Characteristic thunderstorm distribution in the Sydney area

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The spatial distribution of deep convection in the greater Sydney area is examined. The primary source of data is the incoherent, broadbeam 10 cm radar at Sydney's Mascot Airport. For 25 years significant storm cells on the radar screen were manually logged. A composite storm cell density map is produced. Under certain assumptions, this map can be converted to a storm probability distribution. Such distribution can be produced for any subset of the entire database (e.g. a given time of the day), and the anomalous storm probability under the conditions of the subset can be examined. We focus on anomaly maps for a set of six synoptic situations in which thunderstorms occur most commonly. These synoptic classes are defined solely on the basis of mean sea-level pressure (MSLP) patterns, because MSLP charts are available at the highest time and space resolution, and because MSLP, via its relation to the low-level flow, is an important synoptic-scale discriminant for local storm distribution. We find that in some areas the low-level flow has a significant impact on storm distribution. These anomaly maps directly link the local storm predictability to the regional weather predictability.

The results are compared to data from much more recent, more objective but climatologically inadequate alternative data sources: automatically recorded significant radar echoes, a lightning network, and a storm spotters network. While the comparison is difficult, some basic patterns are verified.

Introduction

This paper aims to document and interpret the spatial distribution of deep convection in the greater Sydney area (Fig. 1). Thunderstorms are common around Sydney, especially in summer, and the most severe ones constitute by far the most expensive insured natural disaster in the area (Blong 1991). Very little beyond forecasters' experience is known about thunderstorm evolution in the area, although some case studies of extreme events have been published (Spillane 1969; Colquhoun 1972; Birch 1973; Morgan 1979; Mitchell and Griffiths 1993; Speer and Geerts 1994).

A unique source of data to study thunderstorms in the Sydney area is an archive of 25 years of manually sampled incoherent radar data. This archive, maintained by the Australian Bureau of Meteorology from 1965 to 1989, is by far the longest and most complete source, long enough for statistically significant climatologies. This paper focuses on the effect synoptic variations have on local thunderstorm distribution. The question is not 'will thunderstorms occur?' but rather 'when thunderstorms do occur, where exactly will they be?' We are still far from the numerical prediction of resolved deep convection accurate enough for routine forecasting, even on a short time-scale (e.g. Lilly 1990). Any significant synoptic effect on the local distribution of thunderstorms could provide guidance for forecasters on the time-scale of numerical weather prediction.

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Fig. 1 Map of the Sydney metropolitan area showing relevant localities. The circle with a radius of 111 km shows the maximum range of the Mascot radar used in this study. Land over 200 m (1000 m) altitude is shaded diagonally (cross-diagonally).

(NWP), which is much longer than that of the thunderstorms themselves.

The large-scale environment conducive to long-lived convective systems is fairly well understood (e.g. Fovell and Ogura (1989) for multicell storms; Klemp (1987) for supercell storms; and Rotunno et al. (1988) for squall lines). However, the initiation and detailed development of convection is affected by factors which are poorly understood and not resolved by observation networks and NWP models. Complicating factors include thunderstorm interactions (e.g. Barnes and Newton 1986) and flow over heterogeneous terrain such as the Sydney area (e.g. Negri et al. 1994). Complex terrain has some systematic effect on thunderstorm distributions, and this effect depends on the synoptic situation, in particular the MSLP pattern (e.g. Neumann 1951). The relation between local thunderstorm distribution and unique (but classifiable) synoptic state motivates the development of a synoptic climatology (Yarnal 1993). The MSLP field appears to be the most commonly used variable for a synoptic climatology (e.g. Mueller 1977). Ideally, a combination of fields is used, such as MSLP plus upper-level charts (e.g. Doswell 1980). More generally, the thunderstorm spatial patterns can be related to an array of synoptic variables at various levels using principal component analysis (Davis and Rogers 1992). We used the MSLP charts only for three reasons: because they are available at higher resolution in space and time (three-hourly) than the upper-level charts, because the low-level flow and convergence is related to the MSLP field, and because in the Sydney area a MSLP chart is sufficient to differentiate between two distinct tropospheric synoptic patterns in which thunderstorms may occur, i.e. frontal and non-frontal (Speer and Geerts 1994). We realise that organised convection and its mesoscale environment have a characteristic mesoscale MSLP pattern (e.g. Schaeffer et al. 1985; Johnson and Hamilton 1988; Fritsch et al. 1994); however, we are interested in the larger scale MSLP patterns.

In the next section we describe the data source and how storm probability maps are derived. We then demonstrate how different synoptic settings are associated with a significantly different thunderstorm likelihood in certain areas. Finally, we explore other sources to estimate thunderstorm distributions.

The radar echo database

The main source of data is a series of logbooks of radar echoes recorded by the Bureau of Meteorology to provide guidance for aircraft operations near Sydney's Mascot Airport. The radar, located at Mascot, was a 10 cm WF44 radar with a 3rd horizontal beamwidth. Every 10 minutes, the location (PPI scan) and cloud top (RHI scan) of 'significant' echoes were registered, and occasionally also their radar reflectivity and movement. An echo was considered 'significant' if the reflectivity on a PPI scan exceeded a threshold value (47.8 dBZ), the echo was located within 111 km from Mascot (Fig. 1), and it had 'priority' for aircraft operations. Prioritisation occurred only on occasions when there was too much storm activity (more than ~7 candidate cells at one time) for complete recording. As evidence for this prioritisation we compared the distribution of recorded thunderstorms on those days with a 'severe' storm to the distribution of all recorded thunderstorms. Severe storm days are recorded in the Bureau's severe weather database (Ryan 1989). On severe storm days, 'significant' storm cells generally are closer to Mascot than on all storm days (this comparison is based on the anomaly mapping technique discussed below), especially within a 30 km radius. Because the severe weather database covers the entire larger Sydney area (the same area shown in Fig. 1), this hints strongly towards prioritisation, which is more likely in the event of severe storm activity.
The outer radar range is limited to 111 km, not because of the increased scanning elevation (a radar scanning at 1.5° elevation angle looks at a height of only about 3.7 km at 111 km (e.g. Rinehart 1991)), but primarily because of the beam widening (at 111 km the beam is 5.8 km wide), which causes a serious storm detection efficiency decrease with increasing range. This is due to incomplete beam filling and is exacerbated by the relatively high threshold radar reflectivity used. In the absence of hail, a reflectivity of 47.8 dBZ implies a rain rate of ~36 mm/h. The radar-based detection efficiency is defined here as the fraction of significant cells (rain rate over 36 mm/h) that can be seen by the radar as a significant cell (reflectivity over 47.8 dBZ). Using the same radar, Birch (1973) mentions that the effect of incomplete beam filling is perceptible from a range (R) of about 30 km; Clarke (1988), using the same type of radar in Melbourne, suggests that the detection efficiency decreases as R^-0.5 at distances greater than 85 km. In other words, the radar-based detection efficiency is, to a first approximation, quantifiable.

Within a radius of ~10 km, the radar was unable to detect echoes because of ground clutter (Morgan 1979). To compensate for this ‘blind zone’, an entry for a thunderstorm at Mascot was routinely made in the logbooks whenever (at 10-minute intervals) thunder was heard there. Because the thunder from one lightning strike can be heard over a distance larger than 10 km (e.g. Veenema 1952) and because thunder may occur at reflectivities below 47.8 dBZ, this leads to an overestimate of thunderstorm occurrence within this range, which is hard to quantify. This, together with the storm cell prioritisation during active times, made the logbook record fairly subjective.

From the logbooks we extracted 959 storm events and a total of 28,453 storm cells. A storm event is defined as a continuous period (maximum gap 30 minutes) during which ‘significant’ storm cells occurred. A storm event typically lasted several hours, with a (prescribed) maximum duration of 24 hours. A storm cell is a single entry in the logbook, unique in time and space. The logbook sometimes recorded lines of cells, and (more rarely) polygonal areas in which the reflectivity exceeded the threshold value. The lines and polygons were discretised to a series of adjacent cells. The annual number of storm events has been fairly constant since 1978, but was much smaller from 1972 to 1977 because some Bureau operators preferred to trace significant cells from the screen rather than enter them in the logbooks. These tracings were not archived. This only reduces the record size and is not expected to have a systematic effect on any storm classification. The number of cells per event was ~10 until 1980 and jumped to ~50 from 1981 onwards. This is mainly because lines and polygons came into vogue in the eighties, and they may contribute a large number of cells.

In the transformation from the polar coordinates (range-azimuth) to cartesian coordinates, cells (point information) were given an areal dimension by interpolating them on a grid using a Cressman weighting function (W),

\[ W = \frac{1 - r^2}{1 + r^2} \]

where \( r = d/D \), i.e. the distance between a cell and a grid-point (d), relative to the maximum distance (D), beyond which \( W = 0 \). We assume that D increases slightly with cloud-top height \( (Z_t) \), in km:

\[ D = -4 + 6 \exp\left(\frac{Z_t - 30}{30}\right) \] (km)

This empirical relation is consistent with data in Birch (1973) for Sydney. In practice, D usually is between 4 and 5 km. For a storm cell to be adequately resolved, it needs to fall in the area of influence of at least ~9 grid-points (three points in one dimension); therefore, we selected a grid spacing of 2.5 km. A cumulation of \( W (0 < W < 1) \) over a selected period is a measure of the number of ‘significant’ storm cells that were centred at the grid-point during that period. This number is referred to as the storm probability index and depends on the size of the storm sample.

Cumulated over all 25 years and normalised by the maximum value, we obtain a relative storm probability map as shown in Fig. 2. The concentric pattern is similar to the distributions in Clarke (1988) and it largely conforms to the radially dependent echo-detection efficiency of the radar. However, there are three important departures: (a) a spike occurs at Mascot; (b) the centre of the concentric pattern is shifted inland of the radar at Mascot; (c) and there are various departures from radial symmetry, the larger ones being towards the Southern Highlands and the Hornsby Plateau. Departure (a) has been explained before; we cannot be certain that (b) and (c) are real, i.e. that heavily precipitating thunderstorms are more likely over land, and in particular over the plateaus. Points (b) and (c) may be affected by the ‘prioritisation’ mentioned before. We traced the progression of storm cells in ~50 storm events (Matthews 1993). In all cases except one, cells moved from a westerly direction (between 180° and 360°). Coastal crossings of storm tracks were rare, and all except one were in an offshore direction. Many tracks approach Mascot, but few leave it. All this, together with point (b), is strong evidence for subjectivity: once east of Mascot, storm cells are no longer of interest. In short, it is dangerous to divide the field of Fig. 2 by.
an empirical radar echo-detection efficiency function and to interpret the resulting departures. It appears impossible to partition the probability distribution in Fig. 2 as the product of a radar-based detection efficiency, a human detection efficiency and a real probability of significant storm cells.

We can, however, use Fig. 2 as a base map against which we compare normalised storm probability maps for a subset of all storms. Such comparison (subset map minus base map, both normalised) will be referred to hereafter as *anomaly map*. For instance, Fig. 3 shows an anomaly map for all storms occurring in winter. This map indicates that 'significant' storm cells are generally more common (positive anomaly) offshore and less common (negative anomaly) onshore, except for the northern beaches. In summer, on the other hand (not shown), storms are relatively more common over land, except over the Southern Tablelands (where they are less likely) and offshore from Gosford (where they are more likely).

As a further test of the feasibility of anomaly mapping, the storm cells were categorised according to their time of occurrence. We found that storms are highly modulated by the diurnal cycle with an afternoon peak (3–4 pm) which is well known (e.g. Griffiths et al. 1993). More interestingly, we find a west to east (or SW to NE) progression of storms, as shown in Fig. 4: storms are
more common over the Southern Highlands and
the Blue Mountains around noon, cross the
metropolitan area in the afternoon and stall off-
shore at night. This fact is known amongst fore-
casters and has been documented in some case
studies (e.g. Mitchell and Griffiths 1993), but it is
the first time that such evolution is shown in an
aggregate of storms. Classified in three-hour
blocks (Fig. 4), storm cells are more common
along a broad axis that is aligned NW–SE over the
Blue Mountains from 10–13 EST, and that turns
to a N–S orientation as it moves offshore at night
(1900–0700 EST) (Matthews 1993).

Synoptic classification

In an attempt to find any systematic and signifi-
cant effect of the synoptic situation on the dis-
tribution of thunderstorms in the Sydney area, we
classified all storm events into classes. The classi-
fication of a continuum of MSLP patterns into a
discrete set is at least to some extent inherently
subjective, and various studies have attempted to
minimise that subjectivity (Jacobs 1946; Hare
1955; Court 1957; Mueller 1977; Yarnal 1993).
To minimise the subjectivity, and to ensure
mutual exclusivity and completeness, we used a
set of defining criteria, which will be discussed
later. Yet there were still a few storm events for
which the criteria were found to be either too
exclusive (i.e. a pattern fitted in none of the
classes) or else too broad (i.e. a pattern fitted into
more than one class). In the former case, the storm
event was discarded; in the latter, the most fitting
synoptic class was subjectively assigned. Any
storm event was assigned to only one class, even if
during its lifespan the synoptic situation changed.
In that case, the synoptic situation leading up to
the storm event was chosen.

An essential discrimination is between frontal
and non-frontal settings. Speer and Geerts (1994)
have shown that thunderstorms in the vicinity of a
frontal system usually are associated with more
convective available potential energy and also
more convective inhibition (i.e., negative energy)
than non-frontal deep convection. In accordance
with Speer and Geerts (1994), we distinguish
three types of frontal settings, pre-frontal trough,
pre-frontal and post-frontal. In the case of a pre-
frontal trough (Fig. 5(a)), one or more troughs
occur separate from and well ahead of the frontal
trough (e.g. Colquhoun 1972; Mitchell and
Griffiths 1993). This troughing in the vicinity of
Sydney, with lower pressures towards the south,
may be weak but it is significant, especially in
view of the fact that ridging is very common along
Australia’s east coast (Speer and Leslie 1994). In a
pre-frontal situation storms occurred at or ahead
of the local passage of a cold front (Fig. 5(b)). The
cold front needs to be analysed for at least 12
hours (i.e. 3 or 4 charts). Often the cold front
appears as a coastal tongue (the southerly change
or southerly buster, Colquhoun et al. (1985)), in
which case the tongue has not yet reached Sydney.
Storm events occurring immediately after the
passage of a cold front through Sydney are classi-
ified as post-frontal (Fig. 5(c)). The post-frontal
class is identical to that in Speer and Geerts
(1994).

We distinguish the following three types of non-
frontal situations: inland trough, offshore low and
offshore high. A case study of an inland trough
event is given by Morgan (1979). Unlike Speer
and Geerts (1994), we do not separate between
trough and low. Our nomenclature simply arises
from the fact that inland depressions are usually
troughs (Fig. 5(d)), offshore ones usually closed
lows (Fig. 5(e)). The difference is of little dynamic
importance. No front is analysed on the surface
charts near Sydney for at least 12 hours. In con-
trast to the frontal classes, lower pressures occur
towards the north in the case of a trough. In the
case of an offshore high (Fig. 5(f)), a warm moist
airflow from the NE produces a large pool of low
static stability. No clear troughing occurs near
Sydney, and no front is analysed in its vicinity.

Inland trough events are most common (Table
1), but frontal events (49 per cent) are just as com-
mon as non-frontal events (51 per cent). Also, the
number of cells per event is fairly invariant: for
instance, frontal events are not shorter lived than
non-frontal events (Table 1).

The thunderstorm probability anomaly maps,
specific to various synoptic situations, would be
of more value if we had a measure of confidence
in these maps. The dataset contains 28 453 storm
cells. This may seem significant, but when this
number is divided by 4900 (the number of grid-
points) and by six (the number of synoptic
classes), the number is just one, i.e. statistically
insignificant. Note, however, that the distribution
is very uneven, especially in space, and also that
one cell typically affects in the order of ten grid-
points, therefore, in some areas we expect a stat-
istically significant sample. A sufficient number
of storm cell occurrences is only a necessary
condition for confidence. Confidence at any grid-
point was ensured by dividing all storms in a syn-
optic class into two sets of about the same size
(both a random selection of twelve years), and
then by checking that the grid-point had a similar
storm probability anomaly in both subsets. In
summary, the internal consistency check was based
on the following criteria applied at any grid-
point and for any synoptic class: (a) the storm
probability index is at least five; and (b) the
anomaly values for two randomly selected subsets
Fig. 5 Selected MSLP charts illustrating the six synoptic classes (only the last two digits of the MSLP in hPa are shown): (a) pre-frontal trough (6/5/85 at 0200 UTC); (b) pre-frontal (16/12/85 at 0100 UTC); (c) post-frontal (9/1/87 at 1800 UTC); (d) inland trough (8/1/85 at 0400 UTC); (e) offshore low (20/6/85 at 2300 UTC); (f) offshore high (14/1/86 at 0700 UTC).
Table 1. Number of storm events as a percentage of the total (959 events) and average number of cells per event, for the six synoptic classes.

<table>
<thead>
<tr>
<th>Synoptic class</th>
<th>Number of events (%)</th>
<th>Average number of cells per event</th>
</tr>
</thead>
<tbody>
<tr>
<td>pre-frontal trough</td>
<td>15.6</td>
<td>34.5</td>
</tr>
<tr>
<td>pre-frontal</td>
<td>21.1</td>
<td>31.5</td>
</tr>
<tr>
<td>post-frontal</td>
<td>12.3</td>
<td>24.5</td>
</tr>
<tr>
<td>inland trough</td>
<td>31.0</td>
<td>31.3</td>
</tr>
<tr>
<td>offshore low</td>
<td>9.7</td>
<td>32.2</td>
</tr>
<tr>
<td>offshore high</td>
<td>10.3</td>
<td>20.5</td>
</tr>
</tbody>
</table>

are within 20 per cent of each other. While these criteria are arbitrarily set, they were chosen to impose stringent constraints. Because the inland trough and pre-frontal classes are most common (Table 1) (i.e. they have generally higher storm probability indices), they can be expected to have a larger area with internally consistent thunderstorm occurrences.

For all six synoptic situations, Fig. 6 shows the areas that are positively anomalous, i.e. they have an increased likelihood of thunderstorms, and also the areas that are, in addition, internally consistent (based on the above two criteria). Assuming that the biases have been removed, we can now look for physical interpretations. The explanations are only speculative, since they are generalisations of a detailed analysis of at least one case in each class.

The distribution of thunderstorms in pre-frontal trough synoptic situations (Fig. 6(a)) is not very different from the overall distribution, therefore positive anomalies are found only in small scattered areas. These areas are mostly offshore or nearshore, consistent with the higher occurrence of pre-frontal trough patterns in winter. In pre-frontal situations, a low-level dry northwesterly wind is found inland of a more humid north-easterly breeze along the coast. This may explain why in this case the storm activity is stronger near the coastline (Fig. 6(b)), especially the southern coastline and the northern beaches, due to the coastal topography (Southern Tablelands and Hornsby Plateau). The post-frontal deep convection (Fig. 6(c)) is mostly to the north and offshore, in association with the position of the front, i.e. though the front has passed through Sydney it may still be acting as a trigger for storms north of Sydney.

In the case of an inland trough (Fig. 6(d)), increased thunderstorm activity is observed in large areas, primarily in bands normal to the low-level northeasterly flow (Morgan 1979), with concentrations along the up-slope side of the Hornsby Plateau, Southern Tablelands and the Blue Mountains. In the presence of an offshore low, a south to southeasterly surface flow veers rapidly with height. It is not clear why in this case deep convection is more likely in the Hawkesbury Basin and offshore (Fig. 6(e)). Only small positive areas are internally consistent, because few thunderstorm events are of this type (Table 1). Finally, in the presence of an offshore high, thunderstorm activity is higher on the foothills of the Blue Mountains (Fig. 6(f)). We believe that in such situations, topographically controlled, thermally forced convergence is a primary trigger of convection. In fact, the diurnal modulation of storm cells in the case of an offshore high is more prominent than for all cases, with a peak at 3–5 pm EST.

Comparison to other data sources

The existence of biases in the logbooks justifies the need to compare thunderstorm distributions and the effect of synoptic patterns to an independent data source. Three sources were available for this purpose. Two of these were unbiased and therefore provided absolute measures of storm probability, i.e. there was no need to normalise and deduce anomalies. All three sources are very recent and, except for one, commenced after the manual recording of significant radar echoes was terminated in June 1990. At that time it was replaced by an automatic system. The automatic system used the same radar and the same threshold reflectivity, but it was entirely objective, and the time step was only three minutes. On the other hand, the system did not record cloud top or other parameters, and since it was terminated two years later, the record is climatologically inadequate.

Nevertheless, cumulative storm cell probabilities were derived for all six synoptic classes. We did not check internal consistency, because at most grid-points the cumulative number was too small. Figure 7 shows the storm cell densities (or thunderstorm probability) for the six synoptic classes. Considering the non-simultaneity, the brevity of the automatic record, and the recording and processing differences, it is not surprising to see little correspondence between Figs 6 and 7. Areas of similarity include: the high thunderstorm probability offshore Gosford in pre-frontal trough situations (Fig. 7(a)); the highs over the Hornsby Plateau and the coastal area south of Mascot in pre-frontal situations (Fig. 7(b)); the highs offshore and the northern part of the map in post-frontal situations (Fig. 7(c)); the highs near Wollongong, the foothills of the Blue Mountains and the area east of and near Gosford in the event of an inland trough (Fig. 7(d)); the highs in the Hawkesbury Basin in offshore low situations (Fig. 7(e)); and the highs over higher terrain in the event of an offshore high (Fig. 7(f)). There are
Fig. 6  Thunderstorms are more probable in the diagonally shaded areas, and consistently more probable in the cross-diagonally shaded areas, under the following synoptic situations: (a) pre-frontal trough; (b) pre-frontal; (c) post-frontal; (d) inland trough; (e) offshore low; (f) offshore high. See text for details.
Fig. 7 Thunderstorm density based on automatically recorded significant radar echoes, in units of number of cells per 280 km$^2$ per year, under the following synoptic situations: (a) pre-frontal trough; (b) pre-frontal; (c) post-frontal; (d) inland trough; (e) offshore low; (f) offshore high.
Fig. 8  Lightning density for single thunderstorm events based on data from the NSW lightning detection network, in units of number of strikes per km² per event, under the following synoptic situations: (a) pre-frontal trough (22/92/92); (b) pre-frontal (09/11/92); (c) post-frontal (23/2/93); (d) inland trough (06/01/93); (e) offshore low (06/12/92); (f) offshore high (23/12/92).
some areas of contradiction, e.g. the high over the northern beaches in Fig. 7(d) and the high in the metropolitan area NW of Mascot in Fig. 7(f).

A second source of independent comparison is lightning data. Since early 1992, a lightning detection network has been in operation in the eastern half of NSW with an efficiency of 95 per cent and a resolution of 500 m (Laudet et al. 1994). Caution is required in this comparison, since lightning and heavy precipitation (or hail) are different phenomena. Certainly lightning strikes cover a broader spectrum of convection than radar-detected storm cells. For each of the six synoptic situations, Fig. 8 shows the density of lightning strikes for one storm event. The automated radar echo recording serves as the best comparison, because the observation period largely overlaps. For the pre-frontal trough (Fig. 8(a)) case and the offshore high case (Fig. 8(f)), the correspondence is excellent. For the offshore low case (Fig. 8(e)), the correspondence is fair. For the post-frontal case (Fig. 8(c)) and the inland trough case (Fig. 8(d)), it is poor, except for the NW sector in Fig. 8(e) and the area near Wollongong and Gosford in Fig. 8(d), where the comparison is better. There were not enough lightning strikes in the pre-frontal case (Fig. 8(b)).

A final source of potential comparison is the Bureau's severe weather database, which is based on human observations. The annual number of recorded severe storms varies a lot, depending on the number of spotters, and both have increased rapidly in the last few years. The distribution of severe storms proved to be too highly biased towards the population centres to be used as validation of thunderstorm distributions in various synoptic situations, even when anomaly maps are used.

Conclusions

The distribution of reported severe storms is biased towards population centres within the Sydney area (Ken Batt, personal communication), as it is within NSW (Griffiths et al. 1993), and extreme caution is needed to study spatial or temporal characteristics. The most detailed source of thunderstorm data in the Sydney area to date is the WF44 radar at Mascot. The broad radar beam, the high threshold reflectivity, the subjective biases of the logbook entries, and the termination of the archiving in mid-1992 all impose restrictions on the usefulness of this resource. Nevertheless, composite thunderstorm patterns can be obtained that are at least to some extent internally consistent, physically plausible, and verifiable by other sources. The presence of some non-simultaneous correspondence between manually logged and automatically recorded radar data is encouraging. The comparison between radar data and lightning data was rather poor, due to the paucity of cases with lightning data and the fundamental difference between the two observation techniques.

This study focused on the characteristic thunderstorm distributions in Sydney under different synoptic conditions. Storms occur in a number of distinctively different synoptic settings, both frontal and non-frontal. In different synoptic conditions storm distributions are distinct, and general patterns can be understood in terms of low-level flow, topography and land-sea differences.

To further validate and gain physical insight in the observed thunderstorm distributions, a composite picture of the 3D airflow, moisture and temperature patterns for each of the six synoptic classes defined here is required. A composite of the convective precipitation patterns derived from mesoscale numerical simulations of selected events for each class can be compared to the observed distribution and can be used to gain physical insight.

More importantly, this study demonstrates that a larger amount of objectively archived radar data is required to derive climatologically significant thunderstorm distributions. While at the time of writing the amount of lightning network data is building up (Laudet et al. 1994), lightning distributions are distinct from radar-derived storm distributions and are less relevant to the hazards of severe storms (hail, wind gusts, flash-floods . . .). Therefore we propose that high reflectivity radar data be archived again.

Acknowledgments

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References


