Cumulus cloud characteristics of the Eastern Transvaal Lowveld

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Abstract

General cumulus cloud characteristics for the Eastern Transvaal Lowveld are examined from a variety of sources and observations for comparison with other localities. Cumulus convection is a seasonal phenomenon that produces hail within 50 km of Nelspruit on about 33 days per annum. The most severe storms generally occur in the early summer months when strong wind shear is experienced in association with the propagation of the subtropical jet stream. Convective activity is strongly diurnal with fewer than 5 % of storms occurring at night, and it is also directly influenced by the steep topographical features of the region.

Severe storms in the Lowveld are shown to display many of the features observed in other regions of the world, although some concern is expressed at discrepancies found in the frequency distribution of certain parameters related to the inner high radar reflectivity cores of storms.

Introduction

Cumulus clouds and their associated larger mesoscale systems (hailstorms and squall lines) produce about three quarters of the precipitation in the tropics and sub-tropics (Simpson, 1976). These large mesoscale systems and their frequently accompanying microscale phenomena (eg. tornadoes) cause millions of dollars worth of damage each year to vital commodities (Gokhale, 1975; Carte, 1977). The immense importance of all these forms of cumulus convection in providing the rainfall as well as their destructive ability has led to large commitments by both private and government agencies throughout the world to pursue research into the processes involved in cumulus development and the possibilities of modifying them to man's advantage (Simpson, 1976; Dennis, 1980).

In the central and north-eastern region of South Africa (Figure 1) there is a high incidence of hail and thunder (Schultze,

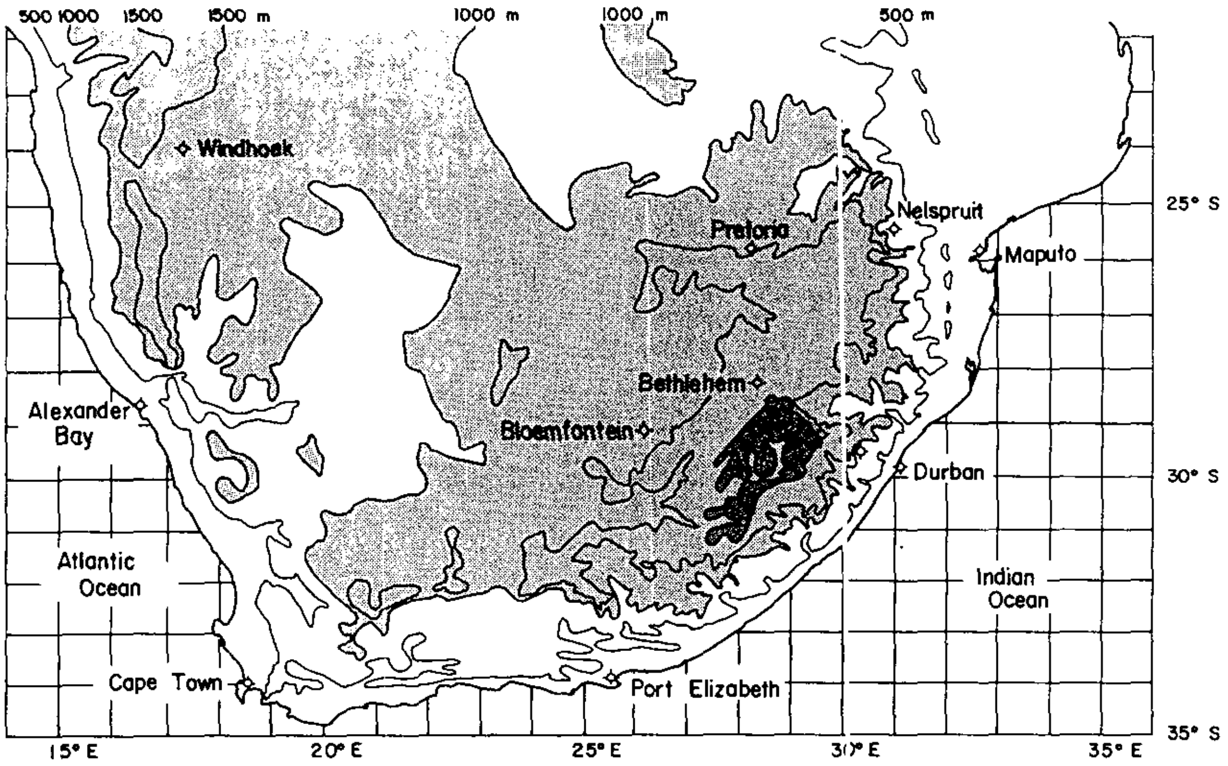

Figure 1
The topographical features of Southern Africa.

1972). Within this region there are government sponsored research programmes at the Council for Scientific and Industrial Research (CSIR) in Pretoria (Carte, 1979) and the S.A. Weather Modification Experiment (BEWMEX) at Bethlehem (Harrison, 1974). Prior to 1980, a privately sponsored hail suppression programme was also operating in the Nelspruit area of the Eastern Transvaal Lowveld (Mather, 1977). Subsequently, this programme has been converted into a research project whose goals include the assessment of the potential of rain augmentation in the Lowveld and the extent to which the technology can be transferred to other localities in South Africa (Garstang, Emmitt and Kelbe, 1981).

This paper presents an initial climatology of cumulus convection prevailing in the Eastern Transvaal Lowveld region near Nelspruit (Figure 1). It is not intended to be a synoptic climatology but rather a presentation of the general characteristics of cumulus conditions in the region. The data have, of necessity, been extracted from many sources and consequently are not necessarily in the most appropriate form for a detailed assessment of the Lowveld conditions. They do, however, give some indication of the prevailing conditions for an initial appraisal and allow some comparison with the other localities.

Data

A decade of weather modification operations in the Lowveld (CIC, 1971-1980) has provided a means of identifying many days with deep convective activity in the region (Nelspruit). Operations at Nelspruit use a C-band radar, interfaced to a digital computer to detect the existence, locality and severity of clouds within approximately 50 km of Nelspruit. Legal constraints on the seeding operations required the precise recording of the time, azimuth and range of each seeding event together with the number of AgI flares discharged. Summaries of the seeding operations provided a complete inventory for the past decade as well as limited, select radar data. The radar data are limited in the sense that they are available for only those days on which seeding occurred, and select in that they were analysed for only those storms that were seeded near or within the protected area (Figure 2). Daily summaries of the seeding events have been published for 1972 – 1980 by CIC (1972 – 1980).

A survey of the descriptive summaries revealed that there were days when seeding was restricted due to mechanical failures of the aircraft or radar, or visual obscurity of the seedable clouds (towers). There were also occasions when aircraft were dispatched to "patrol" the protected area due to the close proximity of seedable storms to the protected area or the existence of storms within the protected area that were close to, but never actually achieved, the seeding criteria. The seeding criteria were based *a priori*, on the height attained by specific radar reflectivity levels (Mather, Treddenick and Parsons, 1976).

The fragmented nature of the operational area (Figure 2) caused discontinuities in the radar data that may have resulted in some deep convective storms remaining unaccounted for in the above data set. The use of a voluntary observer network has, therefore, been used to supplement the data. The deep convective days have consequently been defined as those 24 h periods when

- *hail* was reported within or near the protected area by insurance claims or the voluntary observers;
- *seeding* operations were performed; or
- *patrols* were instigated.

The local agricultural cooperative (LKB) provides insurance coverage for tobacco crops in the area and consequently has kept

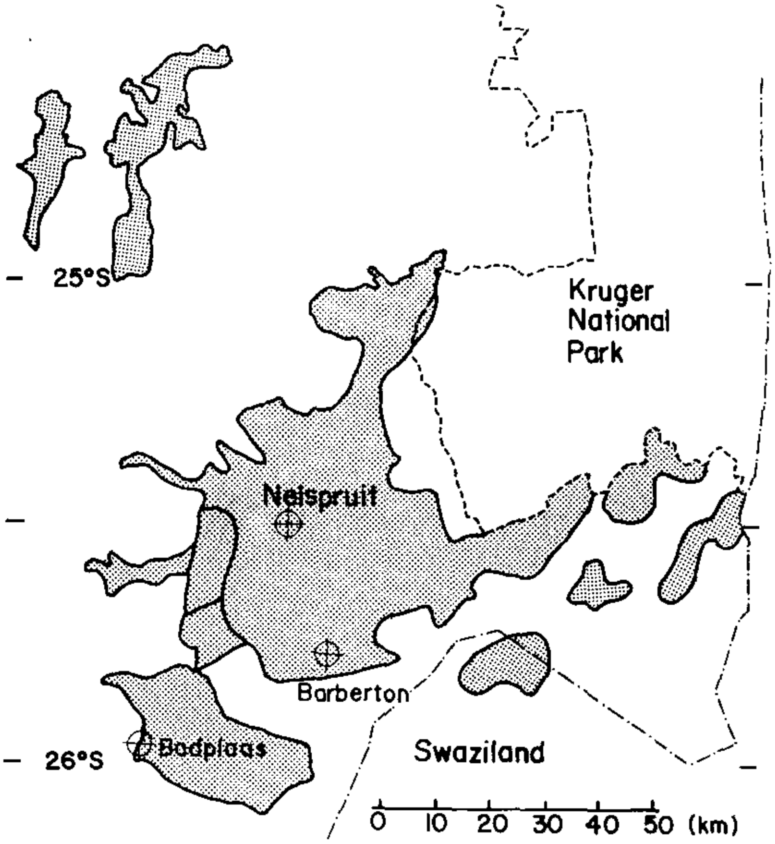

Figure 2
The primary area of the Weather Modification Programme in the Eastern Transvaal.

TABLE 1
RELATIVE FREQUENCY (%) OF CLOUD OBSERVATION AT NELSPRUIT

Time (SAST)	No Cloud	Cumulus				Stratocumulus			Stratus	
		Shallow		Deep						
Cloud Code	0	1	2	3	9	4	5	8	6	7
08:00	17,1	2,5	11,0	2,6	10,7	4,5	11,0	16,6	12,0	12,0
14:00	3,9	1,4	17,7	9,8	36,4	2,8	15,5	6,4	1,5	4,6
20:00	25,5	0,3	2,7	0,8	38,0	5,7	9,6	5,7	6,8	4,9

quantitative records of daily hail damage in the area since 1961/62. The damage assessment technique has been described by Mather (1977). Briefly, 100 % damage to a tabacco crop is logged when 12 leaves (the average for a 6 week crop) have been thoroughly perforated by hail while 6 damaged leaves would contribute 50 % damage. The overall area damaged by hail can be normalized to 100 % damage by multiplying the area hit by the percentage damage. These daily values of tobacco damage corrected to 100 % are given by CIC (1972-1980).

Cloud frequencies

Visual observations of cloud type and amount are extremely subjective but are nevertheless indicative of general conditions. Standard Weather Bureau observations were obtained from Nelspruit (Friedenheim) for the period September to May (1972 to 1979) and have been summarized in Table 1. The ten coded low cloud types have been grouped into four broad categories:

- No clouds observed (code 0)
- Cumulus clouds – shallow (codes 1 and 2)
  – deep (codes 3 and 9)
- Strato-cumulus clouds (codes 4, 5 and 8)
- Stratus type clouds (codes 6 and 7).

There are seldom any days in midsummer when no clouds can be observed (< 4 % of all days). During the period of observation from November to March only 5 days out of a total of nearly 1 700 days had no observed cloud at 14h00 SAST (Figure 3).

It is apparent from Table 1 that the mornings in the Lowveld are dominated by stratus or stratocumulus clouds (70 % of cloudy days). However, by 14h00 SAST nearly 70 % of all cloudy days were experiencing cumulus convection (48 % deep and 20 % shallow), which appears to have persisted into the evening.

Seasonal variability in cloud type occurrence is shown in Figure 3. There is a rapid decline in cloud cover towards the winter months which is reflected in the regional rainfall (Kelbe, Garstang and Brier, 1983). Stratus, and to a lesser extent stratocumulus conditions remain constant throughout the summer half of the year while the cumulus events show a marked seasonality. Presumably, the inverse relationship between the occurrence of shallow and deep cumulus conditions is a reflection of the changes in atmospheric stability with the changing seasons.

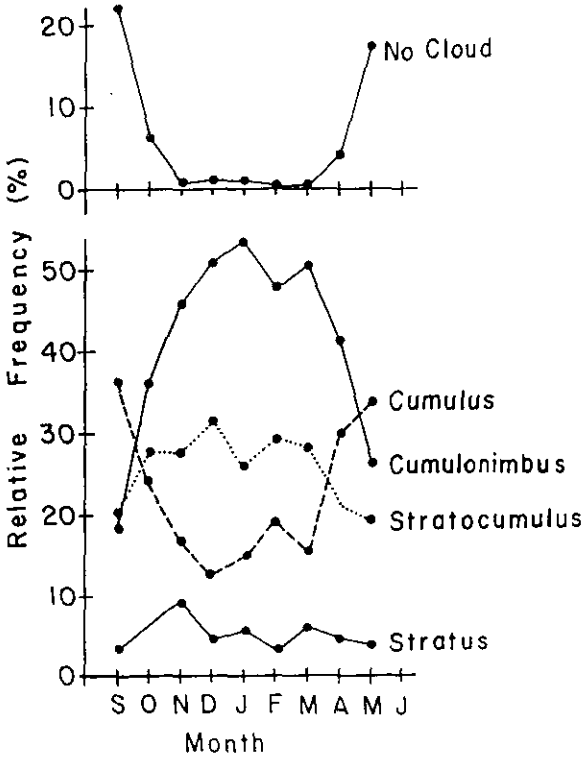

Figure 3
Relative frequency of cloud observations at Nelspruit for 14:00 SAST.

TABLE 2
OCCURRENCE OF DEEP CONVECTION BY SEASONS

Season	Hail	Seed	Patrol	Total
1972/73	33	39	0	72
1973/74	33	21	16	70
1974/75	45	8	10	63
1975/76	36	9	9	54
1976/77	44	15	2	61
1977/78	31	20	0	51
1978/79	55	8	6	69
1979/80	36	24	0	60
1980/81	22	29	0	51
MEAN	33,2			61,2

Severe storm frequencies

During the period of operation of the weather modification programme there has been an average of 64 storm days per season (September to May) within approximately 50 km of Nelspruit. The season totals (Table 2) have ranged from a high of 72 in

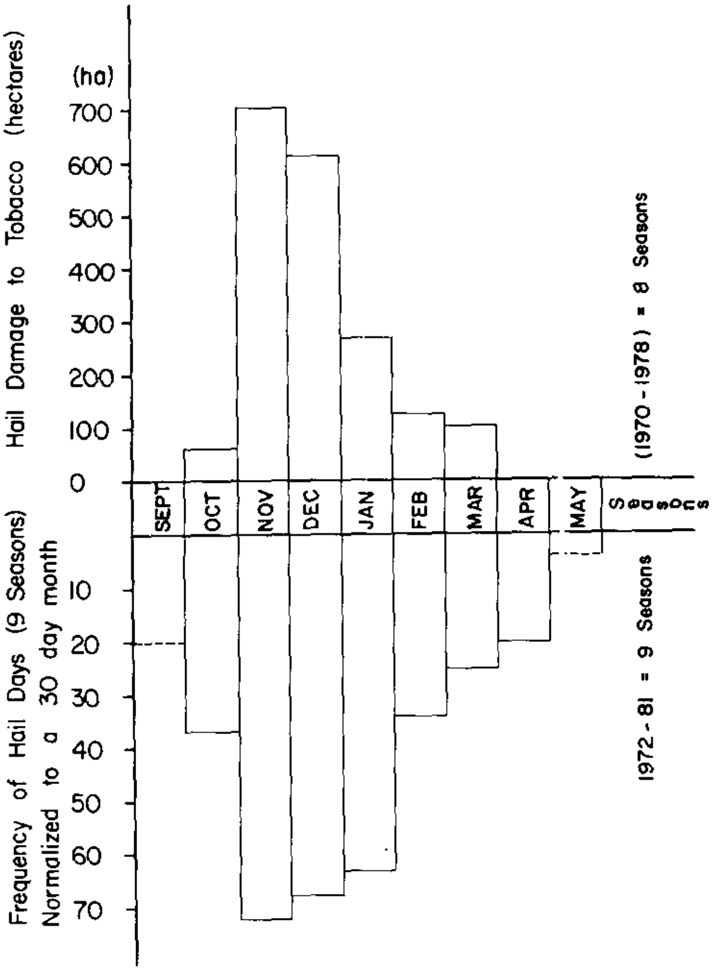

Figure 4
The frequency of hail days over 9 seasons (1972 – 1981) and the total hail damage to tobacco for 8 seasons (1970 – 1978).

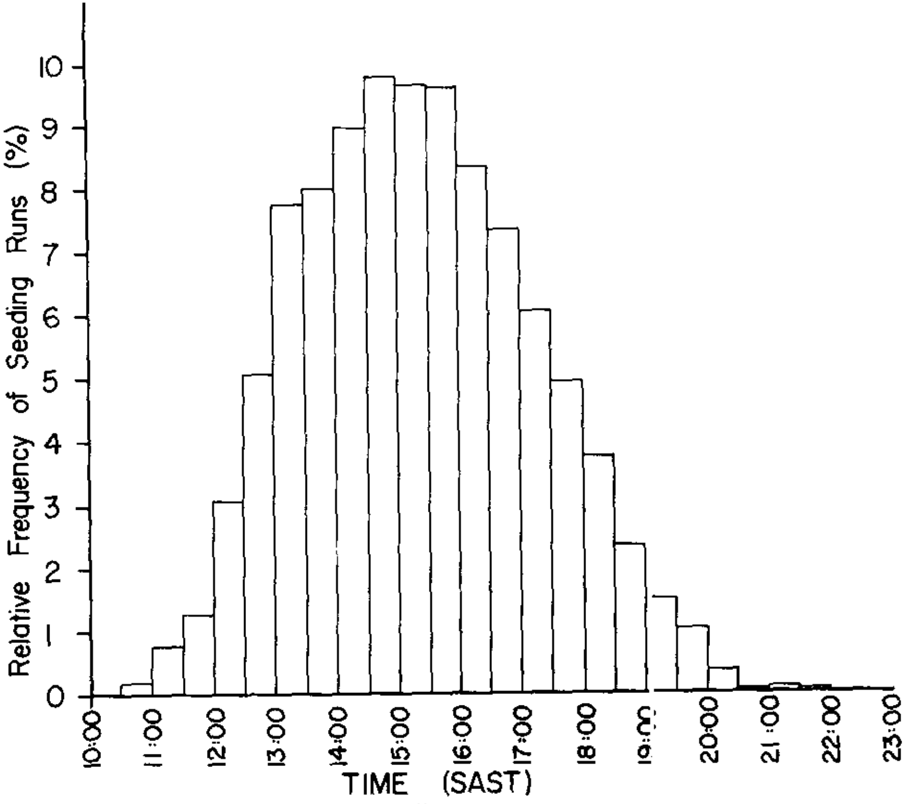

Figure 5
Relative frequency of the time of seeding events.

1972/73 to a low of 51. Hail was recorded on an average of 33 days per season. Nearly 65 % of these hailfalls occurred during November to January inclusive (Figure 4). Carte and Held (1978) and Court (1979) have indicated similar seasonal variations in the occurrence of hail in the highveld areas near Pretoria and Bethlehem respectively. Although no records are available for the winter months at Nelspruit, experience suggests that few storms occur between May and September. Carte and Held (1978) found that the winter on the highveld produced less than 5 % of the annual total number of hail days.

Hail damage to tobacco in the Lowveld is restricted mainly to the months of November and December (Figure 4). Since the tobacco season is from October to March there is about the same potential for damage in November and December as there is in January and February. Although there is a high incidence of hail days in January and February there is not a corresponding area of tobacco damage when compared with November and December. This would suggest that the hail storms during the early summer months are much more severe (destructive) than the later summer storms. Since the crop damage statistics are undoubtedly controlled by the stage of crop development, they cannot be expected to reflect the severity of the spring-early summer season storms in September and October. However, Carte and Held (1978) show that these earlier months (October and November) produce the most extensive hail falls as well as producing most of the larger size hail stones (> 3 cm) over the Highveld. This could also be a feature of the Lowveld storms.

Rainfall in the Eastern Transvaal is generally greatest in January with December and February providing approximately equal proportions of the seasonal total. However, there is a definite tendency for February to be the second wettest month in the Lowveld region to the north of Nelspruit, while December is wetter than February in the region to the south (Kelbe *et al*, 1983). This spatial variability in the seasonality of rainfall may also be a trait of the severe storms.

An analysis of the time of each seeding event (Figure 5) shows the clear diurnal nature of the local convective activity. The time of maximum frequency is between 14h00 and 16h00 SAST when surface heating is expected to reach a maximum. Court (1979) shows a similar diurnal cycle for the occurrence of hail at Bethlehem but indicates that the maximum frequency occurs between 15h00 and 18h00 SAST, an hour or two later than the maximum for the Lowveld. Since seeding of cumulonimbus for hail suppression purposes must precede the hail formation process, this lag between the two regional maximum frequencies may only be a reflection of the different indices. Nocturnal storms do occur in both regions but they are relatively infrequent (Figure 5).

The range and azimuth of all seeding events provided an estimate of the spatial distribution of the convective activity for

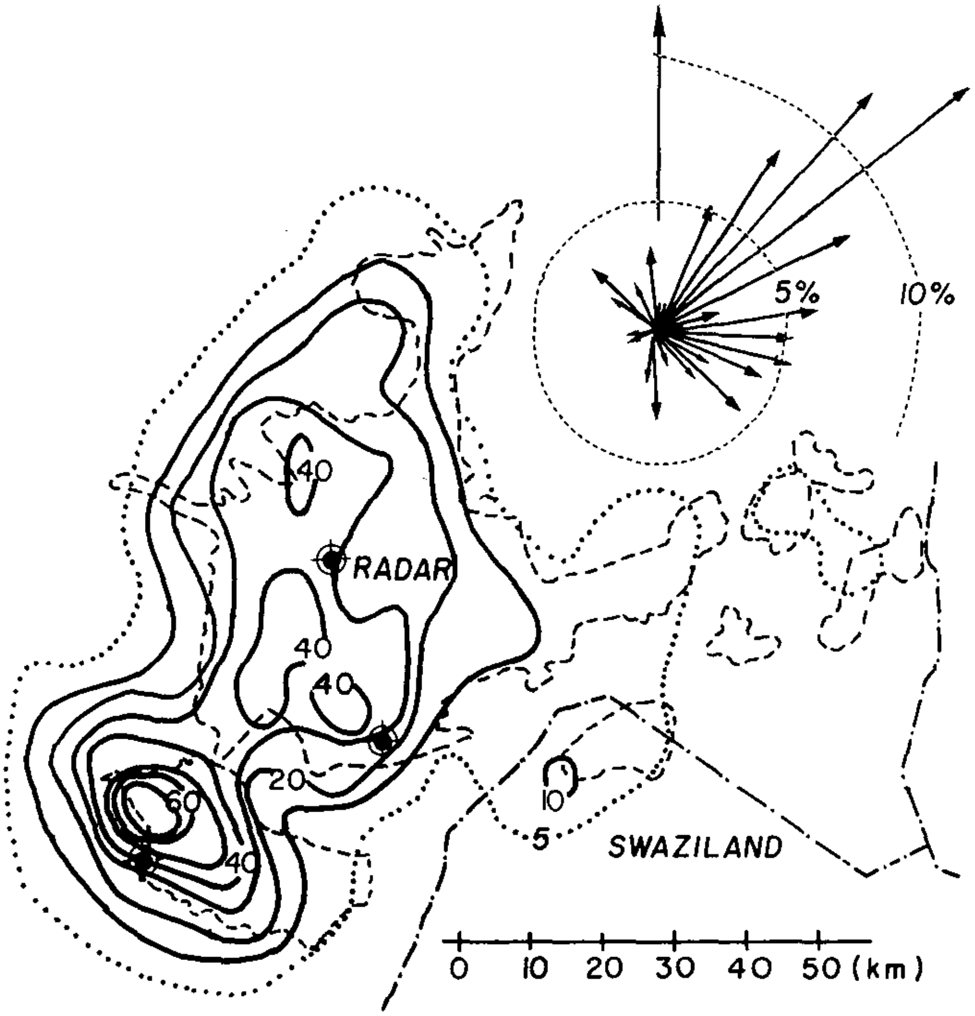

Figure 6
The seeding density (events/km²) in relation to the protected area (---) together with the relative frequency in the direction of storm movement.

the protected areas of the Lowveld (Figure 6). Because of the operational restrictions on the seeding already alluded to, the spatial density in storm occurrence will only be reflected within the operations area (i.e. up to approximately 20 km outside the protected area boundaries). Nevertheless, there appears to be areas of preferential storm development. The most southerly region (Badplaas valley) has a much higher incidence of cumulus activity than the central regions (Barberton and Crocodile River valleys). There is also a definite decline in the seeding density eastwards toward the coast (Mozambique) which is reflected in the regional rainfall patterns (Kelbe *et al.*, 1983).

Storm structure

Storms are known to exhibit the three stages of active development, maturity and dissipation during their life cycles (Byers and Braham, 1949). It is also well established that many storms consist of individual cells which develop to maturity and dissipate in such a manner that ensures the general propagation of the overall storm (Lilly, 1979). While storms are known to exist that do not show this multicellular nature (Marwitz, 1972), it is generally believed that most severe storms in the Transvaal are multicellular in character (Carte and Held, 1978). A detailed case study of a storm in the Eastern Transvaal region clearly shows this multicelled nature (Kelbe, 1975).

Utilizing the relatively fast acquisition, display and storage capabilities of the Nelspruit radar (CIC, 1975) a single storm that produced 11 mm of rainfall at one gauge was documented for almost 45 min. Radar contour maps in either the Plan Position Indicator (PPI) mode or Range Height Indicator (RHI) mode were obtained at approximately 1 min intervals. Two of the volume scans (constant angle PPI – CAPPI) taken 10 min apart are shown in Figures 7 and 8. The first CAPPI shows a storm with at least three separate centres of high radar reflectivities which have been reduced to a single cell 10 min later (Figure 8).

The time sequence of consecutive RHI profiles for 4 reflectivity levels are given by Kelbe (1975).

Changes in both the antennae azimuth and the range of the echo intensity cores afford the means of separating the individual cells. By plotting the heights of the identifiable towers against time, Kelbe (1975) gave estimates for the growth rates of the individual cells (Figure 9). Similar estimates for the 45 dbz contour are also shown in Figure 9. From these plots it would appear that the individual cells developed and decayed at approximately 5 – 6 m s^{-1} with a probable duration of the order of 30 min.

Storm movements

Based on an assessment of consecutive 15 min PPI's, Dixon (1977) analysed 98 storms in the Lowveld which exhibited signs of all three stages of their life cycles. From these he deduced that the

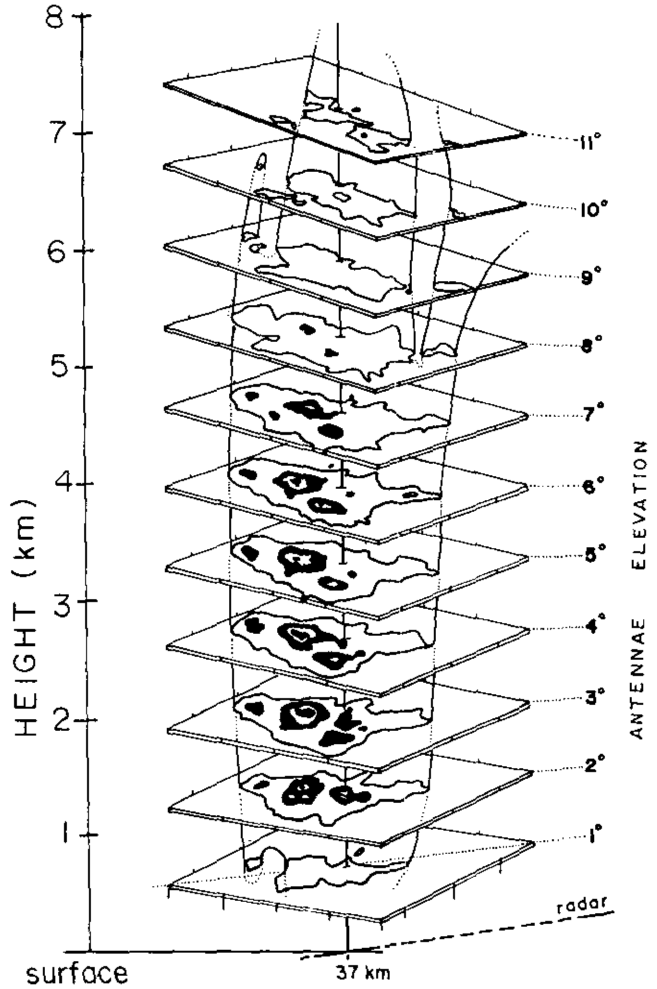

Figure 7
Three-dimensional representation of the radar volume scan of the storm on January 14, 1975 at 11h50 SAST.

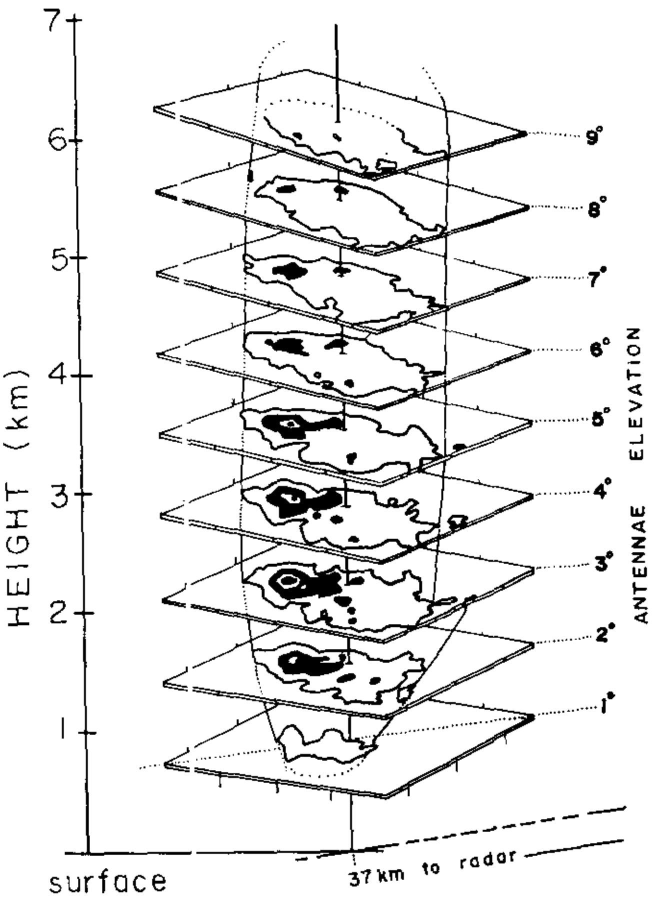

Figure 8
Three-dimensional representation of the radar volume scan of the storm on January 14, 1975 at 12h00 SAST.

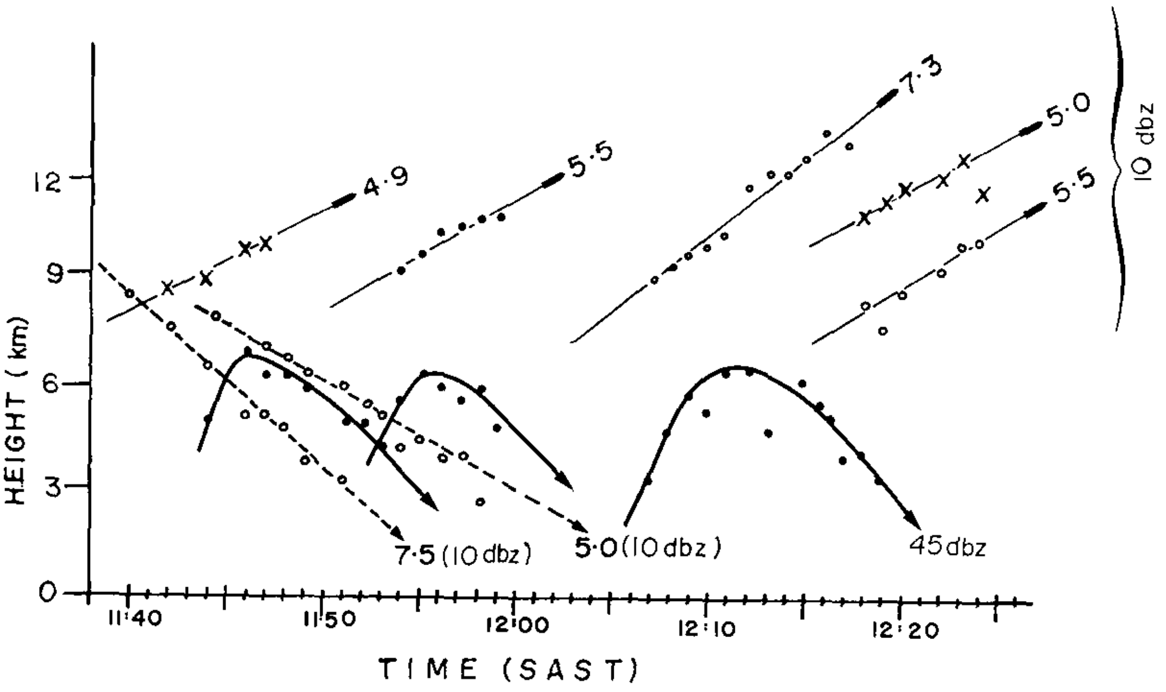

Figure 9
Time-height plots of the 10 and 45 dbz contour peak heights for the storm on January 14, 1975. Dashed lines are subjective estimates of the time rates of change.

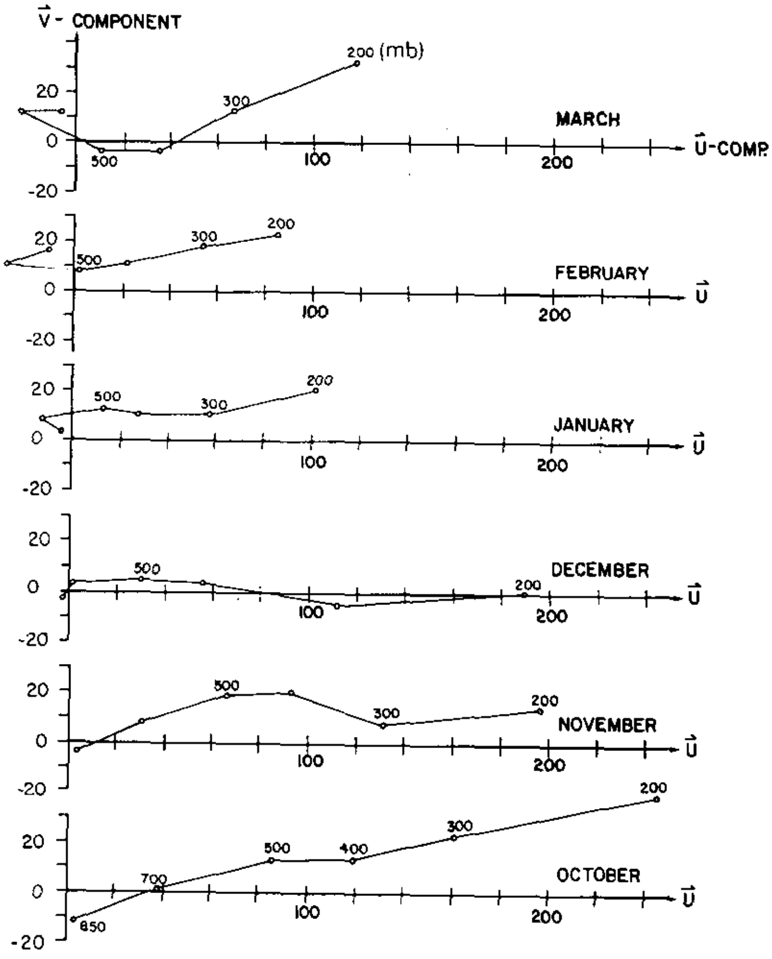

Figure 10
Hodograph of the 10 year mean monthly wind profiles taken at 08h00 SAST, Nelspruit. Velocities are in km h⁻¹.

average storm velocity in the Lowveld was 22 km h^{-1} in a northeasterly direction. The frequency distribution of storm direction is included in Figure 6. It thus appears that many storms develop over the Badplaas valley and propagate towards the Barberton valley. With a mean speed of 22 km h^{-1} and a median duration of approximately 120 min, many of these storms would have reached maturity and started to dissipate over the Barberton valley.

As the storms propagate in a northeasterly direction to the left of the upper level winds (Figure 10), the new development is usually found of the northern or northwestern flank. The low level winds near cloud base (850 – 700 mb) during the early summer months (October – November) provide inflow on the northwestern quadrant of the storm that would be expected to promote new development in this region. The more westerly-southwesterly flow during the later summer months, however, would suggest inflow into the southwestern quadrant. This low level southwesterly flow and the relatively weaker upper tropospheric westerlies (Figure 10) could be a major factor in the apparent reduced severity of storms during the later months when conditions over the Lowveld are more characteristic of the tropics (Kelbe and Garstang, 1983). Chisholm and Rennick (1972) observed weak winds up to a level of 10 km with sporadic hail but they believe that well organized severe storms require strong wind shear. Although the wind hodographs for Nelspruit show similar shear to those presemted by Chisholm and Renick (1972) few, if any, supercell (Marwitz, 1972) storms have been observed over South Africa.

While supercell storms have yet to be recorded, it would appear from the operational summaries of the weather modification programme that simultaneous left and right moving storms (Frankhauser, 1971) do occur, an example of which is given in Figure 11. These storms are believed to be due to concurrent development on both flanks of the initial storm. As the storm expands, it eventually splits into two separate components with the left moving storm generally propagating faster in the southern hemisphere. Based on the envelope enclosing the 35 dbz contours of consecutive PPI's, the left moving storm did achieve greater dimensions but not necessarily a faster propagation velocity (Figure 11).

Storm size and duration characteristics

Cumulus clouds are known to vary greatly in their temporal and spatial characteristics. Lopez (1977) suggests that the radar echo heights, horizontal dimensions and durations are lognormally distributed. Lopez (1976) and Biondini (1976) attributed the growth and development of cumulus clouds to a process which follows the law of proportionate effects.

Dixon (1977) has presented estimates of parameters reflecting the horizontal dimensions (area) and duration of 98 storms over the Lowveld. The horizontal area and the duration of the overall storm as reflected by the 25 dbz contour levels, exhibit the same lognormal properties (Figures 12 and 13) as those observed by Lopez (1977). The duration curve (Figure 13) shows some departure for the longer duration storms which can be attributed to truncation effects (Lopez, 1977). The higher radar intensity levels (35 and 45 dbz), however, show considerable departures from lognormality. The area and duration estimates for the 45 dbz echoes show large deviations from the expected curves at both tails of the distribution. Although the goodness of fit test (χ^2) indicates acceptable probability limits (0,1 %) for the lognormal distribution, a truncation of the distribution towards the origin (low values) is expected to cause the reverse departures. That is, the over-abundance of smaller values than would be expected from a lognormal distribution cannot be explained by a truncation of the series near the origin. This rejection of the lognormal hypothesis for the 35 and 45 dbz levels could be caused by the integration of the area over more than one cloud cell, if it is assumed that the 35 and 45 dbz contours define these separate smaller mesoscale features. Since the dimensions of the individual cells (cores of 35 dbz) are not available, only the in-

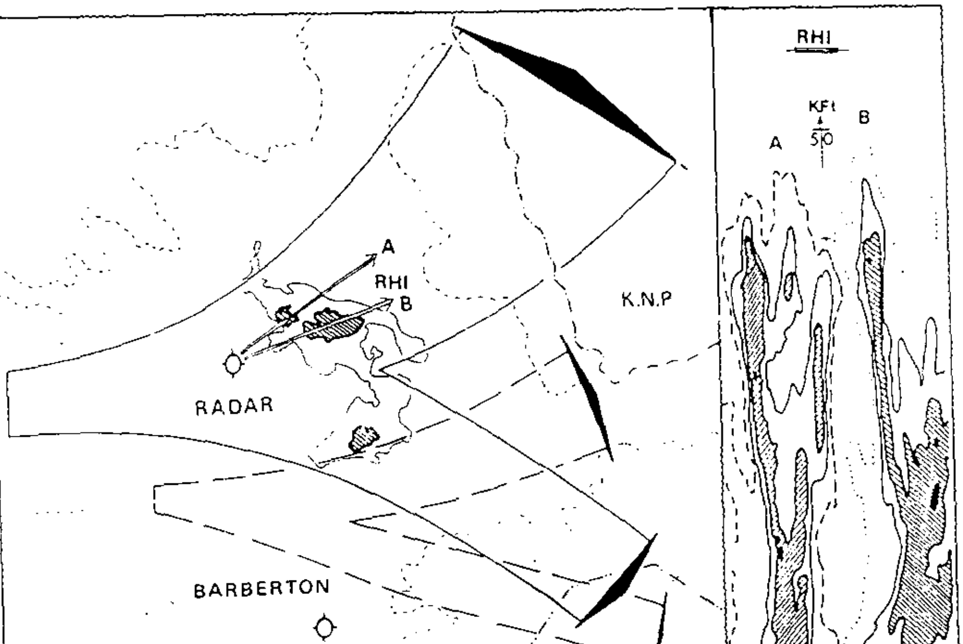

Figure 11
General propagation of two storms on November 9, 1976 as depicted by the envelope of the 35 dbz PPI contours (after CIC, 1978).

tegrated areas over all existing cells within the storm, it is not known if these cells would display different characteristics.

The individual 45 dbz centres of action are expected to be short-lived – particularly if they define cells. Therefore, the 15 min interval between consecutive PPI's may be an insufficient sampling rate for elements that have a characteristic life time of less than 45 min. However, one would not expect the larger 35 dbz contours to suffer similar constraints. Since these higher intensity contour levels define the most intense regions of the cloud and are therefore presumably related to the hail process (Mather *et al.*, 1976), the surface hail falls (damage) would be expected to exhibit a similar distribution. The hail damage, normalized to 100 % of tobacco loss (hectares) and published by CIC (1972-1980), exhibits lognormal characteristics (Figure 14). Thus one could expect the area of the storm centres of action (35 and 45 dbz) to be lognormally distributed and that the observed discrepancy may be attributed to the sampling interval.

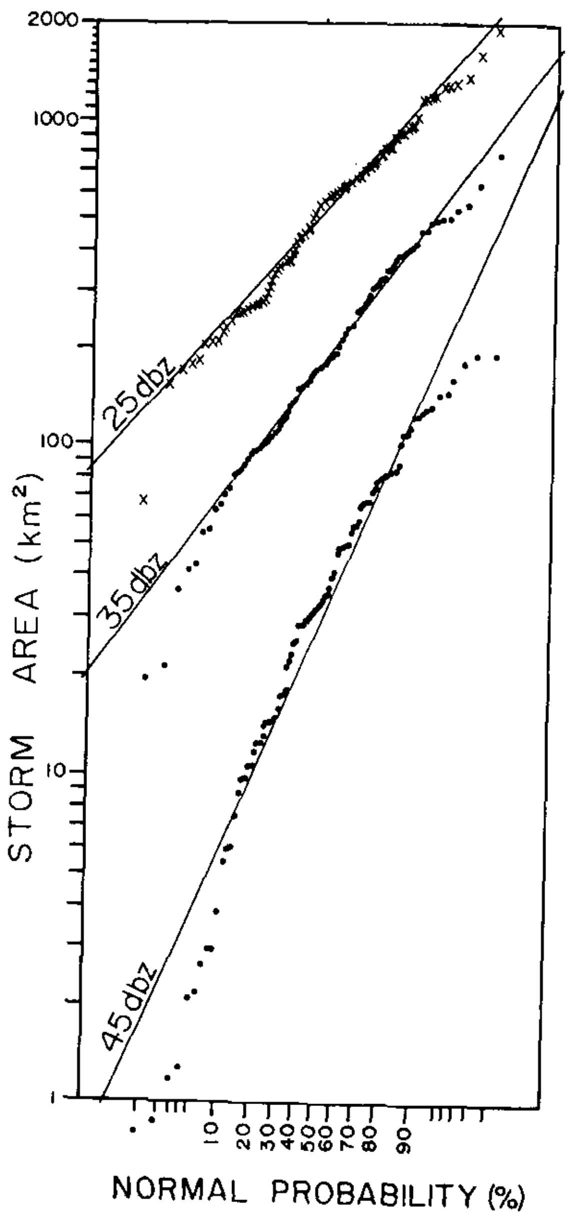

Figure 12
Probability density function for storm areas defined by three radar reflectivity levels (25,35 and 45 dbz).

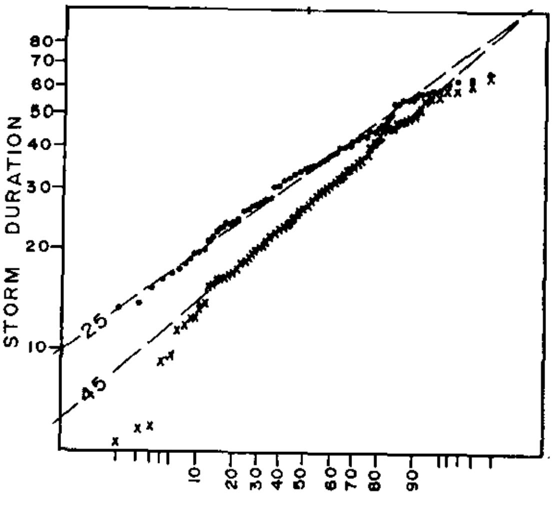

Figure 13
Probability density function for the duration of storm echo intensity contours of 25 and 45 dbz.

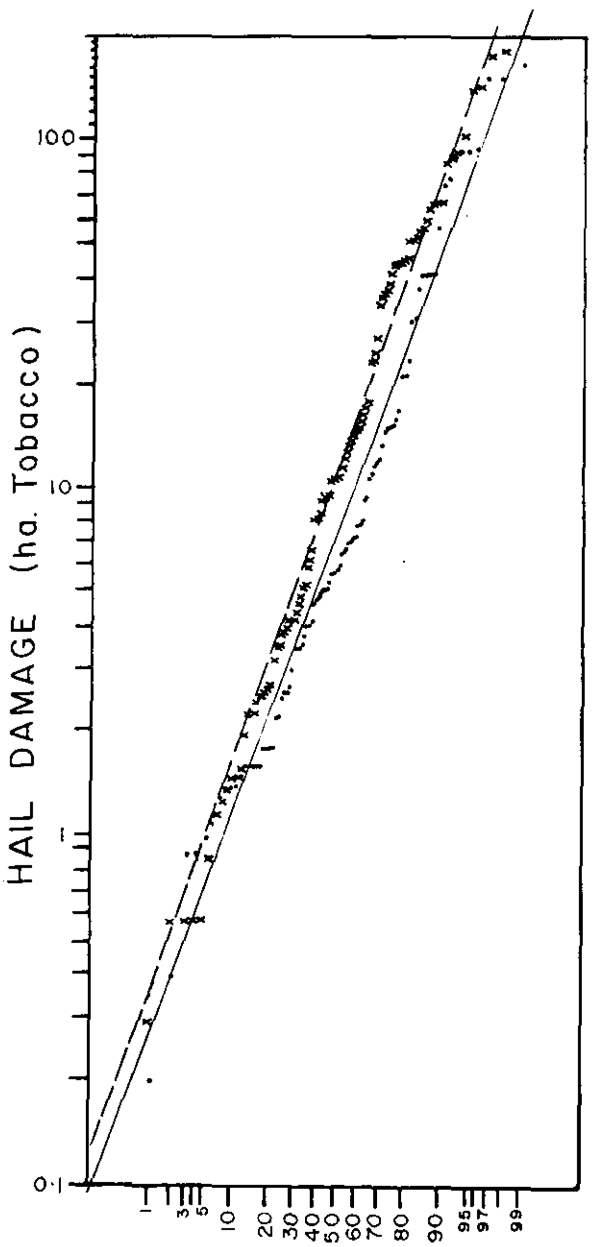

Figure 14
Probability density function for hail damage to tobacco in the Nelspruit area. X *October to December and* ● *January to May.*

Conclusions

Forced convection (stratus situations) is a year round phenomenon that occurs relatively infrequently over the Lowveld. Free convection, however, is a regular feature during the summer half of the year and provides most of the regional rainfall and nearly all the hail events. While these are general characteristics for the Highveld as well, there may be some difference in the diurnal forcing between the Lowveld and Bethlehem which is unaccounted for in the seeding hypothesis.

Deep convective storms are most prevelant during the summer period between November and March. The earlier months during this period, however, appear to have the more severe storms although large crop losses can still occur in January due to hail falls. This difference in the severity of the storms can be partially attributed to the seasonal changes in the wind shear. In the later summer months, the wind fields become more charateristic of the tropics with reduced speed and frequent low level easterly flow. Although storm situations are usually associated with a low level westerly flow (Kelbe and Garstang, 1983), the negative meridional component in early summer, compared with the more positive meridional flow during late summer, could be a major influence on the storm structure and propagation characteristics, and hence their severity.

The spatial variability in the rainfall regime together with the seeding density suggests that the topography has a very strong influence on the development of the Lowveld storms. It has been shown (Kelbe and Garstang, 1983) that there is a direct correlation between the low level wind structure and the existence of a strong thermal inversion over Nelspruit. This is attributed to subsidence in the lee of the Drakensberg Mountains. Since severe storms are also correlated to the low level winds, their development may be linked to topographical influence as well. Consequently there may be significant differences in the initiation processes of storms developing over the Lowveld when compared with the Bethlehem area which could be reflected in their diurnal response.

The storms in the Lowveld show similar structure and general characteristics to those observed in other parts of the world. While supercell storms have not been documented anywhere in Southern Africa, multicellular storms are common. Similarly the splitting of a single storm into concurrent "left" and "right' propagating systems is not a rare phenomenon. The overall storm dimensions and duration together with the hail damage statistics appear to adhere closely to the lognormal distribution. The more intense centres of the storm, however, show some departures from the lognormal hypothesis that cannot be attributed to truncation effects but may be a direct result of the sampling procedure.

Acknowledgement

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