IV	SD(0,1)			
V	SD(0,1)	SD(0,1)		
Vs	SD(0,1)	SD(0,1)	NSD	
VI	SD(0,1)	NSD	SD(0,1)	SD(0,1)

DISCUSSION

Both the F and t -tests indicate that, in general, the categories of the weather type scheme have significantly different rainfall characteristics. Type I/II has a significantly lower mean than all the other categories due to the fact that the convective clouds on these days produce little or no rainfall. However, the differences between the means of the hailfall category (VI) and the stratiform rain type (IV) is not significant. Within the categories of active convection (V, Vs and VI) differences are statistically significant except for that between V and Vs. The classification scheme reduces natural variance as indicated by mean daily rainfall within the set of experimental days.

2. Storm environment characteristics.

Of the 135 days during the summer of 1978/79 that were classified according to the weather type scheme, 0700GMT upper-air data for Bethlehem, from which the parameters Showalter index, total precipitable water and total static energy are calculated, is available on 131 days.

The distribution of the parameter Showalter index by classes is given in Table 8.3 and Fig. 8.2.

WEATHER TYPE	SHOWALTER INDEX (x)							TOTAL	MEAN
	$x \leq -5$	$-5 < x \leq -3$	$-3 < x \leq -1$	$-1 < x \leq 1$	$1 < x \leq 3$	$3 < x \leq 5$	$x > 5$		
I/II	0	1	5	9	9	5	4	33	1,6303
IV	0	1	5	3	2	0	0	11	-1,2273
V	1	10	17	9	7	0	0	44	-1,6341
Vs	0	3	2	7	2	0	0	14	-0,8714
VI	4	9	11	4	1	0	0	29	-2,9103
TOTAL	5	24	40	32	21	5	4	131	-

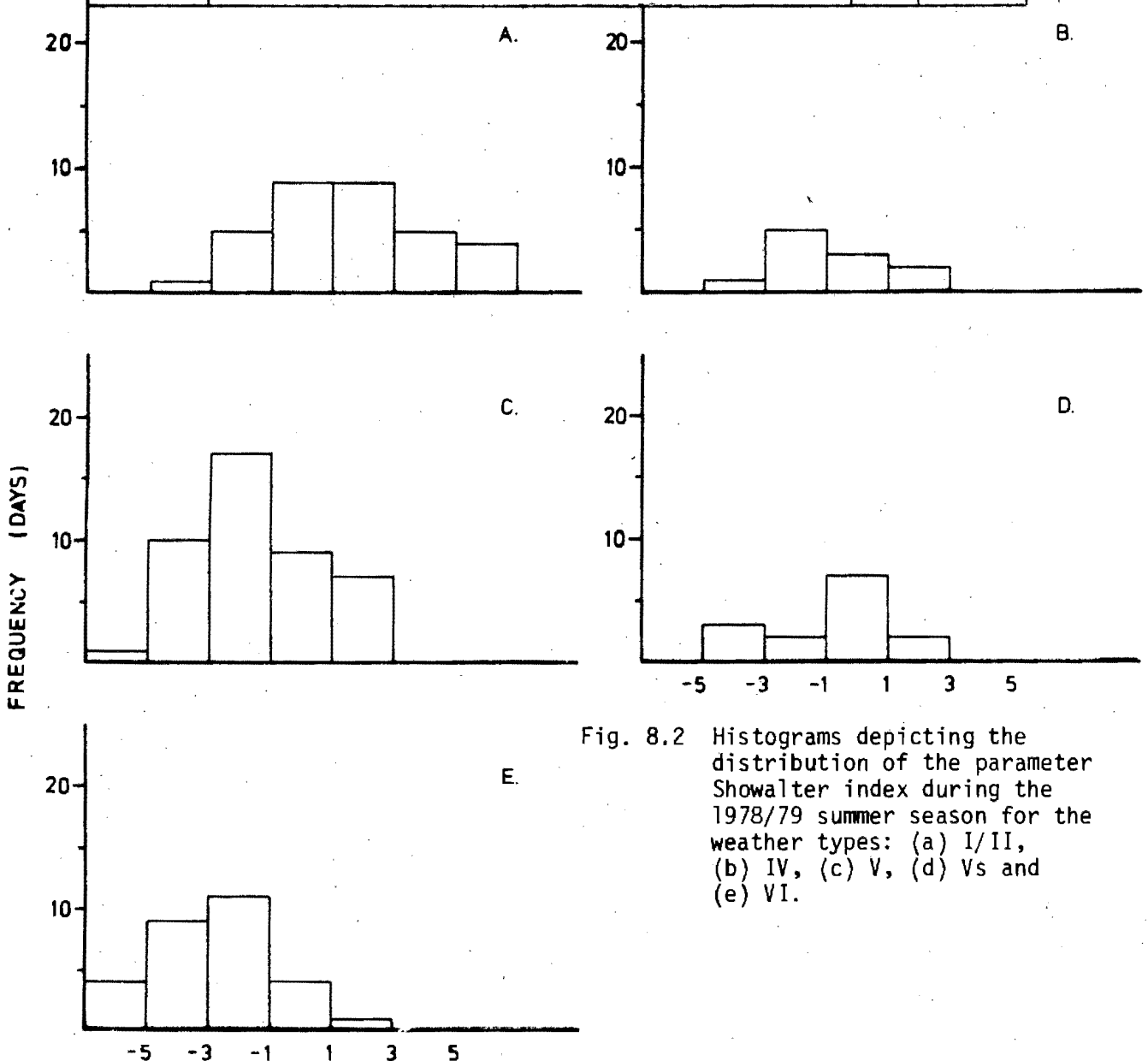


Fig. 8.2 Histograms depicting the distribution of the parameter Showalter index during the 1978/79 summer season for the weather types: (a) I/II, (b) IV, (c) V, (d) Vs and (e) VI.

STATISTICAL TESTS

Statistical test results using the parametric *F* and *t* tests are presented in Table 8.4.

Table 8.4 Summary of parametric (<i>F</i> and <i>t</i>) test results for the parameter Showlater index.					
Analysis of variance					
WEATHER TYPES INCLUDED	F calculated	F _{0,00}	F _{0,01}	F _{0,005}	RESULT
ALL	16,92	2,44	3,47	3,91	SD(>0,5%)
V, Vs, VI	5,62	3,11	4,88	5,68	SD(>1,0%)
Student's <i>t</i> -test					
WEATHER TYPE	I/II	IV	V	Vs	
IV	SD(0,1)				
V	SD(0,1)	NSD			
Vs	SD(0,1)	NSD	NSD		
VI	SD(0,1)	SD(5)	SD(5)	SD(0,1)	

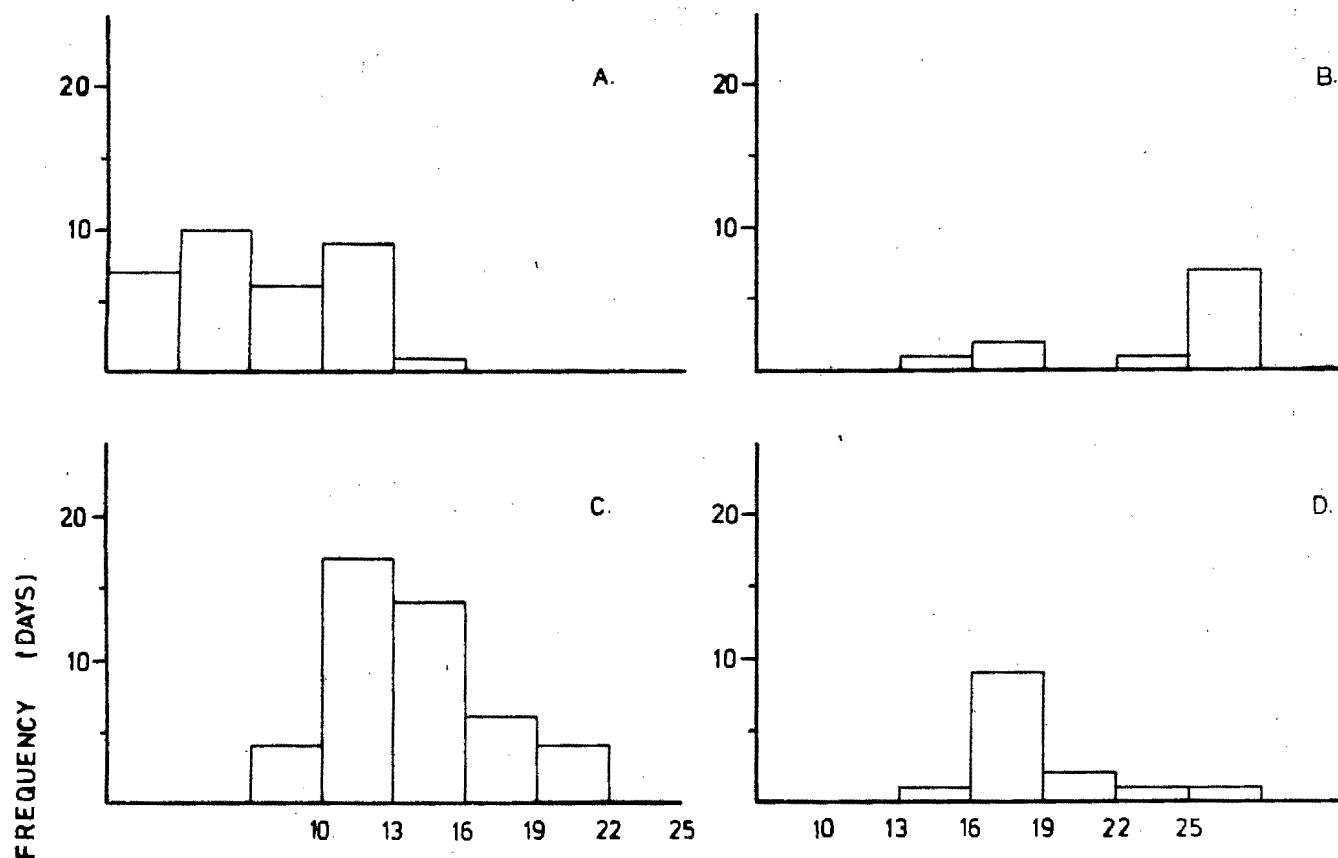
DISCUSSION

The weather situations associated with little or no convection (I/II) and strong convective activity (VI) have mean Showalter index values that are respectively higher and lower than the other categories. No significant differences exist between the means of any combination of the categories IV, V and Vs. It is unusual that stratiform rain situations should possess environmental stability conditions that are similar to those associated with convective events.

b) Total precipitable water.

The distribution of total precipitable water, a parameter in which indicates the quantity of moisture in the atmosphere available for rainfall production, is tabulated below (Table 8.5) and presented graphically in Fig. 8.3.

WEATHER TYPE	TOTAL PRECIPITABLE WATER (x) IN mm							TOTAL	MEAN
	$x < 10$	$10 \leq x < 13$	$13 \leq x < 16$	$16 \leq x < 19$	$19 \leq x < 22$	$22 \leq x < 25$	$x \geq 25$		
I/II	7	10	6	9	1	0	0	33	12,9258
IV	0	0	1	2	0	1	7	11	24,5509
V	0	0	4	17	14	6	4	43	19,7807
Vs	0	0	1	9	2	1	1	14	18,5450
VI	0	0	2	6	9	11	1	29	20,8386
TOTAL	7	10	14	43	26	19	13	130	-



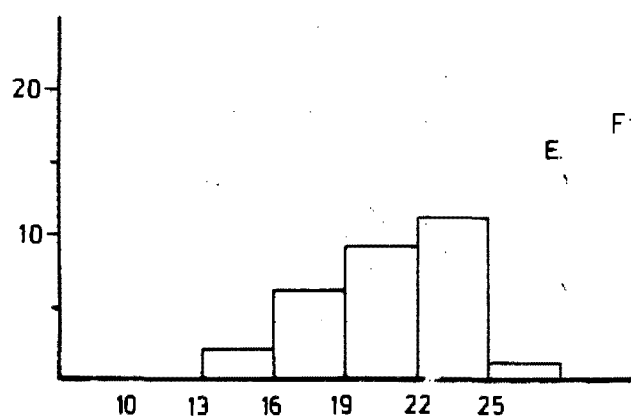


Fig. 8.3 Histograms depicting the distribution of the parameter total precipitable water (mm) during the 1978/79 summer season for the weather types: (a) I/II, (b) IV, (c) V, (d) Vs and (e) VI.

STATISTICAL TESTS

The statistical significance of differences between the categories are established by test carried out using the variance ratio (F) and t statistics. The results are presented in Table 8.6.

Analysis variance					
WEATHER TYPES INCLUDED	F calculated	$F_{0,05}$	$F_{0,01}$	$F_{0,005}$	RESULT
ALL	36,73	2,44	3,47	3,91	SD(>0,50%)
V, Vs, VI	2,84	3,11	4,88	5,68	NSD
Student's t -test					
WEATHER TYPE	I/II	IV	V	Vs	
IV	SD(0,1)				
V	SD(0,1)	SD(0,1)			
Vs	SD(0,1)	SD(0,1)	NSD		
VI	SD(0,1)	SD(0,1)	NSD	SD(5)	

DISCUSSION

An analysis of variance test on all five groups shows that differences between the categories are highly significant. Further analysis on the groups V, Vs and VI shows that differences are most significant between the major divisions I/II, IV and the groups representing active convection (V, Vs and VI) and that differences within the group of categories V, Vs and VI are minimal. This finding is substantiated by the results of the Student's t -test. The stratiform rain category (IV) has a significantly higher mean precipitable water than the other four weather types. Similarly the convection-free category (I/II) has a significantly lower mean than the other groups. With regard to the categories of active convection, apart from a weakly significant difference between Vs and VI (at the 5% level), differences between the means of any combination of the categories V, Vs and VI are non-significant.

c) Total static energy

The vertical profiles of total static energy (Fig. 8.4) indicate that the categories with the most distinctive energy characteristics are I/II and IV. Category I/II is different from V, Vs and VI in that the area enclosed by a line extending vertically from the 800 mb value and the curve is small and the energy curve cuts this line at a low pressure level (500 mb). The principal distinguishing feature between the category I/II and type IV is the difference in absolute energy values. In its turn category IV is different from the groups V, Vs and VI for the same reasons that type I/II is different from these groups. The groups of active convection differ from the categories I/II and IV as described above, but show very little diversity between one another. All three have large areas enclosed by the curve and a vertical line from the 800 mb energy value and similar absolute energy values (especially V and VI). In addition shapes of the graphs for V and VI are almost identical.

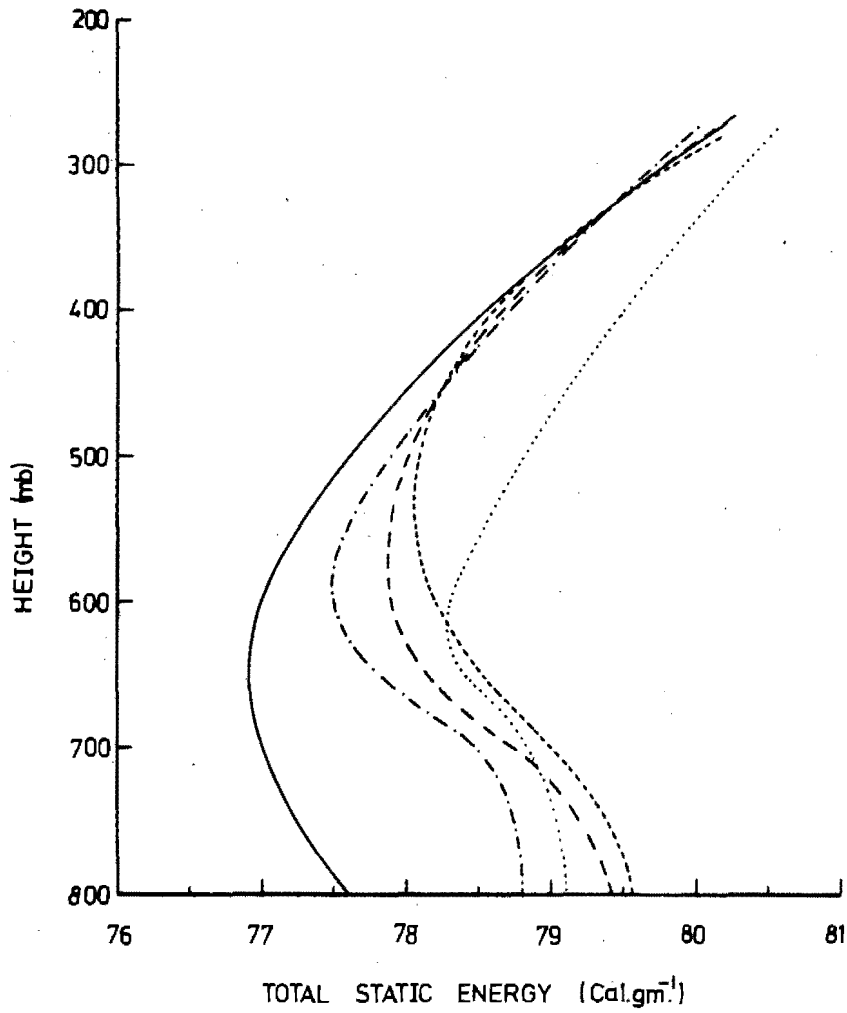


Fig. 8.4 Vertical profiles of total static energy, as derived from Bethlehem's upper-air data during the 1978/79 summer season, for the weather types:

- (a) ————— I/II,
- (b) IV,
- (c) - - - - - V,
- (d) - · - · - Vs, and
- (e) - - - - - VI.

Analysis of the parameters Showalter index, total precipitable water and total static energy, measures of environmental stability, moisture and energy characteristics show that the greatest differences exist between the primary divisions of the weather type scheme and that differences between categories within these divisions are minimal.

3. Discriminant Analysis.

The set of variables and computed indices, derived from 0700 GMT surface and upper-air data each day at Bethlehem, employed in the testing of the synoptic systems scheme, is used to investigate the effectiveness with which the weather type scheme stratifies experimental units into its various categories. Discriminant analysis is performed on the data using the weather types I/II, IV, V, Vs and VI as the pre-determined groups. To ensure a significance level of 1% in the analysis, an *F to include* value of 2.4 is utilized. Using the *stepwise* method and minimum Wilks' lambda as selection criterion, the following set of variables are chosen as the most effective discriminators:

- i) Total precipitable water,
- ii) total totals index,
- iii) maximum temperature predicted,
- iv) difference between the relative humidity at 800 mb and 300 mb,
- v) difference in total static energy at 700 mb and 500 mb, and
- vi) convective temperature.

The multivariate *F* matrices associated with each of these variables is presented in Table 8.7. These matrices indicate the relative importance of each selected variable in discriminating between any two weather types. Larger *F* denotes greater discriminating power.

Table 8.7		Multivariate F matrices for the variables chosen by the discriminant analysis technique as those with the greatest discriminating power.			
VARIABLE	WEATHER TYPE	I/II	IV	V	Vs
TOTAL PRECIPITABLE WATER	IV	80,0			
	V	72,2	12,6		
	Vs	22,2	18,7	2,9	
	VI	81,0	6,5	1,7	6,9
TOTAL TOTALS INDEX	IV	48,2			
	V	74,3	7,5		
	Vs	20,3	9,3	4,2	
	VI	83,5	6,1	1,8	8,7
MAXIMUM TEMPERATURE PREDICTED	IV	45,5			
	V	49,7	15,7		
	Vs	13,5	16,7	3,1	
	VI	57,6	10,6	1,9	7,2
DIFFERENCE IN RELATIVE HUMIDITY AT 800 mb AND 300 mb	IV	38,7			
	V	37,0	17,1		
	Vs	10,1	17,3	2,4	
	VI	42,9	13,5	1,5	5,4
DIFFERENCE IN TOTAL STATIC ENERGY AT 700 mb AND 500 mb	IV	31,4			
	V	33,4	13,8		
	Vs	10,6	14,0	1,9	
	VI	38,6	11,2	1,3	4,3
CONVECTIVE TEMPERATURE	IV	28,1			
	V	30,6	11,6		
	Vs	11,0	11,6	1,6	
	VI	33,7	9,5	1,1	3,7

DISCUSSION

The set of best discriminators includes two moisture parameters, one measuring absolute conditions (total precipitable water) and one assessing the vertical distribution of humidity (difference in relative humidity at 800 mb and 300 mb). There are two thermal indices, maximum temperature predicted and convective temperature. Two measures of convective potential, the total totals index and static energy difference between 700 mb and 500 mb (similar to Darkow's severe storm index), are among the selected variables. It is noteworthy that no wind field variables are included. Moisture parameters are most important in discriminating between type IV and the other categories. Absolute moisture differences (total precipitable water) are foremost in separating types I/II and Vs from IV whereas the difference in relative humidity between 800 mb and 300 mb is the primary factor in differentiating between category IV and the categories representing moderate to strong convection (V and VI). Category I/II is segregated most effectively by moisture parameters from IV and Vs and by convective potential indicators from V and VI. The principal parameters discriminating between the groups of active convection (V, Vs and VI) are the total totals index and maximum temperature predicted. Both of these are non-moisture parameters. In fact, in the case of category VI, total precipitable water, the primary discriminating parameter, is not the leading discriminator between type VI and any of the other categories. It is noteworthy that the multivariate *F* values associated with types I/II and IV are considerably greater for each discriminating variable than those for the categories V, Vs and VI. This shows that the most heterogeneous categories of the weather type classification scheme are I/II and IV. There is no particular tropospheric level at which several of the discriminating parameters are concentrated as is the case with the synoptic systems scheme. In addition, no wind field parameters are included as powerful discriminating variables. This is consistent with the fact that the weather type scheme

partitions according to observed weather conditions rather than by investigation of the prevailing synoptic situation.

In Table 8.8 the actual group membership is compared to that group membership, predicted by the discriminant analysis, which will force the groups to be as heterogeneous as possible. The predicted group membership is that which maximizes variance between the groups and minimizes variance within the groups, thereby optimally reducing natural variability within the entire set of experimental units (days). Table 8.8 therefore enables examination of the classification scheme's overall ability to stratify experimental units.

Table 8.8 Comparison of actual group membership and predicted group membership for the weather type classification scheme.

WEATHER TYPE	NUMBER of DAYS	PREDICTED GROUP MEMBERSHIP				
		I/II	IV	V	Vs	VI
I/II	32	26 81,3%	0 0%	3 9,4%	3 9,4%	0 0%
IV	10	0 0%	8 80%	1 10%	0 0%	1 10%
V	42	0 0%	2 4,8%	30 71,4%	2 4,8%	8 19,0%
Vs	15	1 6,7%	0 0%	8 53,3%	5 33,3%	1 6,7%
VI	29	0 0%	2 6,9%	17 58,6%	1 3,4%	9 31,0%
Percentage of Grouped Cases Correctly Classified = 60,94%						

Discriminant analysis confirms the results obtained from the parametric F and t tests. Table 8.8 shows that the weather type scheme discriminates most effectively between category I/II and the other categories and type IV and the remaining groups. The analysis indicates that the scheme does not reduce natural variability significantly within the categories of active convection. That is why the greatest degree of 'misclassification' is shown to occur between the weather types V, Vs and VI. Predicted group membership correlates with actual group membership in 60,94% of the cases. Thus the overall ability of the weather type scheme to reduce natural variability by classification does not compare favourably with the competence of the synoptic systems classification scheme to do so.

4. Cloud base temperature: an indicator of Cumulus Cloud Seedability.

The importance of the parameter cloud base temperature in the assessment of ice-nuclei treatment effects has been discussed. The distribution of the parameter cloud base temperature during the summer of 1978/79 by classes for each weather type is given in Table 8.9 and the corresponding histograms are presented in Fig. 8.5.

WEATHER TYPE	CLOUD BASE TEMPERATURE (x) in °C								TOTAL	MEAN (°C)
	$x \leq 0$	$0 < x \leq 2$	$2 < x \leq 4$	$4 < x \leq 6$	$6 < x \leq 8$	$8 < x \leq 10$	$10 < x \leq 12$	$x > 12$		
I/II	3	5	8	4	8	5	0	0	33	4,1424
IV	0	0	0	0	5	2	4	0	11	8,8000
V	0	0	5	11	10	11	6	1	44	6,9523
Vs	0	0	1	4	4	5	0	0	14	6,2571
VI	0	0	3	5	4	10	4	3	29	8,0345
TOTAL	3	5	17	24	31	33	14	4	131	-

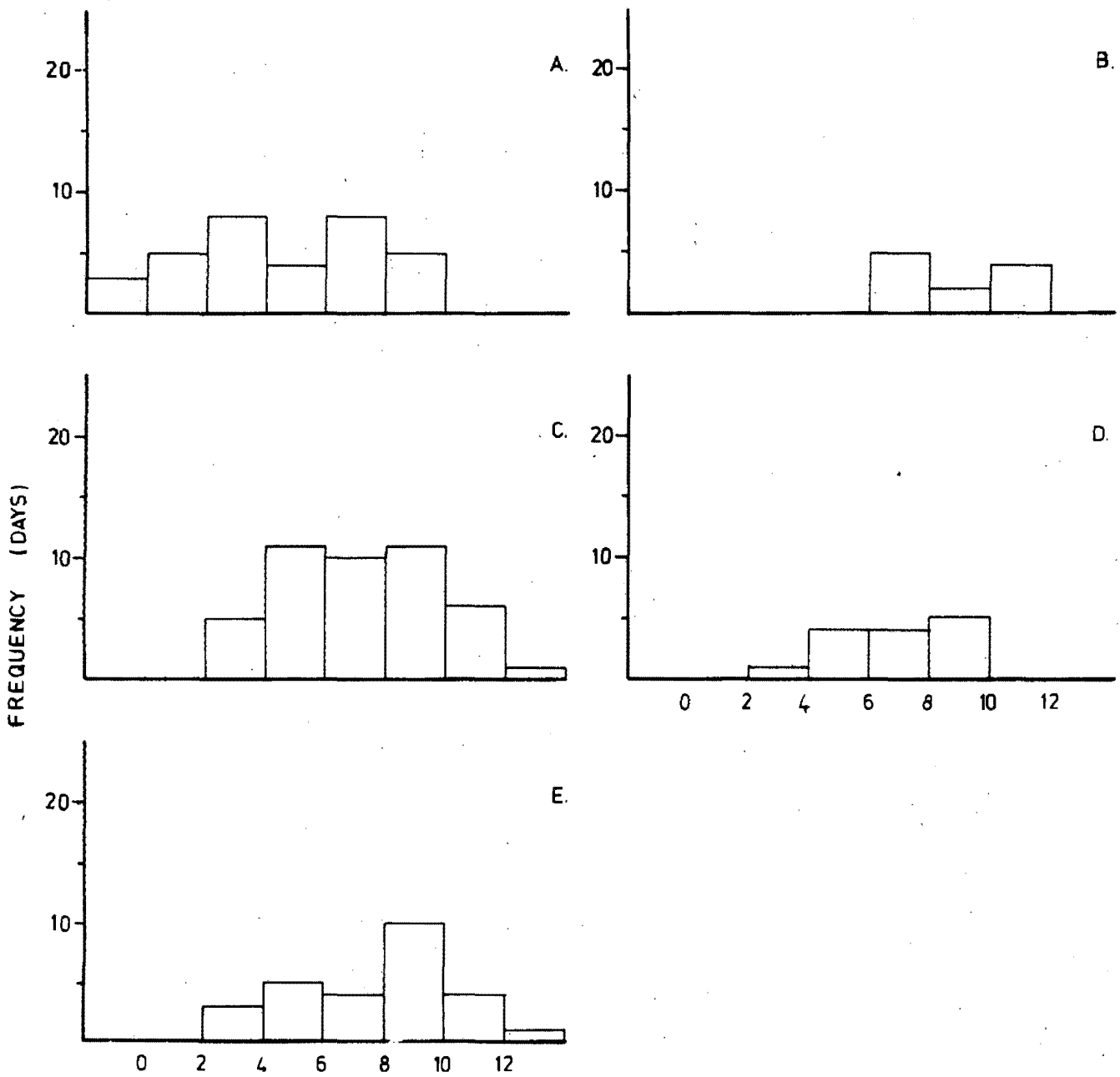


Fig. 8.5 Histograms depicting the distribution of the parameter cloud base temperature ($^{\circ}\text{C}$) during the 1978/79 summer season for the weather types: (a) I/II, (b) IV, (c) V, (d) Vs and (e) VI.

STATISTICAL TESTS

The analysis of variance (F) and Student's t -test are used to examine differences between the categories and the results of these tests are presented in Table 8.10

Table 8.10 Summary of parametric (F and t) test results for the parameter cloud base temperature.					
Analysis of variance					
WEATHER TYPES INCLUDED	F calculated	$F_{0,05}$	$F_{0,01}$	$F_{0,005}$	RESULT
ALL	10,09	2,44	3,47	3,91	SD(>0,5%)
V, Vs, VI	0,58	3,11	4,88	5,68	NSD
Student's t -test					
WEATHER TYPE	I/II	IV	V	Vs	
IV	SD(0,1)				
V	SD(0,1)	SD(5)			
Vs	SD(0,1)	SD(0,1)	NSD		
VI	SD(0,1)	NSD	NSD	SD(5)	

DISCUSSION

When all five categories are considered, the variance ratio test indicates that the differences between the groups are significant. However if categories associated with significant convection (cumulus cloud tops colder than -5°C) are examined then no significant differences are observed between the groups. The Student's t -test shows that the means of the categories display differences in the same manner. Between the categories of active convection (V, Vs and VI) no significant differences exist with regard to the parameter cloud base temperature except for a weakly significant difference between Vs and VI (at the 5% level). The category showing

significantly colder cloud base temperatures, I/II, is automatically excluded when seeding potential is considered since the cumuli associated with this category do not develop above the -5°C level. In addition, type IV is the stratiform rain category and days in this group are excluded from the set of experimental units since BEWMEX is only concerned with cumulus cloud modification.

B. EVALUATION.

The weather type scheme endeavours to accomplish the objectives of classification by partitioning experimental days on the basis of whether:

- i) cumulus clouds do not develop above the -5°C level (Types I and II),
- ii) stratiform rains prevail (Type IV),
- iii) cumulus cloud tops are colder than -5°C (Types V, Vs and VI).

The classification criteria suggest that these primary divisions should manifest significant differences between one another with regard to environmental stability, moisture and energy characteristics. Analyses of the parameters Showalter index, total precipitable water and total static energy confirm that these differences do exist (Table 8.11). Discriminant analysis reveals that the scheme differentiates most effectively between category I/II and the remaining categories, and type IV and the other groups. By classifying experimental days into one of these primary divisions the weather type scheme reduces natural variability to some degree and, with regard to the design and evaluation of seeding strategies, isolates types V, Vs and VI (cumulus cloud tops colder than -5°C) for consideration. It is this feature of the weather type scheme that will be

Parameter	test	Category												F test results																		
		I/II		IV		V		Vs		VI																						
		G.T.	L.T.	G.T.	L.T.	G.T.	L.T.	G.T.	L.T.	G.T.	L.T.	G.T.	L.T.	I/II	IV	V	Vs	VI														
Precipitation	Mean Daily Rainfall	t	I/II	-	-	I/II	X		I/II	X		I/II	X		I/II	X								Differences Signif.	X	X	X	X	X			
			IV		X	IV	-	-	IV		X	IV		X	IV																	
			V		X	V	X		V			V			V	X																
			Vs		X	Vs	X		Vs			Vs	-	-	Vs	X																
			VI		X	VI			VI		X	VI		X		-	-															
Storm Environment	Showalter Index	t	G.T.	L.T.	G.T.	L.T.	G.T.	L.T.	G.T.	L.T.	G.T.	L.T.	G.T.	L.T.	I/II	IV	V	Vs	VI	Differences Signif.	X	X	X	X	X							
			I/II	-	-	I/II		X	I/II		X	I/II		X	I/II		X															
			IV	X		IV	-	-	IV			IV			IV		X															
			V	X		V			V	-	-	V			V		X															
			Vs	X		Vs			Vs			Vs	-	-	Vs		X															
	Total Precipitable Water	t	G.T.	L.T.	G.T.	L.T.	G.T.	L.T.	G.T.	L.T.	G.T.	L.T.	G.T.	L.T.	I/II	IV	V	Vs	VI	Differences Signif.	X	X	X	X	X							
			I/II	-	-	I/II	X		I/II	X		I/II	X		I/II	X																
			IV		X	IV	-	-	IV		X	IV		X	IV		X															
			V		X	V	X		V	-	-	V			V																	
			Vs		X	Vs	X		Vs			Vs	-	-	Vs	X																
	Total Static Energy	Profiles																														
			I/II	-	-	I/II	X		I/II	X		I/II	X		I/II	X																
			IV		X	IV	-	-	IV		X	IV		X	IV		X															
V				X	V	X		V	-	-	V			V																		
Vs				X	Vs	X		Vs			Vs	-	-	Vs	X																	
Seedability	Cloud Base Temperature	t	G.T.	L.T.	G.T.	L.T.	G.T.	L.T.	G.T.	L.T.	G.T.	L.T.	G.T.	L.T.	I/II	IV	V	Vs	VI	Differences Signif.	X	X	X	X	X							
			I/II	-	-	I/II			I/II	X		I/II	X		I/II	X																
			IV		X	IV	-	-	IV		X	IV		X	IV																	
			V		X	V	X		V	-	-	V			V																	
			Vs		X	Vs	X		Vs			Vs	-	-	Vs	X																
Seedability	Cloud Base Temperature	t	VI		X	VI			VI		X	VI		-	-																	

Fig. 8.11

Summary of statistically significant differences between the categories defined by the weather type classification scheme. (G.T.≡ greater than, L.T.≡ less than.)

utilized in the formulation of a procedure whereby experimental days can be classified in both a predictive and an *a posteriori* sense. However, since this study is concerned with the modification of cumulus clouds, if a classification scheme is to be of use in the evaluation and formulation of seeding strategies, it is essential that the scheme should stratify *convective events* into categories possessing significantly different physical characteristics. Table 8.11 indicates that the weather type scheme is not effective in classifying convective events into categories displaying differences in the distributions of the parameters Showalter index, total precipitable water and total static energy which reflect variations in the physical condition of the storm environment and hence also of the attendant cumulus clouds. Categories V and Vs manifest no significant differences in environmental stability, moisture and energy characteristics and these weather types also have similar precipitation regimes. Types V and VI have almost identical energy profiles, similar atmospheric moisture conditions and stability characteristics that are only marginally different. Yet they have completely discordant precipitation regimes, type VI possessing a much higher mean rainfall than V and being associated with all hail-fall events. Differences between Vs and VI are restricted to environmental stability and the precipitation regimes of these categories are also dissimilar. Discriminant analysis shows that the greatest degree of 'misclassification' occurs between the groups V, Vs and VI. Thus statistical investigation shows that the weather type classification scheme does not decrease variability within the set of convective events since variance within the categories V, Vs and VI is not significantly less than variance between the categories. The primary objective of classification is therefore only partially attained by the scheme.

One of the most conclusive findings of the parametric F and t tests is that related to cloud base temperature conditions within the group of

of categories associated with active convection (V, Vs and VI). Both the tests show that no differences exist between these categories. Since the parameter cloud base temperature is a principal indicator of the manner in which cumuli will respond to ice-nuclei seeding it is doubtful whether the weather type scheme is able to classify convective events to categories of varying response to seeding with artificial ice-nuclei.

The shortcomings of the weather type classification scheme arise because it does not link cumulus cloud development to the synoptic systems giving rise to and supporting their formation. By neglecting this inter-relationship the scheme overlooks the fact that the fundamental determinants of convective activity, atmospheric moisture, environmental instability, the vertical energy gradient and horizontal streamline convergence are all connected to physical processes occurring on the synoptic scale.

CHAPTER 9

AN INTEGRATED CLASSIFICATION PROCEDURE

In the proceeding chapters an evaluation has been made of how and to what extent the weather type and synoptic systems classification schemes reduce natural variability within the set of experimental units. The weather type scheme differentiates effectively between

- i) situations where cumulus clouds do not develop above the -5°C level
- ii) stratiform rain situations, and
- iii) situations of active convection, where cumuli have tops colder than -5°C .

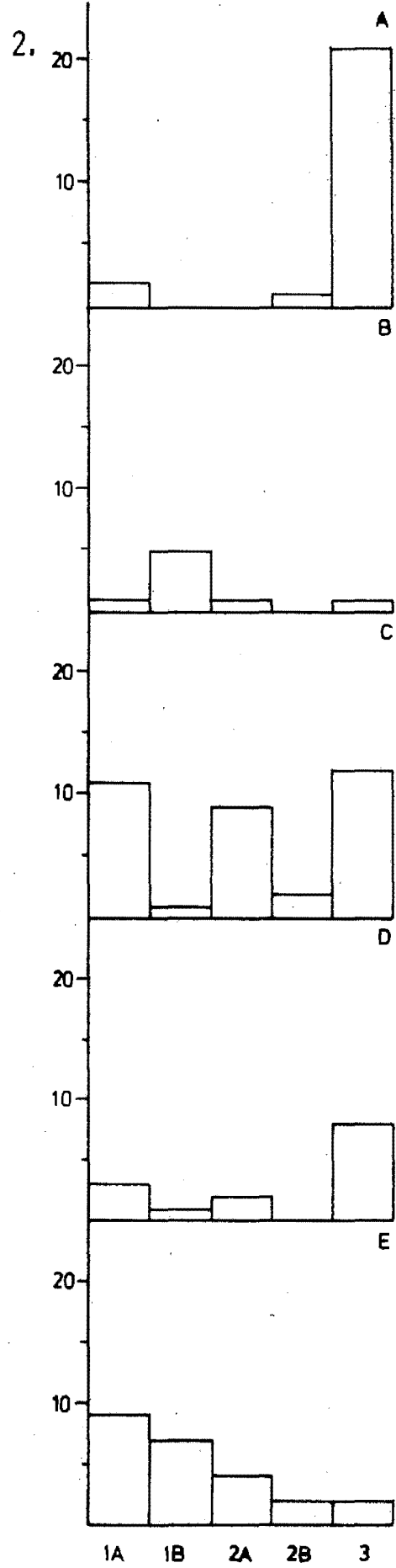
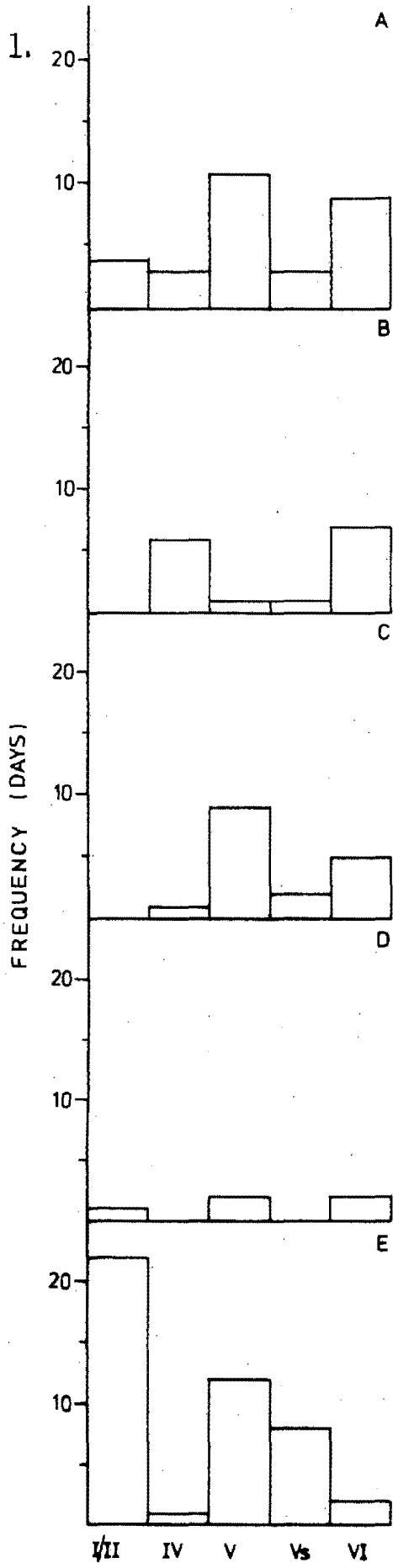
However, the scheme does not serve to reduce natural variability within the third division and will therefore be of minimal use in the evaluation process of cumulus cloud weather modification experiments. On the other hand, the synoptic systems scheme decreases cumulus cloud variability in a manner that will aid in the evaluation of treatment effects and in the formulation of seeding strategies. The main shortcoming of this scheme is that stratiform rain events and situations with cumulus cloud tops warmer than -5°C are included along with events of significant cumulus development in the set of days belonging to a particular category. In the case of experiments concerned with cumulus cloud modification it is essential that only days on which cumuli have tops colder than -5°C , be incorporated in the set of experimental units.

These assessments disclose that deficiencies in the synoptic systems scheme correspond to attributes of the weather type scheme and *vice versa*. Consequently, joint application of the schemes should accomplish the greatest reduction of cumulus cloud variability in the most desirable fashion, since expedient features of the schemes compliment one another. In order to investigate whether this is in fact the case, experimental days for the 1978/79 summer are classified by both the weather type and synoptic systems classification schemes. Cross-classification in this manner produces the matrix in Table 9.1. The corresponding histograms are presented in Fig. 9.1.

Table 9.1 Cross-classification matrix for experimental days during the 1978/79 summer season using the weather type and synoptic systems classification schemes.					
CATEGORY	I/II	IV	V	Vs	VI
1A	4	3	11	3	9
1B	0	6	1	1	7
2A	0	1	9	2	5
2B	1	0	2	0	2
3	22	1	12	8	2

Fig. 9.1 Histograms depicting cross-classification of experimental days during the 1978/79 summer season for:

- 1) The synoptic systems scheme, with the categories, (a) 1A, (b) 1B, (c) 2A, (d) 2B and (e) 3.
- 2) The weather type scheme, with the categories, (a) I/II, (b) IV, (c) V, (d) Vs and (e) VI.



DISCUSSION

Cross-classification of experimental days shows that the situations defined by the synoptic systems scheme may be attended by the entire spectrum of weather types and that the weather types, including the categories of active convection, may be accompanied by a wide variety of synoptic situations. A significant number of days in categories 1B and 3 are associated, respectively with stratiform rains and inconsequent cumulus cloud development. Elimination of these days would therefore reduce the number of experimental units to be considered in the evaluation process. This can be accomplished by application of the weather type classification scheme. Also, the categories of active convection (V, Vs and VI) are not correlated with particular synoptic situations. In view of the importance of directing attention to the synoptic situations responsible for cumulus cloud formation and development when stratifying convective events, classification by the synoptic systems scheme is also necessary. Consequently, by integration of the weather type and synoptic systems schemes a classification procedure can be formulated which will facilitate the most effective classification of experimental units on cumulus cloud weather modification projects. This procedure is presented in the form of a flow diagram in Fig. 9.2.

In addition to the fact that the classification procedure will assist *a posteriori* analyses in the evaluation process, it will also be advantageous to real-time investigations of cumulus clouds. There is no need for detailed forecasts to be made on each experimental day. It merely has to be decided which of the primary divisions I, II or III best describe the weather expected for that day and what the likelihood of rainfall is. The synoptic situation can be classified quickly and easily

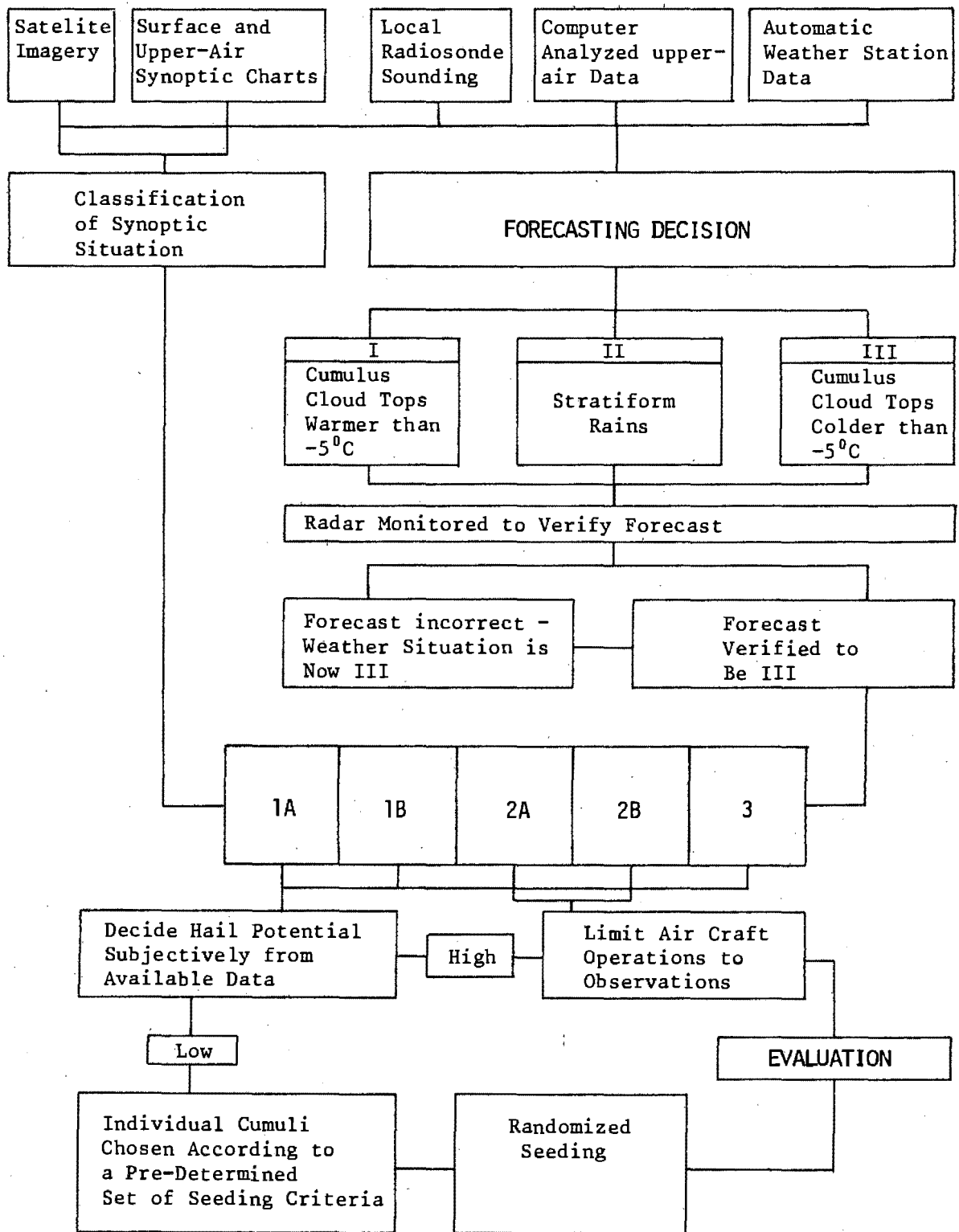


Fig. 9.2 A classification procedure for specific use on cumulus cloud weather modification experiments.

from the most recent satellite imagery and synoptic charts. Thereafter the radar scope should be monitored in order to verify the forecast. This can even be done automatically by computer. Once convective echoes appear on the radar scope the appropriate course of action can be taken.

In the evaluation process, days on which active convection occurred can be grouped according to the categories defined by the synoptic systems scheme and case studies made accordingly. Once the procedure has been applied for one or more operational seasons and investigated further, both statistically and physically, the extent to which the categories are, in fact, different can be established. Should progressive examination show that the categories are nearly mutually exclusive, experimental days can even be selected on a random basis within the categories. Thus the number of experimental units required in the evaluation process can be reduced substantially. In this way evaluation can be accomplished most successfully, in the shortest possible period of time and at the lowest cost. Also, if certain categories are associated with cumulus clouds that are likely to respond positively to ice-nuclei seeding, then the procedure presented in Fig. 9.2 can be used directly in designing seeding strategies in the final part of the experimental stage and, should the experiment indicate that rainfall can be augmented at an economic rate, also in the operational stage.

CHAPTER 10

SUMMARY - CONCLUSION

This study has been concerned with the formulation and evaluation of classification schemes to be employed on weather modification experiments designed to investigate the possibility of augmenting rainfall from cumulus clouds by artificial ice-nuclei seeding. Efficient evaluation of treatment effects on these experiments is hindered by variability that exists naturally in atmospheric phenomena. However financial and time constraints prevent the analysis of each experimental case. Consequently, methods must be devised whereby objective assessment of treatment effects can be made using fewer experimental units in the evaluation process. Classification of recurring but significantly different meteorological situations into separate categories aid evaluation in this manner. In the case of cumulus cloud weather modification experiments, it is particularly with regard to convective events that the categories defined by a classification scheme should manifest differences. If a scheme is to assist, additionally, in the design of an operational project then the manner in which cumulus cloud variability is reduced by the scheme is also of importance. In this regard, the scheme should identify situations in which the cumuli are likely to respond positively to ice-nuclei seeding.

The potential of two classification schemes, one of which was formulated as part of the study, to aid in the evaluation of treatment effects on a cumulus cloud weather modification experiment has been examined. Considera-

tion has also been given to the capacity of the schemes to stratify convective events into categories of varying response to seeding with artificial ice-nuclei. Thereafter the schemes were integrated to form a classification procedure whereby the most effective stratification of experimental days can be accomplished. The conclusions which proceed from investigations made in this study are presented summarily in this chapter.

The weather type classification scheme endeavours to reduce natural variability within the set of experimental days by differentiating between the following major weather situations:

- i) insignificant cumulus development - cloud tops warmer than -5°C (Types I and II),
- ii) stratiform rains (Type IV),
- iii) significant cumulus development - cloud tops colder than -5°C (Types V, Vs and VI).

The categories of active convection (V, Vs and VI) are segregated on the basis of whether:

- i) hailfall is probable (Type VI),
- ii) hailfall is not probable (Type V),
- iii) hailfall is not probable and the cumuli do not satisfy a set of seeding criteria (Vs).

From the statistical examination of differences between the categories defined by the weather type scheme, the following can be concluded:

1. The categories of the weather type scheme have significantly different precipitation characteristics.
 - a) The scheme is particularly effective in differentiating type I/II, which has a significantly lower mean daily rainfall than the other categories, and type VI which has the highest mean daily rainfall.
 - b) Category VI, by definition, is associated with all hailfall events.

2. Analysis of the parameters indicating environmental stability, moisture and energy conditions shows that differences are most significant between the primary divisions (I/II), (IV), and (V, Vs, VI) and that differences between the categories of active convection are minimal. In particular:
 - a) The category of insignificant convection (I/II) has more stable environmental conditions than the other categories, while the category of strong convection (VI) is associated with significantly greater storm environment instability than the remaining weather types.
 - b) All the rainfall producing categories (IV, V, Vs and VI) have similar environmental moisture conditions. Differences that do exist are not consistent with anomalies evident in the precipitation regimes of the categories.
 - c) The vertical gradients of total static energy associated with the convective weather situations (V, Vs and VI) are not substantially different and, in addition, the absolute energy values of these categories are similar.

3. Discriminant analysis confirms that the most heterogeneous categories of the weather type scheme are I/II and IV. The analysis shows that differences between the categories V, Vs and VI are not significant

statistically.

4. With regard to cumulus cloud seedability, investigation of the parameter cloud base temperature for the categories of significant convective activity, indicates that the weather type scheme is not likely to divide convective events into situations where the response of cumuli to ice-nuclei seeding will be significantly different.

The synoptic systems classification scheme is based on the premise that convective event variability is a consequence of physical processes operating in association with synoptic scale weather systems. Thus the scheme stratifies experimental days by categorizing the attendant synoptic situation. The categories are defined according to whether convection is initiated and maintained by:

- i) systems of tropical origin (Types 1A and 1B),
- ii) systems of temperate origin (Types 2A and 2B),
- iii) local factors (Type 3).

Categories within these major divisions are distinguished primarily on the basis of anomalies in the windfields attending the synoptic situations. Differences in the precipitation regimes, storm environment characteristics and seedability conditions of the categories defined by the synoptic systems scheme have been examined statistically. The following conclusions proceed from the analysis:

1. The categories defined by the synoptic systems classification scheme have significantly different rainfall characteristics, but unrelated synoptic situations may produce similar amounts of rainfall. More specifically, the conclusions derived are:
 - a) There is a preference for hailfalls, especially extensive hailfalls, to occur when temperate disturbances and air-masses influence whether conditions.
 - b) Category 3 has a significantly lower mean daily rainfall than the other types, while tropical systems tend to cause higher rainfalls than temperate disturbances.

2. Examination of environmental stability, moisture and energy characteristics by statistical analysis indicates that the categories of the synoptic systems classification scheme are most different with respect to moisture and energy conditions. Since low level windflow patterns are incorporated in the classification criteria, by definition, the categories also have varioform windfield characteristics. The examination produces the following conclusions:
 - a) All the situations attended by synoptically generated streamline convergence (1A, 1B, 2A and 2B) have similar environmental stability conditions as indicated by the Showalter index, while category 3 has significantly more stable environmental characteristics.
 - b) The synoptic situations are associated with diverse moisture regimes, ranging from 1B, the most moist, through 2B, 1A, 2A to 3, the driest.

- c) Findings with respect to the parameter total precipitable water, a measure of environmental moisture conditions, indicate that anomalies observed in the precipitation characteristics of the categories defined by the synoptic systems scheme are caused by tropospheric moisture and windflow peculiarities rather than differences in environmental instability as indicated by Showalter index.
 - d) Noteworthy differences are evident in the shape and location of the static energy profiles of the synoptic categories, as follows:
 - i) Situations involving tropical disturbances and air-masses are associated with lower-tropospheric energy deficiencies and high absolute values of total energy.
 - ii) Temperate systems are attended by a storm environment with upper-tropospheric energy deficiencies and lower absolute values of total static energy than types 1A and 1B.
 - iii) Category 3 has a vertical energy profile that is symmetric about the mid-tropospheric energy minimum and has energy surpluses, induced by adiabatic heating through subsidence, above 450 mb.
3. Discriminant analysis shows that the synoptic systems scheme facilitates effective classification of experimental days and that differences between any combination of categories are statistically significant. Also, the fact that moisture indicators and parameters reflecting middle and low tropospheric conditions, rather than upper-air characteristics, discriminate most effectively between the groups is consistent with the criteria by which the scheme performs classification.

4. Consideration of cloud base temperature conditions in conjunction with the environmental stability, moisture, energy and windfield characteristics associated with the categories of the synoptic systems scheme suggests that ice-nuclei seeding is likely to:
- a) have no effect on or detrimentally influence precipitation formation under synoptic conditions 1A and 1B,
 - b) be superfluous in the case of categories 2A and 2B,
 - c) have the best chance of increasing rainfall under synoptic situation 3.

Following statistical examination of the weather type and synoptic systems classification schemes an evaluation was made of the extent to which and the manner in which the schemes achieve the objectives of classification, namely:

- i) reduction of random variance within the set of experimental units, in particular the reduction of convective event variability, and
- ii) the stratification of convective situations into categories of varying response to ice-nuclei seeding.

Assessment of the schemes reveals that:

- a) The weather type classification scheme differentiates effectively between the situations of active convection, stratiform rains and inconsequent convective activity but fails to decrease natural

variability within the set of convective events and therefore achieves the primary objective of classification only to a limited degree.

- b) Random variance within the set of experimental days, specifically, cumulus cloud variability can be reduced significantly if the days are classified on the basis of the synoptic systems which give rise to and maintain convection.
- c) There are positive indications that the synoptic systems scheme will be able to assist in the formulation of seeding strategies, but it is certain that the weather type scheme will not be able to aid in this manner.
- d) The overall ability of the weather type scheme to be of use in the evaluation of treatment effects and subsequently in the design of seeding strategies does not compare favourably with the competence of the synoptic systems scheme to do so.

The only shortcoming of the synoptic systems scheme that has bearing upon the classification of experimental units is the fact that the scheme does not eliminate days of stratiform rains and days on which cumuli have tops warmer than -5°C from the set of experimental days. However, this shortcoming of the synoptic systems scheme is the major attribute of the weather type scheme. Cross-classification of experimental days using both the weather type and synoptic systems schemes shows that:

- a) In the classification of convective events, attention should be directed towards stratification of the synoptic situations responsible for cumulus cloud formation.

- b) The evaluation process of cumulus cloud weather modification experiments may be improved and streamlined by application of a classification procedure which integrates the expedient features of the weather type and synoptic systems classification schemes.

In this study particular attention has been given to the influence which large-scale systems have on convective events. By virtue of southern Africa's latitudinal position, between low and middle latitudes, the synoptic situations which initiate and support convective activity in this region involve disturbances and air masses of both tropical and temperate origin. Therefore, in this region, it is important that the constraints which large scale physical processes impose on cumulus cloud characteristics be given attention in the formulation of schemes to classify convective events. The study has shown that, by classifying situations of convective activity on the basis of the synoptic systems responsible for the convection, cumulus cloud variability can be reduced in a manner which will aid in assessing the results of ice-nuclei seeding on cumulus cloud weather modification experiments. Where similar experiments are being conducted in other regions with correspondingly diverse synoptic regimes, the findings of the study suggest that evaluation of treatment effects may be accomplished more effectively and in a shorter period of time if the constraints which synoptic systems exercise on the physical characteristics of cumulus clouds are recognized.

APPENDIX A

The criteria used for test cell selection during the 1978/79 summer season are as follows:

1. Cloud Top
 - (a) should show active convection
 - (b) temperature $< -5^{\circ}\text{C}$
 - (c) show no visual glaciation

2. Cloud Base
 - (a) should be firm and continuous
 - (b) diameter > 2 km
 - (c) should be isolated from adjacent cloud bases

3. Cloud depth should be between
2 400 m and 7 600 m

4. The horizontal cloud dimensions should be
 $\geq 50\%$ of the cloud's vertical dimensions

5. Cloud base must be wider than cloud top
(i.e: No "V" or hourglass shaped clouds)

6. All test cells must be in the BEWMEX area
and not further than 93 km (50 nm) from
the Bethlehem radar site

7. If suitable clouds with isolated bases are not available, then feeder cells or cells in line developments will be chosen but
 - (a) Only suitable cells near the end of a line development will be selected
 - (b) if more than one suitable cell is present in a feeder line, the one furthest from the main storm will be selected.

(after Shaw *et al*, 1979, p.2)

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