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Hailstones across the Greater Sydney Metropolitan Area

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Abstract

This study addresses the recent climatology of hail occurrence in the Greater Metropolitan Severe Thunderstorm Warning Area (GMSTWA) of New South Wales, Australia, which is a sprawling suburban area, with a population of nearly 4.7 million and one of Australia's largest metropolis. The main objective is to highlight the recent temporal-spatial fluctuations of hailstone frequencies and magnitudes for each of recognized and vastly inhabited Local Government Areas (LGAs).

The relevant hail event data from 1989 to 2013 were initially derived from the severe storm archive of Australian Bureau of Meteorology. A climatologically oriented GIS technique was applied in the examining and mapping procedure of all hail events and hail days reported throughout the study area. By applying a specific criterion, all severe hails (defined as 2 cm or more in diameter) were cautiously selected and then imported into the ArcGIS software for relevant analysis. Appropriate data layers were stored in a unique database to allow logical integration of the data directly into some geoprocessing functions, mainly for querying, analyzing and mapping purposes in a model-builder setting. The database includes 357 hailstones with sizes 2–11 cm and occurred in 169 hail days across the region during the past 25 years.

The models have established that hailstones are neither temporally nor spatially uniform in magnitude throughout the study area. Temporal analysis indicated that most of hail events occurred predominately in the afternoons with peak time of 1–5 p.m. EST. They were particularly common in spring and summer, and reached maximum frequency in November and December. There was an average of 14.3 events each year, but a significant decreasing trend in terms of hail frequency and associated magnitude in the recent years has been identified. In turn, spatial models also established three main distribution patterns over the study area, which include the Sydney Metropolitan, coastal and pronounced topographic effects. Based on the understanding of the favorable factors for thunderstorm development in the GMSTWA, the potential impacts from climate variability and future climate change have been briefly discussed.

1 Introduction

In Australia, severe thunderstorms are defined as those that produce any of the four weather phenomena such as: hailstones with a diameter of 2 cm or more; wind gusts of 90 km h^{-1} or greater; tornadoes and flash flooding (BoM, 2011). Hailstones likely produce dissimilar categories of damages to the natural environment and often disastrous consequences upon people in the region (Griffiths et al., 1993; Allen et al., 2011). Severe hailstorms are localised events, usually affecting smaller areas that are more common than any other natural hazards, and are responsible for continuous damages (Alford, 1994; Johnson et al., 1995). Such storms affect communities across the region every year, causing fatalities, destroying properties and crops, and disrupting businesses (Middelmann, 2007). Each year on average, severe hailstorms across the Greater Metropolitan Severe Thunderstorm Warning Area (GMSTWA) of New South Wales (NSW), Australia occur and damage worth more than AUD 100 million is caused as a result of catastrophic severe hail events (DECCW, 2010). These storms could far exceed with maximum hail sizes larger than 7 cm, and sometimes causing injuries and even deaths (EMA, 2009). Hails can occur in anywhere and anytime throughout the GMSTWA, however, in the past many hail events were reported from the Sydney Metropolitan Area primarily because it is a densely populated area with long period and detailed records (Mitchell and Griffiths, 1993; Schuster et al., 2005). It is reasonable to state that many other areas of NSW, in particular the remote coastal and mountainous areas, are equally if not more at risk from these destructive hail occurrences (Natural Disasters Organisation, 1989; Leigh and Kuhnel, 2001).

During the past decades, many individual hail events occurred in the extent of NSW, which have been well highlighted by previous investigators (Zillman, 1999). Majority of such research documents described individual severe or damaging hailstorms in the Sydney region and NSW (Alford et al., 1995; BoM, 1995a, 2006). Some others highlighted the several qualities of hail events at local or regional scales, targeting urban and agricultural areas (Hannay and Wilson, 1954; Morgan, 1979; McMaster, 2001). Hail

climatology in Australia and NSW has been studied in details by some meteorologists and climatologist in the past decades. For example, Grace et al. (1989) generated severe thunderstorm climatology for South Australia, and Harper et al. (2001) discussed severe thunderstorm risks in southeast Queensland. A climatology for NSW by Griffiths et al. (1993) provided details on the atmospheric phenomena associated with severe thunderstorms. More recently, Schuster et al. (2005) described hail climatology of the Greater Sydney Area and NSW. They found that the most active hail fall regions are located in the northern NSW and Sydney's most densely populated suburbs. On the whole, it was found that severe thunderstorms in the region impose distinct daily and seasonal distributions, similar to those in many parts of the world, with maxima in the warmer months (October to February) and during the late afternoon. A few examples of such major hail events are given in Table 1.

Hence, the current paper describes more recent hailstone climatology of the GMSTWA by analyzing hail reports from 1989 to 2013, taking into account most records with the least missing reports. Parameters analyzed include hail frequency, hail days and hail magnitudes in the Local Government Areas (LGAs) during the last 25 years. Based on the created data sets, different temporal patterns with time scales of diurnal, monthly, seasonal and yearly time series have been firstly addressed. Then, to visualize the spatial distributions of hailstone sizes for different LGAs, Geographic Information System (GIS) functions were applied and the relevant digital layers were generated in the associated software setting. The emphasis was given to model all temporal-spatial fluctuations in order to identify the overall trends in the hail dataset. This was done based on an adjusted TORRO Hailstorm Intensity Scale in recognising the hazardous LGAs within the GMSTWA (Webb et al., 1986).

2 Climatic characteristics

The GMSTWA is located on the southeastern coast of NSW, Australia, which is in the western part of the Tasman Sea and has the South Pacific Ocean to the east. It includes the Sydney metropolitan area, which is expanding rapidly inland and contains highly industrialized pockets. Such area contains the Sydney metropolitan, Wollongong, Shellharbour, Kiama, Wingecarribee, Wollondilly, Blue Mountains, Hawkesbury, Gosford and Wyong LGAs (BoM, 2012a). The GMSTWA is defined by the Bureau of Meteorology (BoM) as a particular warning area in which severe thunderstorm warnings can be issued, whenever severe thunderstorms are occurring in an area or are expected to develop or move into the area during the ensuing few hours. The warnings describe the area under threat and the particular hazards likely to be associated with the hailstorms. Such region, with its sprawling suburban area and a population of approximately 4.7 million, is Australia's oldest and the most populated region. More than a forth of Australians live in such a severe thundery warning defined area. The geographic location of the study area, including the location of the study area, is shown in Fig. 1.

At a wide-ranging outlook, the study area enjoys a temperate climate and generally the broad-scale wind pattern is westerly in the winter, and easterly in the summer. This climate can be classified as being temperate with cool to cold winters and warm to hot summers (Sumner, 1983). Generally the climate of this region arises from a complex interaction of synoptic scale, regional and local controls. On the synoptic scale the region is under the influence of mainly drier westerly airstreams in the winter, and predominantly moist, easterly air streams in the summer months (Linacre and Hobbs, 1977). Each year, upwards of many thunderstorms in the region are strong enough to produce one or more of disastrous costly effects in the GMSTWA (Kuleshov et al., 2002; Davies et al., 2008). However, hailstones range in different intensities so powerful that could introduce very distractive even occasionally super hailstones; imposing wide-extended disastrous damages to the GMSTWA's environment and communities (BoM, 1993; Davis et al., 2008). Sydney, as the nation's largest city, is located in the eastern inner part of the GMSTWA (Fig. 2a).

The Sydney region is bowl-shaped with a low plain in the middle of which is effectively walled in on three sides by hills and mountains (Fig. 2b). In the centre of the region

there is the Cumberland Plain opening to the Pacific Ocean from the east. To the north of the plain, the rise is about 450 m to the top of a ridge lying eastward from the Great Dividing Range towards the coast. To the south, the rise in elevation on average is over 350 m. Southeast of the study area the coastal range rises from 150 to 500 m just northwest of Wollongong. To the north of Sydney the land rises from about 150 m near Broken Bay to 450 m at the northern boundary. However, the western region rises sharply to over 1200 m at the top of the Blue Mountains and parts of the Central Tablelands. The elevation map of the GMSTWA illustrates the topographic features of the region, including the location of the main LGAs.

3 Data and methodology

3.1 Data selection procedure

Many thunderstorms occur each year throughout the GMSTWA (BoM, 2011). Although all thunderstorms produce lightning, tornados, gusty winds and hailstones that are dangerous themselves, not all of them are "severe" or likely to produce intense hailstone occurrence in the region. According to BoM (2012a) severe thunderstorm hail events are meteorologically defined as those that produce hail sizes equal to 2 cm or larger. It has been found that many thunderstorms seem to occur in an independent manner in time and space, as the results of researchers such as Colquhoun (1972) and Rasuly and Cheung (2013) have indicated that thunderstorms are typically strongly skewed in space, occasionally with extremely intense localised events. The estimation of the temporal-spatial distribution of hailstorms can be biased by these cases, particularly where there is missing data and lack of a dense hailpad network in the region. As a result, the present study examines the distribution of hail events within the long period of over 25 years and in the spatial context of a meteorologically defined area.

All hail events were extracted from the BoM Severe Storms Archive, which contains information relating to recorded severe hails, their geographic coordinates and relevant temporal attributes. In the data extracting process, a related interface device was first used to query the appropriate database. Then, all matched data were transferred to a worksheet and subsequently processed into an ArcGIS setting (Mitchell, 2005). According to BoM (2011) using these sorts of data may result in different kinds of limitations namely, completeness of data and lack of recorded observations in particularly unpopulated areas. To avoid such errors in the data and in order to analyze only the severe hail events across the region, the observations were constrained using a number of analytic stages and associated criteria. Primarily all observations recorded with incomplete records were removed from the dataset and only records evident with hails equal or larger than 2 cm have been chosen. In the final data-matching procedure, all observations were cautiously verified with the BoM's Significant Weather & Monthly Weather Review reports.

3.2 Techniques applied

In the temporal-spatial analysis of severe hailstones, a set of simple to advanced techniques were applied to the created datasets. First, an electronic worksheet was used to manage all data taken from the Australian Severe Storms Archive. Hail records for the past 25 years from 1989 to 2013 were selected because of their qualified accuracy and the current study aims. Then, the ArcGIS software was applied to manage different sorts of data layers. Sequences of entering, editing, database-creation, querying, analyzing, modelling and mapping processes have been progressively tied up (Mitchell, 2005). By creation of the main database, it was possible to find out the fundamental temporal-spatial patterns in the data across the GMSTWA framework at a GIS setting.

To understand the ongoing patterns among the data, some of the querying functions were applied. These tools visualize existing temporal-spatial variations in the data and examine spatial patterns in each dataset by fitting the provided statistics or equations to all point, vector, polygon and raster formats. More details on applying spatial indices in the current study can be found in the relevant text books (Illian et al., 2008; Lauren and Mark, 2010). In addition, to visualize distribution of hailstone magnitude

arrangements, some cartographic functions were applied and the relevant maps were generated in the GIS setting. This was done based on an adjusted TORRO Hailstorm Intensity Scale to hail events. It was assumed that hailstones with more than 2 cm in size could enforce potentially severe super hailstones imposing the uppermost possible damages to the plants, crops, buildings, city heavily infrastructures and even fatal injuries to the communities settled in GMSTWA. To illustrate the existing data based on the intensity categories, relevant hail magnitudes have been merged for a straightforward mapping purpose (Table 2).

To gain an appreciation of the longer term variability of hails frequency, the yearly data were analyzed applying a Normalized Residual Mass Curves (NRMC) offered by BoM (1991). The NRMC is defined as the accumulated difference between the actual annual hail-days for each year and the mean annual observations over total years of the record, divided by the mean of these numbers. By fitting a polynomial trend regression to the data, different periods of positive and negative hail years can be markedly recognized. For generalizing the incident geographic locations of hail an occurrence to an entire area, a kernel density interpolation estimator was introduced (Gatrell, 1994). Basically, a kernel density tool calculates the density of point features such as hail occurrence location in a search radius around all similar features. Conceptually, a smooth curved surface is fitted over each incident hail point in kernel density procedures regarding all hail observations (Gatrell et al., 1996). The surface value is highest at the location of the occurrence point and diminishes with increasing distance from the point, reaching zero at the search radius distance from the point. In practice, the density rate at each output raster cell was calculated by adding the values of all the kernel surfaces where they overlay the raster cell centre based on a quadratic kernel function (Silverman, 1986). In the final generated maps, the hail size field was used to weigh observations greater than others, depending on their locations in the geographic context of the study area. The general form of the kernel density estimator is:

$$\hat{f}_\lambda(x) = \frac{hv}{n\lambda} \sum_{i=1}^{n} K_0 \left(\frac{x - x_i}{\lambda} \right) \quad (1)$$

where K_0 (.) is the kernel function, λ is the bandwidth, n is the sample size x_i, h outlines the smoothing factor and v specifies the vertical scaling factor. More details on the subject could be found in the relevant sources (Scott, 1992; Scott et al., 2000).

All the above mentioned spatial analyses were settled and executed in a model builder framework, as automated in the standard ArcGIS software. Simply, each model builder is a geoprocessing application in which there are software facilities to enter, create, edit, query and map all spatial layers in an ArcGIS setting (Scott and Getis, 2008). In repetition, each model is a workflow that string together sequences of geoprocessing tools, feeding the output of one tool into another tool as input. Such model can also be thought of as a visual programming language for building the final models. In the current study, all GIS layers were introduced as major dataset inputs in a specific model builder setting by including spatial analyzing indexes (Rasuly, 2005).

4 Results

4.1 Diurnal patterns and monthly variability

As a result of frequent passages of different air masses and effects of climatic parameters in unstable atmospheric conditions, the GMSTWA experiences a wide variety of severe hailstorms in all seasons. Usually, warmer months have thunderstorms with severe hailstorms, some of them deadly and often quite damaging to the environment, crops, and property (Spark and Casinader, 1995). The goal of the current section is to present information on all time scales and their associated spatial distribution characteristics.

The total number of 357 events ranging from hail size of 2 to 12 cm was selected and for the purposes of the current study was placed into 2 h bins in the Australian Eastern

Standard Time (EST). As it is shown in Fig. 3, there is a marked daily distribution of hail frequency during the afternoons peaking between 3 and 5 p.m., with 131 events and nearly 37 % of all observations. A vast majority of severe hail events (79 %) occurred between 1 and 7 p.m. during the peak surface heating hours in the region. An additional 13 % of all severe hail events occurred during the early to late evening hours (7 to 11 p.m.) when instabilities are still high. A minimum number of events (about 4.5 %) occurred from 1989 to 2013 during overnights (11 p.m.–1 a.m.). Seemingly, the chance of hail occurrence during early morning (3 a.m.) till noon (11 a.m.) is very low, which is less than 3.5 % of all events.

By providing consistent information on hail events in the relevant GIS dataset, the diurnal variation of hail occurrence was examined in details in a spatial context. Simply, all observations were divided into five separate periods as indicated in Table 3. The majority (nearly 69 %) of hails occurs in the afternoon (12–6 p.m.), which is similar to other findings in Australia (e.g., Batt et al., 1995), whereas there are minimum of hails that occurred during the morning. In general, these results indicate that although hails can occur at any time of the day throughout the study area, most of them fall in the afternoon periods.

Figure 4 shows the range of intensity for hailstones in the GMSTWA for different daily time periods. Undoubtedly, the level of damage largely depends on other accompanying severe thunderstorms events (gusty winds or very intense thundery rains), which possibly occurred in the period of individual hailstorm event (Bahr et al., 1973). It can be seen that hailstones ranging from 2–12 cm occurred throughout the study area, while the larger hailstones were also widespread in the GMSTWA, particularly in the Sydney Metropolitan and Blue Mountains GLAs.

The spatial distribution of hailstones during the peak-time occurrence (15:00–17:00 EST) is shown in Fig. 5e. Nearly about 131 hailstone events have been reported within this peak period from 1989 to 2013 inside the LGAs. Majority of larger-sized observations (more than 6 cm) were reported from the study area, somewhere inside the Sydney Metropolitan, south of Hawkesbury and Wingecarribee LGAs; whereas small-size hail events could be seen throughout the GMSTWA.

Over longer time scale, the monthly distribution of hail events shows a marked pattern throughout the year. Figure 6 shows the monthly frequency of hail events within the 25 year period. There is a distinct tendency for all thunderstorms to occur during the months September through to March. This period is normally referred to as the Severe Thunderstorm Season in the region (BoM, 1995b). The increase in storms during this period is primarily due to the increase in energy provided by the sun during the warmer spring (September, October and November) and summer (December, January and February) months, coupled with timely synoptic weather patterns that are favorable for storm growth (Matthews and Geerts, 1995; Matthews, 1996).

Of the 357 severe hail events (hail diameter exceeding 2 cm) across the GMSTWA since 1989, 33 % of the reports occurred from September through November (spring), and 49.5 % from December to February (summer). December is the peak month for the occurrence of severe hails with 22 % of the events reported. May through August is the least likely time to expect severe hail with only 17 events since 1989 until 2013. Meanwhile, March and April as transitional months in term of climate have considerable hail events with more than 12 % of observations. The monthly descriptive statistics of hails for different months is indicated in Table 4. Hailstones are expected to occur most frequently in November and December, and least frequently in June and July. Commonly, the warm months from October to February clearly dominate the hail activities.

More dilates on the spatial patterns of warm-month hailstones based on an adapted TORRO Scale was considered. As shown in Fig. 7, a large spatial variability of hail occurrence was distinguished in the GMSTWA during the warm months (October, November, January and February), with maximum hails observed in the Sydney Metropolitan and Blue Mountains and a general decreasing tendency towards to the west of the study area. An increasing tendency of hailstone frequency and sizes can be noticed from October to November. In a similar manner, it was found that in January, February and even March (as the first month of autumn) spatial corresponding models indicate

that frequency and the range of hailstones are higher in the Sydney Metropolitan and the southwestern parts of the GMSTWA. As it is clear in Fig. 7e, the greater part of hailstones was observed in the Sydney Metropolitan area in December, from 1989 to 2013. The hails were mainly oriented from southwest to northeast direction throughout the GMSTWA. There are also considerable dissimilarities in hailstone sizes reported from the study area.

4.2 Seasonal to internnaual variability

There is a considerable seasonal variation in hail events inside the GMSTWA (Fig. 8). As expected, in response to the warm climatic environment and unstable atmosphere, hailstorm activity is highest during spring (September–November, 33.3 % of events) and summer (December–February, 49.6 %), and weakest during autumn (March–May, 14 %) and winter (June–August, 3 %). For the entire GMSTWA the maximum hail event numbers occur in the late spring and early summer, however, there are considerable differences within the ten LGAs. As is shown in Fig. 9, in spring nearly 119 hail events have been reported in the region. The hail sizes range between 2 to 12 cm and an average of 3 cm. In summer, the number of hails increases to 177, with the maximum of 11 cm in hailstone observations was reported from the Sydney Metropolitan Area. In contrast, in autumn and winter the study area received less hails and minimum of hailstone sizes. On average, higher number of hails are expected to occur in the Sydney Metropolitan, Blue Mountains and Wingecarribee that is mostly parallel to the NSW's Alps.

The broadest time scale over which hail events varies is the year-to-year variation in their frequency and hailstone size. Annual frequency of hail events and associated days, reported in the GMSTWA is shown in Fig. 10a. Comparison of the number of years above and below the averages (14.3 for hail events and 6.8 for associated hail days) shows that there is a fluctuating pattern with high and low years. For example, from 2000 to 2005 and more significantly in 2007 considerable hails have occurred in the region. In contrast, the number of hails was significantly reduced after 2009 with less than 5 events. Likewise, the frequency of hail days during 1989 to 2013 has an average number of 6.8. A maximum of 12 hail days occurred in 2001, while the second maximum of 11 was recorded in 2008. On the other hand, a significant drift in hail days is prominent during the recent years in the study area. It could be argued that, the existence of a speckled relationship between hail frequency and associated hail days may be explained by the skewed nature of thunderstorms and indeterminate observation policy in the region (Tucker, 2002).

To model the longer extent variability of hail days, the yearly data were examined applying a Normalized Residual Mass Curves (NRMC) offered by BoM (1991). The NRMC is defined as the accumulated difference between the actual annual hail days and the hail days for each year and the mean annual observations over total years of the record, divided by the mean of these numbers. A NRMC model was fitted for the GMSTWA's hailstones reported from 1989 to 2013. Figure 10b clearly shows sequences of positive (wet) and negative (dry) years in the time series of hail days. Besides, by toting up a polynomial trend regression to the data, different phases of high and low cyclical progressions of hail occurrences can be explained by the relevant fitting equation (with explained variance $r^2 \approx 0.6$). As it is shown by a blotch line on a yearly scale, the study area was extremely threatened by the higher number of hailstones in two periods of 1990–1994 and 2000–2008 respectively.

Figure 11a indicates the spatial pattern for hail events in different LGAs. Mostly, the higher number of hail events and the largest magnitudes were frequently reported from the Sydney Metropolitan, Blue Mountains, and noticeably the southern and northeastern part of the study area. Hence, in a broad extent the hail frequency and associated sizes are not at all evenly distributed throughout the study area. In a geographic context of the GMSTWA, the overall pattern of hail occurrence can be identified in regard to the LGA boundaries (Fig. 11b). It is clear that many hailstones were observed in the central parts of the GMSTWA, with a west-to-east orientation. In a smaller extent, it also appears that two of the LGAs: Wingecarribee and Hawkesbury received more hail events than the others.

4.3 Hailstone magnitude patterns

One of the more important aspects of hail climatology is the magnitude of the hailstones that occur (Changnon, 1977). The magnitude of a hailstone matters considerably when accounting for damage such as: risk of serious injuries, severe damage to all buildings, city constructions and agricultural products. Some previous studies have concluded that most property damage begins when hailstone diameters are 2 cm or larger (Morrison, 1997). The larger the stones, typically the greater the property damage would result. However, most losses are not linearly related to the stone sizes (Changnon et al., 2012).

Therefore, the key aspect of the current research would be illustrating the hailstone magnitude patterns across the LGAs. Figure 12 presents a series of maps based on an adjusted TORRO Hailstorm Intensity Scale. Comparatively, almost every region inside the GMSTWA is dominated by small stones that vary within 2–4.1 cm. Nonetheless, a few LGAs such as Sydney Metropolitan, Wingecarribee and Gosford LGAs have experienced hails of higher magnitudes. Overall, small- to medium-size hails (2–4.1 cm) show a wider distribution with a large number of stones (72 %) throughout the GMSTWA. Whereas hails with size 4.2–6.1 cm account for 20 % of events, hails with higher magnitude (6.2–12 cm) contributes approximately 8 % in the final areal distribution patterns.

An important finding is that as the hailstone magnitude increases, the largest yearly hailstones were observed merely inside the Sydney Metropolitan Area (Fig. 13a). As Fig. 13b indicates, the number of hailstones with the highest magnitude range reported inside the Sydney Metropolitan was much larger than the other LGAs. This highest yearly hailstone inside the GMSTWA fluctuated in the early part of the study period up to about 2007 (Fig. 14). As the number of hail occurrence is reduced after 2007 (compared with Fig. 10), the associated yearly maximum in magnitude declines correspondingly during the time period considered.

Lastly, Fig. 15 presents the possible patterns for low, moderate, high and very high potential hazardous hailstones based on the available data analyzed. A raster-based distribution pattern evidently indicates that the highest potential on hail occurrence is inside the Sydney Metropolitan and Blue Mountains. In the meantime, hail magnitudes over much of the LGAs appear as low or in a moderate level. By careful inspection of hail distribution patterns, two more incidence causeways can be visually recognized: one passage curving from the southwest to the northeast, another one topping some parts of the coastal districts such as Kiama, Shellharbour, Gosford and Wyong located nearby the Tasman Sea.

5 Discussion

In this study the relevant data on hail events from 1989 to 2013 have been examined by applying a climatologically-oriented GIS in the GMSTWA as an important severe thunderstorm warning area. Based on a modified TORRO intensity scale, the temporal-spatial distribution of hail frequency, hail days and hail magnitudes have been objectively analyzed. It was found that they are neither temporally nor spatially uniform throughout the study area. Temporal models indicated that most of the hailstones occurred predominately in afternoons with peak time of 3–5 p.m. local time, as the results are indicated in Table 3 and illustrated by Figs. 3 and 5. They are particularly common in spring and summer seasons, and reaches maximum frequency in December (see Figs. 7e and 9). Interannual variability of hail frequency and hail days signifies a decreasing trend for the recent years, as it comes out from the NRMC model fitted for trend lines (Fig. 10). In turn, the spatial models established four distribution patterns over the study area, illustrating the Sydney Metropolitan Area, Blue Mountains, and Wingecarribee with non-coastal and likely costal effects (see Figs. 11 and 13). On the whole, results from these models are in accord with those in the literature, with the exception of the temporal-spatial fluctuations in recent years (Fig. 14). Explanations for

the variable nature of hailstorms in the GMSTWA are complex. Various mechanisms could be proposed for the observed diverse temporal-spatial patterns in the region.

The fact that nearly all the LGAs in the GMSTWA have a afternoon/early evening diurnal maximum in hail activity suggests that the distribution of severe hailstones are being controlled by the main local climatic factors such as air and sea-surface temperatures and humidity. Such thermodynamic actions could be intitated by involving solar radiation and local environmetal convection processes (Whetton, 1990; Leslie et al., 2008). It is also likely that some types of severe hailstorms may be influenced by physiographic parameters such as topographic features, Sydney Metropolitan's arrangements and proximity to the Tasman Sea as a potential coastal influence (Carras, 1982; Rasuly, 1996). These parameters may play an important part in the more local nature of severe hailstorms development in the region. Results of the current study lead to an initial conclusion that different landcover/landuse patterns, for example the more dense residential and city areas, are able to affect the temporal-spatial distribution of hailstones. Evidence of a substantial increase in total hail events in the Sydney Metropolitan (with 185 events, nearly 52 % of all observations) can be seen from Figs. 11 and 12. This increase was found stronger for the very distractive and super hailstones. A density analysis quantities model (Fig. 15) confirmed the assumption that in the study area, the effect of "built-up" areas upon the distribution of hailstones is quite real. Spatial models indicated that both aspect and elevation influence the occurrence of hailstones in the study area, particularly in high-altitude areas over the Blue Mountains and Wingecarribee Plateau. There are three possibilities to explain how the region's terrain is able to influence thunderstorm activities and associated hailstorms so considerably.

First, the daily heating of the hillsides generates warm up-slope winds which continue rising after reaching the top of ridges and trigger deep vertical convection. The hailstone patterns (particularly hail size 2–4 cm) over Blue Mountaines throughout the warm months would be dominated by this mechanism. Secondly, convection systems can occasionally be developed over the Tasman sea during unstable conditions

(Buckley et al., 2001). These systems may move toward the west of region, and they may be cut off by the elevated terrains due to an air-mass modification effect. One way or another, this mechanism may explain some of the severe hailstorms with large size hailstones over parts of the elevated areas inside of GMSTWA, which is another sign of orographic control upon the distribution of hail event occurrences. Topographic units located near the coast also have an extra influence upon hailstones patterns. For instance, places along the Illawarra or Hornsby Plateaus experienced relatively more and larger size of hailstones, illustrating the effect of elevation and exposure to humid winds (Shepherd and Colquhoun, 1985). It is evident from the hail distribution maps that the coastal areas east of the Sydney city achieve much higher number and larger size of hailstones than those located inland, as a result of mesoscale circulations in the lower atmosphere over the coastal areas. Such storms may develop in response to a differential surface heating in the region with dissimilar landcovers (Atkinson, 1975). An alternative mechanism is the possiblity that some weather systems such as lows may occasionally be accompanied by convection activity enhanced by neraby seas or advection of heating processes at the coastlines (Andrews et al., 1996). Dominatedly, the combination of moist, warm and unstable air masses provides the most favourable conditions for hailstorm development in the coastal areas. This is why they are more common at or parallel to the coastal weather districts and especially those located over the elevated areas (Schuster et al., 2005). Sydney's bowl-shape region is the last physiographic factor that may affect hailstorm initiation and development. Such landform has a low plain in the middle, named the Cumberland Plain opening to the Pacific Ocean from the east and effectively walled on the three sides by hills and mountains. Such complex physical environment together with the highly "built-up" areas can considerably influence the spatial distribution of hailstones (Rasuly, 1996).

Most importantly, as it was highlighted by different authors such as Kounkou et al. (2009), atmospheric conditions favorable for hailstorm development are often available when synoptic weather patterns and mesoscale mechanisms promote instabilty in the atmosphere or enhance present unstable conditions. Various synoptic-scale

features such as lows and fronts can be also connected with severe hailstones (Ryan, 1992). Recently, McBurney (2012) analyzed the meteorological parameters associated with hailstorm developments in the Sydney Metropolitan Region over a long period of 1950–2010. These parameters include humidity, stability convective available potential energy (CAPE), directional wind shear, precipitable water and existence of dry slot. It was found that hailstroms across Sydney typically developed under only moderate CAPE, however, directional shear, large moisture depth, high precipitable water and dry slot all seemed to be essential ingredients for hailstorm development. Besides, the interannual variability of hail activity is due to the broad synoptic weather patterns that cause convective hailstorms, which vary from year to year resulting in some periods being more active (Knight and Knight, 2001; BoM, 2012b). Lastly, some phenomena such as sea surface temperature anomalies, El Niño Southern Oscillation (ENSO) may meaningfully influence the occurrence of hailstones in the region over long time scales (Yeo et al., 1999; Kuhnel, 1998; Yeo, 2005; Niall and Walsh, 2005). McBurney (2012) also briefly examined how the meteorological parameters associated with hailstorm development were affected over climatic time scale. It was found that the geopotential height at various levels is significantly correlated with the annual hail frequency. The vertical and horizontal wind shears also showed different mean values for active and inactive periods of hailstorm. In regard to climate variability, McBurney (2012) found that besides ENSO, the Southern Annual Mode also has substantial effect to the mean-sea-level pressure and geopotential heights at various levels, and in turn hailstorm development.

To summarize, in the context of the GMSTWA complex climatic environment, each severe hailstorm needs three main ingredients for development. Moist air is a very important necessity because when it condenses to form cloud, heat energy is released making the rising air more buoyant and "fueling" further hailstorm cloud growth (Andrews et al., 1996). Such sources can be injected to the air masses from the nearby Tasman Sea or weather systems occasionally affecting the region. An unstable atmosphere is necessary so that developing cloud is able to rise freely to great heights in the atmosphere (Deslandes et al., 2008). Besides, initiating mechanisms are also needed as they serve as a focus for storm development. Typical mechanisms that initiate hailstorms are fronts, troughs and low pressure systems in the regions (Speer and Casinader, 1994). As was already discussed, features of topography such as hills and mountains may also enhance storm development. The severity of any subsequent hailstorms will depend largely on the buoyancy of the rising air within the supercell thunderstorm, the structure of the wind and available moisture within the atmosphere (Doswell and Brooks, 1993). All the aforementioned concepts have to be verified in future investigations, possibly through numerical modelling, by unfolding other relevant pieces to the current study.

6 Concluding remarks

Hail events vary tremendously in terms of size, location; intensity and considered frequent occurrences throughout GMSTWA. It is assumed that all of the LGAs are uniformly exposed to hailstone samples (357 events) just as they are exposed to the thunderstorms that may generate the subsequent hailstorms. This study analyzes all the available hail events during the past 25 years and their temporal-spatial characteristics by applying a climatologically oriented GIS. Unlike most previous studies that mostly examined single but major hail events over a short period in the region, the present study analyzed all the hailstone observations at a longer time scale with the most precise and accord records. According to the applied criteria and techniques used, the final outcomes are summarised as follow:

- Hailstones are neither temporally nor spatially uniform inside the GMSTWA. They reflect largely the impacts of climatic, environmental parameters and synoptic weather systems in the region.

- Appropriate temporal models indicated that most of the hailstones occurred in afternoon and early evening predominately, particularly in the summer months with a maximum in December.
- Spatial distributions established four main patterns over the study area, including the Sydney Metropolitan, topographic and coastal effects. It was found that some of the LGAs, predominantly the Sydney Metropolitan Area, obtain many more distractive and super hailstorms than others. Such spatial variation is associated with the thermodynamic and kinematic characteristics of the Sydney landuse patterns since intense urbanization results in the heaviest severe hailstorm activities.
- In a wide-ranging scale, the spatial distribution of hailstones follows a gradient between inland and coastal areas. Their spatial appearance suggests that they are being meaningfully controlled by the Sydney’s bowl-shape landscape arreangment.
- Kernel density model, resulted by applying GIS techniques, confirms the reliability of spatial movements of hailstones from the Blue Mountains to the Sydney Metropolitan Area (or vice versa), where three of the major and most required ingredients of severe hailstorm development: moist air, unstable atmosphere and initiating mechanisms are abundantly provided, particularly during the warm months.

Overall, patterns emerged in the final models are in accord with the literature except the results from the temporal-spatial trend models. In the past decade, the GMSTWA has experienced less hail events and fewer distractive and super hailstones. However, this concluding outcome should highlight the substantial hazardous situation of the Sydney Metropolitan Area because the future impacts from climate variability to the hailstorm frequency and magnitude in the region need further studies, especially under an unpredictable future climate change. In any circumstance, the information obtained here can be used in many areas such as urban planning, hailstone impact preparation, risk control programs and emergency response management.

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Table 1. Examples of major hailstorms reported in the GMSTWA extracted from the hail GIS database.

Date (1989–2013)	Nearest Town	Weather Forecast District	Maximum Hail Size (cm)	Intensity Category and Estimated Costs AUD Million Dollars (MD)
18 Mar 1990	Liverpool and Bankstown	Sydney Metropolitan	8	Supper hailstone, 400 MD
21 Jan 1991	Turramurra and Duffys Forest	Sydney Metropolitan	7	Very distractive, 560 MD
14 Apr 1999	Surry Hills	Sydney Metropolitan	9	Supper hailstone, 1.7 Billion
3 Nov 2000	Yennora and Greystanes	Sydney Metropolitan	7	Very distractive, unknown
9 Dec 2007	Sydney suburbs	Sydney Metropolitan	11	Supper hailstone, 470 MD

Table 2. An adjusted TORRO Hailstorm Intensity Scale (H_3 to H_{10}) for the GMSTWA hailstones.

Size Code	Intensity Category	Size (diameter in cm)	Typical Damage
H_3	Potentially Severe	2–3.1	severe damage to gardens, trees, plants and crops
H_4	Severe	3.2–4.1	widespread glass, skylights, likely damages to buildings and cars
H_5–H_6	Destructive	4.2–6.1	widespread destruction of trees, roofs, and risk of injuries, and serous damages to cars, aircraft bodywork dented and brick walls pitted
H_7–H_8	Very Destructive	6.2–7.7	severe roof damage and risk of serious injuries, and severe damage to all buildings and city structures
H_9–H_{10}	Super Hailstones	7.8–14	extensive structural damages and could cause fatal injuries

Table 3. Diurnal distribution of hail events in the GMSTWA.

Local Time (EST)	Number of Hail Events	Percentage	Max Hail Size Seen (in cm)
00:00–06:00	15	4.2	4.4
06:00–12:00	3	0.84	5
12:00–18:00	245	68.62	11
18:00–24:00	94	26.33	7
15:00–17:00	131	36.7	11

Table 4. The monthly statistics of hailstones for different months.

Season	Month	Number	Average (cm)	Maximum (cm)
Spring	Sep	18	3.0	5
	Oct	44	3.8	8
	Nov	57	3.0	7
Summer	Dec	80	4.0	11
	Jan	48	3.0	7
	Feb	49	3.2	7.5
Autumn	Mar	29	3.0	7.5
	Apr	15	3.7	9
	May	6	2.3	3
Winter	Jun	2	2.0	2
	Jul	2	2.5	3
	Aug	7	2.4	3

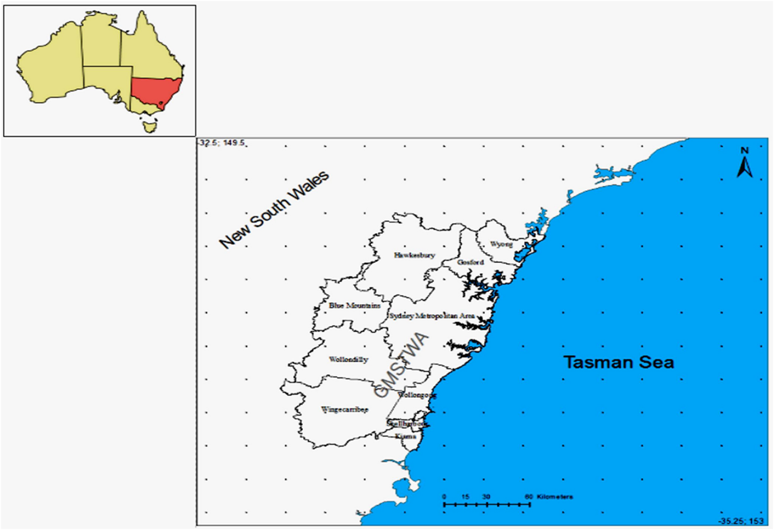

Figure 1. The location map of the study area.

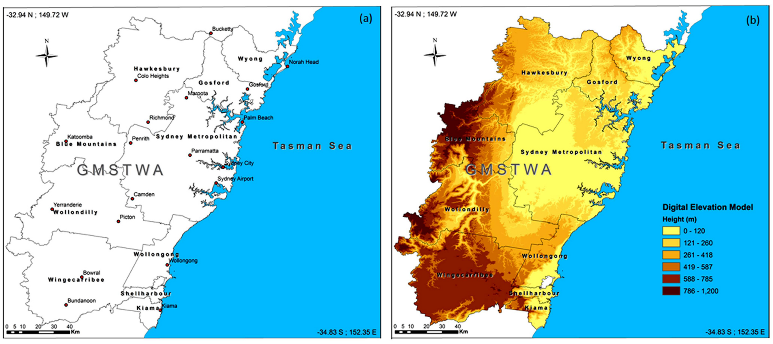

Figure 2. (a) The location map and **(b)** an elevation model of the GMSTWA.

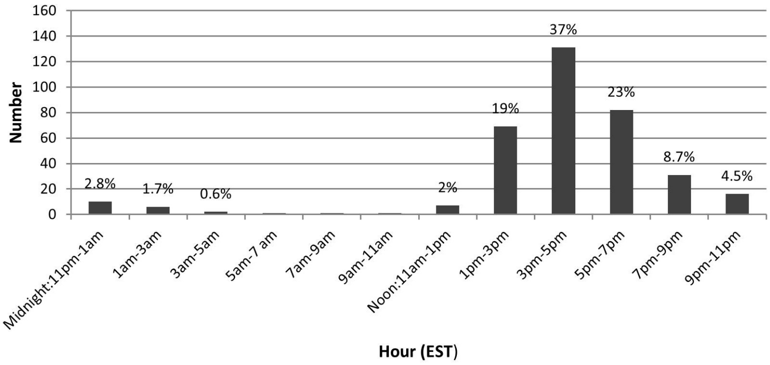

Figure 3. Diurnal distribution of hail events in the GMSTWA during 1989–2013.

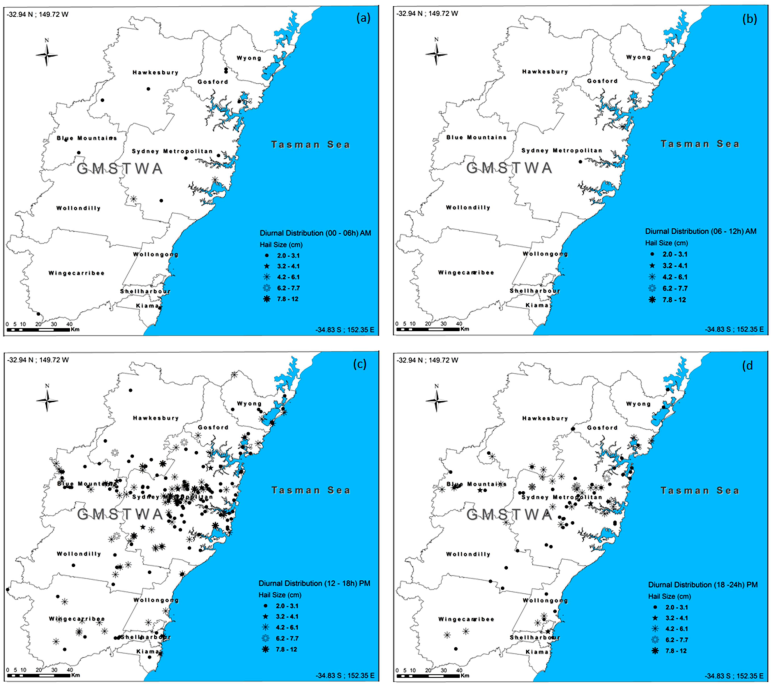

Figure 4. Spatial distribution of the hailstone events in the GMSTWA during **(a)** 00:00–06:00, **(b)** 06:00–12:00, **(c)** 12:00–18:00 and **(d)** 18:00–00:00 EST.

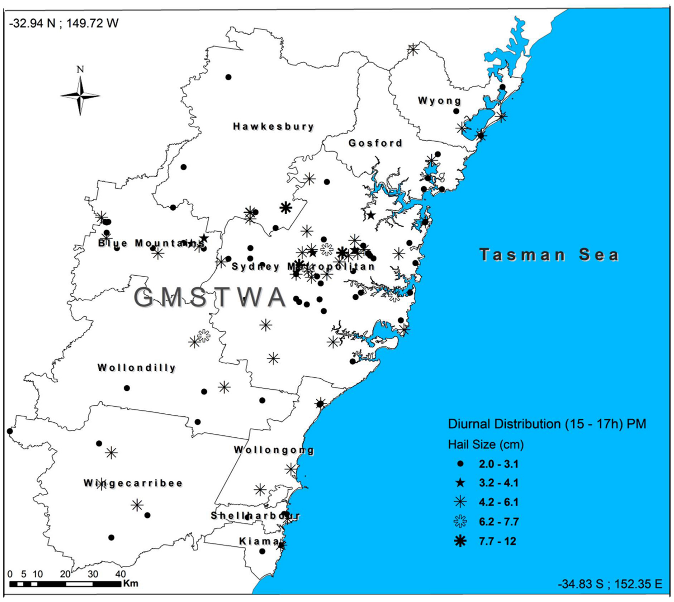

Figure 5. Spatial distribution of the hailstone events for peak time occurrences during 15:00–17:00 LT (EST).

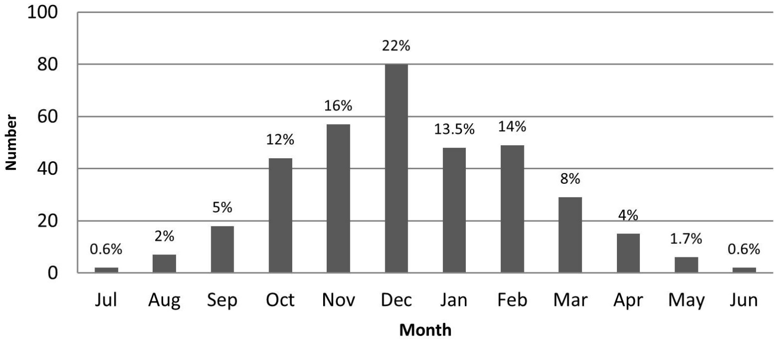

Figure 6. Monthly distribution in percentage of hail frequency in the GMSTWA during 1989–2013.

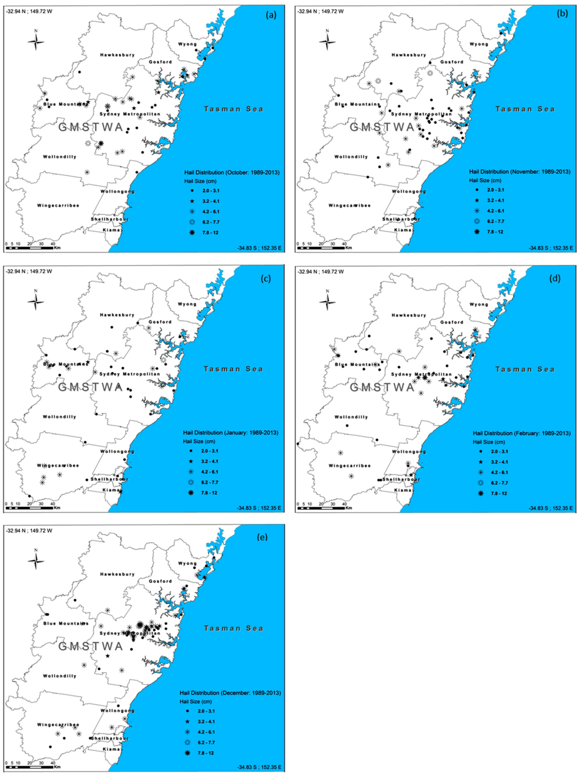

Figure 7. Spatial distribution of hailstones during the warm months of **(a)** October, **(b)** November, **(c)** January, **(d)** February and **(e)** December with peak hail activity in the GMSTWA.

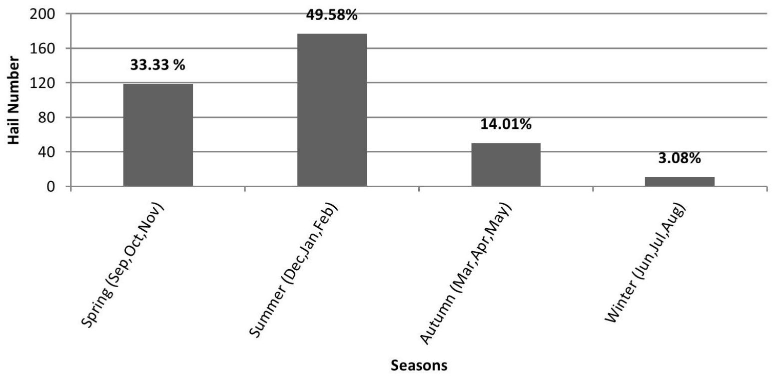

Figure 8. Seasonal distribution in percentage of hail frequency in the GMSTWA during 1989–2013.

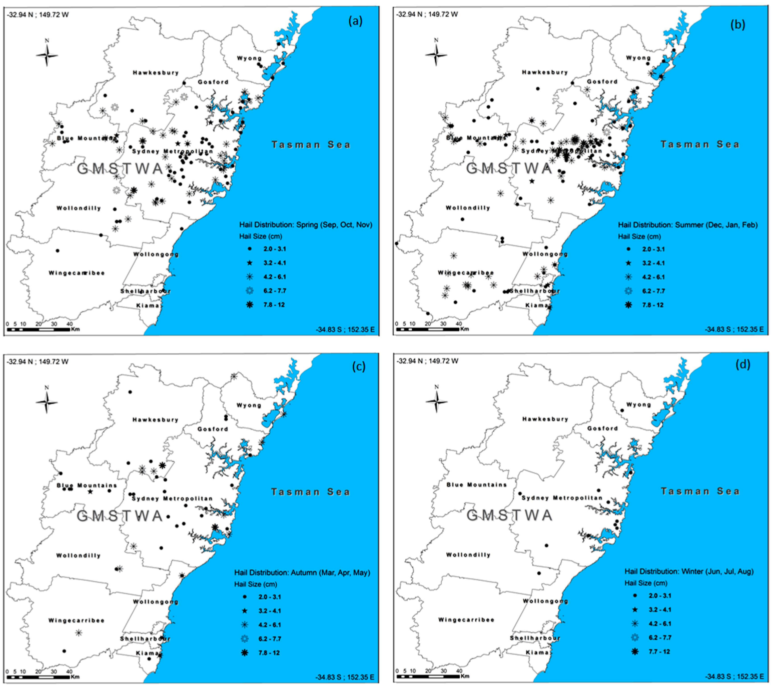

Figure 9. Seasonal distribution of hail events during **(a)** spring, **(b)** summer, **(c)** autumn and **(d)** winter in the GMSTWA during 1989–2013.

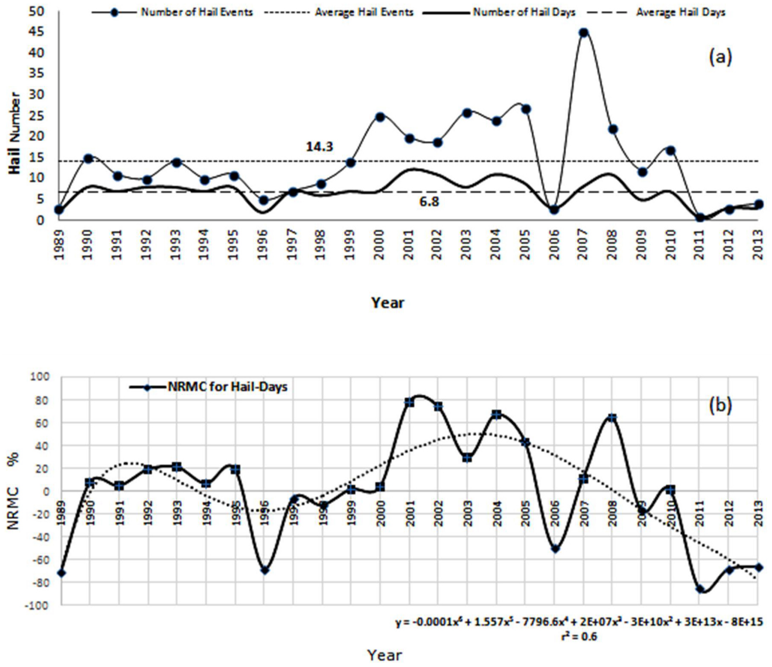

Figure 10. (a) Time series of the hail events and associated hail days and **(b)** NRMC model-fitted trend lines for hail days reported in the GMSTWA during 1989–2013.

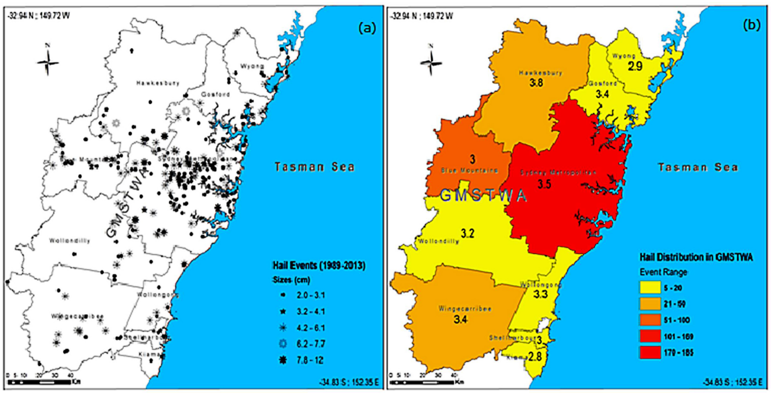

Figure 11. Spatial distribution of **(a)** individual hail events and **(b)** area-average hailstones in the GMSTWA.

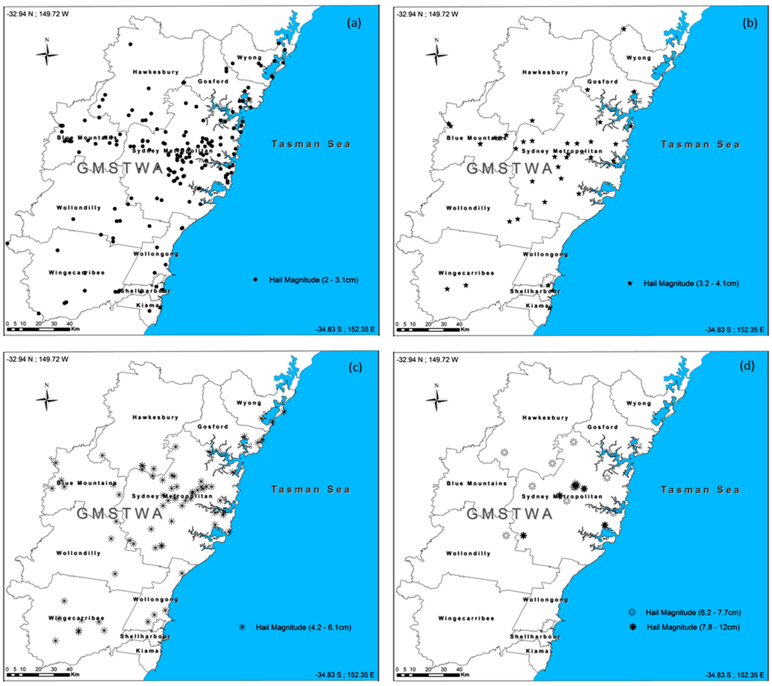

Figure 12. Spatial distribution of hails with magnitude category **(a)** 2–3.1, **(b)** 3.2–4.1, **(c)** 4.2–6.1 and **(d)** 6.2–7.7 and 7.8–12 cm in the GMSTWA.

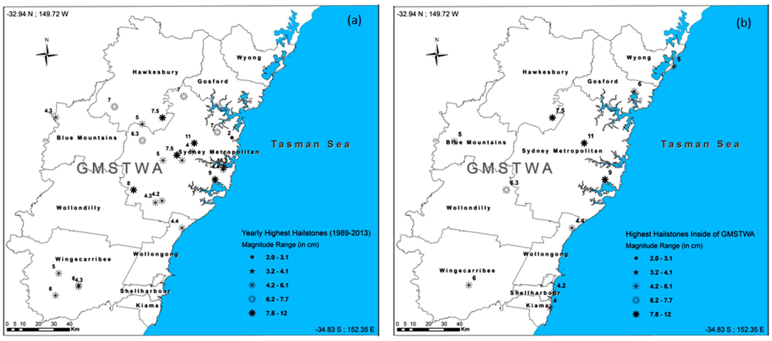

Figure 13. **(a)** The yearly highest hailstones reported from LGAs and **(b)** the largest hailstones observed inside the GMSTWA.

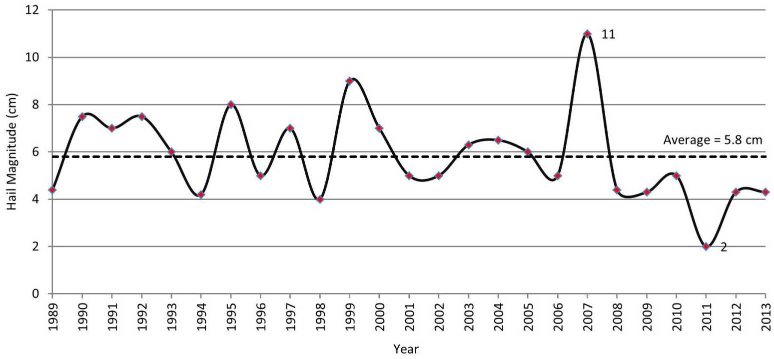

Figure 14. Time series of the frequency of the largest yearly hailstones.

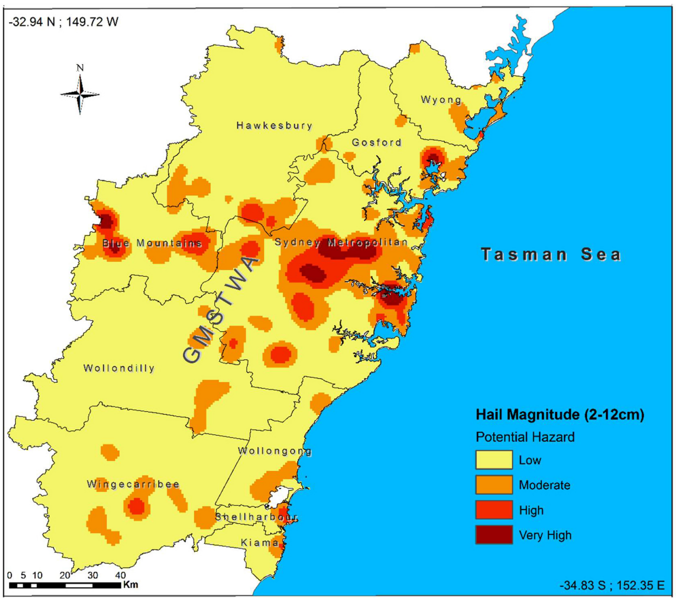

Figure 15. A raster-based hail magnitude density model in the GMSTWA.