142 HAIL CLIMATOLOGY OF AUSTRALIA BASED ON LIGHTNING AND REANALYSIS

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1. INTRODUCTION

The highly uneven distribution of population in Australia creates major shortcomings in the reporting of severe convective storms. With the majority of the population residing on the southeast coast around the major cities of Sydney, Melbourne, and Brisbane (see Fig. 1a), almost all of the storm reports are located there (Fig. 1b). Additional high density reporting areas are around Perth and Adelaide. In order to fill in the gaps and estimate the true severe storm frequency in low population regions, other data sources are sought. Gridded output from numerical models and remotely-sensed observations are two types that offer a method to achieve this. Reanalysis-based severe environments can indicate the potential for severe weather, and lightning indicates the realization of convection. The combination is expected to relate to the occurrence of severe weather. Only hail is investigated in this study.

This paper is divided into the following topics: Section 2 describes the datasets and methodology. Section 3 presents the individual climatologies from the data. These individual climatologies are combined in section 4 to predict the true hail climatology. Section 5 compares the results with other studies, and section 6 provides a summary and conclusions.

2. DATA AND METHODOLOGY

The three datasets used in this study are storm reports, lightning, and reanalyses. The storm reports come from the Bureau of Meteorology (BOM) Severe Storms Archive. This database covers the period 1796-present, with the majority of entries occurring in more recent years. A large increase in the number of hail reports occurs around 1990 (not shown), which corresponds with the beginning of a storm spotter network. After 1990 the number of annual reports appears to level off. Even though the annual number stabilizes, there are still heavy population biases in the data, so the reported number of hail events is still an underestimation of the true count.

Lightning comes from flashes recorded by the Lightning Imaging Sensor (LIS; Christian et al. 1992) onboard the Tropical Rainfall Measuring Mission (TRMM) satellite. The LIS is an optical sensor that detects above background level light flashes. The satellite is only over an area for a short period of time a few times per day, so the total lightning activity is an underestimate. However, since the satellite does not trace the same path with each pass, over an extended period of time any spatial differences should even out allowing for relative magnitudes to be compared. One disadvantage of this sensor for Australia is the orbital inclination of the does not

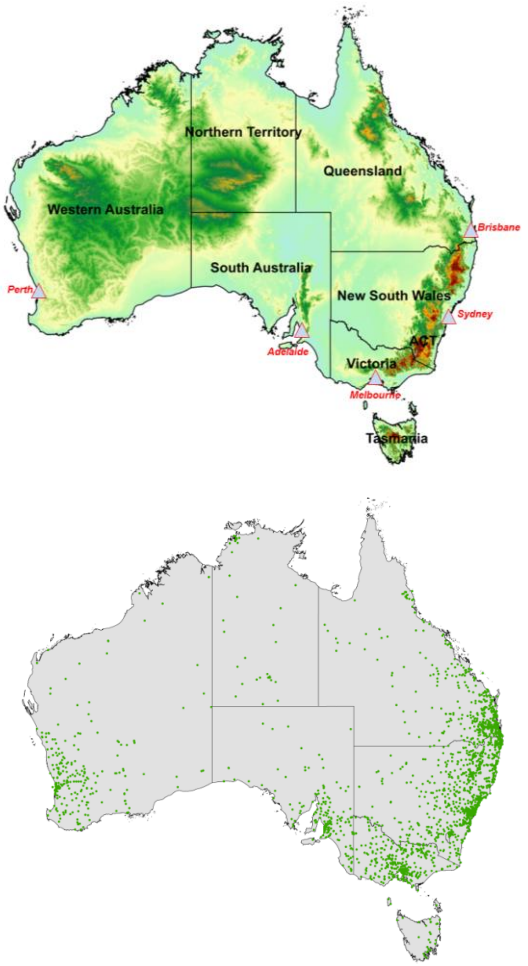

Fig. 1: (top) map of Australia with states and key cities labeled; (bottom) locations of all hail reports in BOM Severe Storms Archive (1795-2013).

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allow Tasmania and parts of southern Victoria to be in the field of view. The first complete year of LIS data is 1998, and it extends to present.

The NCEP Climate Forecast System Reanalysis (CFSR; Saha et al. 2010) is used to represent the atmospheric state and identify severe hail environments. It is based on a coupled atmosphere-ocean model run at approximately 38 km resolution with 64 vertical levels. A GSI 3DVAR system assimilates observations on a six hourly cycle. The product used for this study is available at 0.5° grid spacing on 37 pressure levels for the period 1979-present.

The years 1998-2012 are chosen because all three datasets exist for that period. The CFSR grid is used as the basis for analysis since it is the coarsest of the three. Both hail reports and lightning flashes are binned on the 0.5° grid and aggregated to hail and lightning days. To represent a severe hail environment, the Significant Hail Parameter (SHIP) is calculated from the atmospheric variables in CFSR.

$$SHIP = \frac{CAPE * w_v * \Gamma_{700-500mb} * -T_{500mb} * BWD_{0-6km}}{4.2 * 10^7}$$

where CAPE is the convective available potential energy, w_v is the water vapor mixing ratio, T_{500mb} is the temperature at 500 mb, and BWD_{0-6km} is the bulk wind difference from 0-6 km. Two modifications to this are introduced. First, the bulk wind difference is required to have a minimum value of 10 m s^{-1}. Second, the CAPE is thresholded at 2000 J kg^{-1}. These were added due to consistently high values of CAPE in the tropics that were considered to have too much influence on SHIP. A severe hail environment is identified by the maximum daily (00 to 00 UTC) modified SHIP exceeding a value of 0.5.

On a daily basis the intersection of a severe environment and lightning is calculated for each grid cell, and they are aggregated for the 15 year period. A linear model is fit to the hail reports of the five largest cities: Sydney, Melbourne, Brisbane, Perth, and Adelaide. It is assumed that the reporting is accurate in those locations because of the high population density. This model predicts for all grid cells the true number of hail days based on the number of days of lightning and severe environment intersection.

3. INDIVIDUAL CLIMATOLOGIES

The total reported hail days by grid cell for the period 1998-2012 is shown in Fig. 1. The vast majority of reports occur along the southeast coast, where most of the population resides. Major cities can be identified by local maxima in hail days. The grid cells containing Sydney and Brisbane both report about 3 days per year on average.

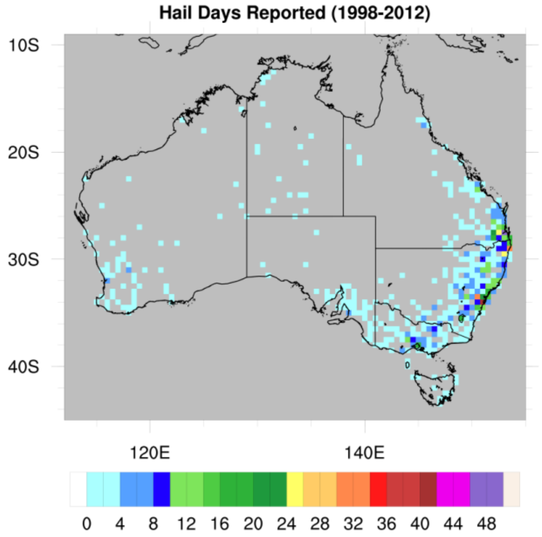

Fig. 2: Total number of reported hail days per grid cell (1998-2012).

Figure 3 shows the total lightning days as calculated from LIS lightning flashes. The greatest activity is along the coast of northeast Western Australia and northwest Northern Territory. There is a secondary maximum in New South Wales. Greater convective activity along the northwest coast is related to the influence of the Indo-Australian Monsoon with which the flow is predominantly onshore from the northwest during the wet season (summer months). In the mid-latitude regions, differences between the east and west coasts are related to ocean currents. The colder current in the west provides a more stable environment, reducing convective activity. The warmer current in the east combined with mountainous terrain near the coast provides a more conducive environment for thunderstorms to develop. The middle of the country is very dry, causing a minimum in lightning activity there.

The total days of severe hail environments—represented by SHIP exceeding a threshold of 0.5—are in Fig. 4. Most frequent locations of environments are the eastern coast, roughly between Sydney, NSW, and Townsville, Qld. There is some extension inland past the Great Dividing Range to this area of higher hail environment frequency. The northwest coast also experiences a high frequency of severe

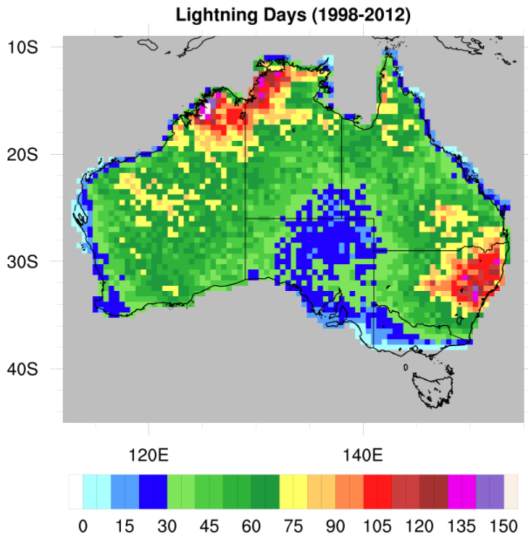

Fig. 3: Total number of lightning days per grid cell (1998-2012) as measured by LIS.

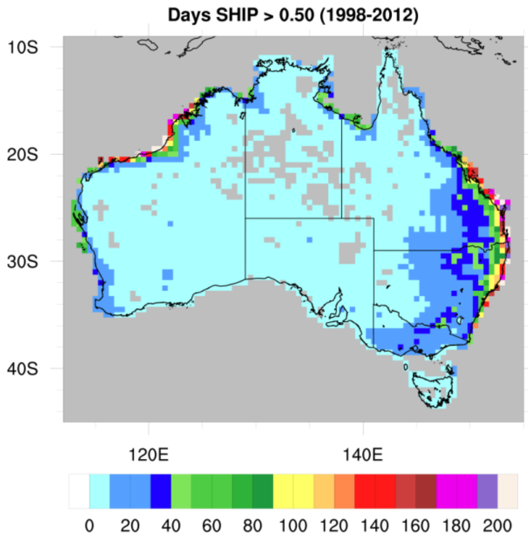

Fig. 4: Total number of days per grid cell (1998-2012) SHIP exceeded a value of 0.5.

environments, however the decay as one heads inland is much more rapid there than on the east coast. Other minor areas of elevated SHIP frequency include the south coast of the Gulf of Carpentaria and the west coast of Western Australia, extending south to Perth. Some locations—particularly in the middle of the country—never exceed the parameter threshold due to the dry, desert environment for much of it. Individually, both the lightning and severe environments tend to coincide with the location of a maximum in hail activity on the east coast. However, the northwest coast is an area where lightning and environments suggest hail activity, but there are practically no reports to back them up. This is a very sparsely populated region, so if there were significant hail activity, it would not be expected to be reported.

4. HAIL CLIMATOLOGY PREDICTION

The aggregated daily intersection of lightning and severe hail environments is smoothed to remove some high frequency variability. Then, the days of reported hail are plotted against the smoothed days of lightning and environment intersection for the grid cells containing Sydney, Melbourne, Brisbane, Perth, and Adelaide (Fig. 5). A linear equation is fit to the data with the constraint of a zero intercept, which conforms to the idea that zero days of lightning and severe hail environment should correspond to zero days of severe hail.

This equation is then used to predict hail days for all grid cells. The map of predicted average annual hail days is in Fig. 6. It shows a clear maximum along the eastern coast, roughly between Sydney and Brisbane. Other smaller magnitude local maxima occur along the northwest coast and around Perth. The isolated areas of higher predicted hail in the lightning “hole” of South Australia could be due to a greater proportion of storms being severe there, just sampling error since the number of events is small. Table 1 presents the reported and predicted average annual number of hail days for select cities. Sydney, Brisbane, Perth, and Adelaide agree well because the model was trained to those grid cells. There is a major under prediction for Melbourne, which is due to it being located at the edge of the LIS visible range, causing an underestimate in lightning activity. If the values of measured lightning in northern Victoria and southern New South Wales were extended south, then Melbourne would fall much closer to the model. The larger cities of Gold Coast and Newcastle have much higher predictions of hail activity than what is reported (approximately a factor of three). Canberra has a lower prediction than that reported. The cells containing Townsville, Darwin, Geraldton, and Alice Springs all have much lower predicted values, which are still larger than the reported numbers since none of them have any reports. The predicted values are still larger than reported values in neighboring grid cells though.

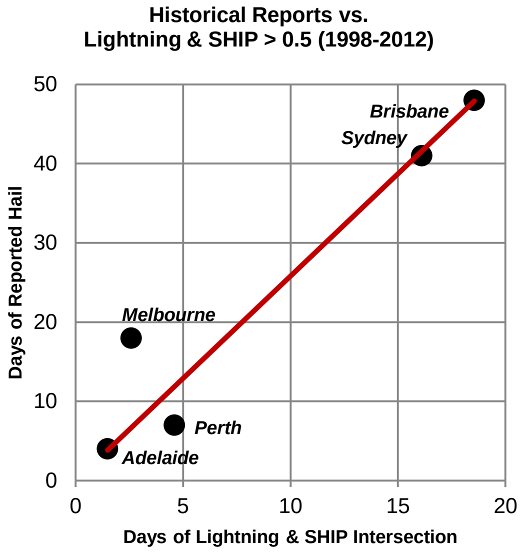

Fig. 5: Total reported hail days vs. total days of lightning and severe hail environments (1998-2012) for grid cells containing the 5 largest cities by population. Line is the fit to the data with a zero intercept constraint.

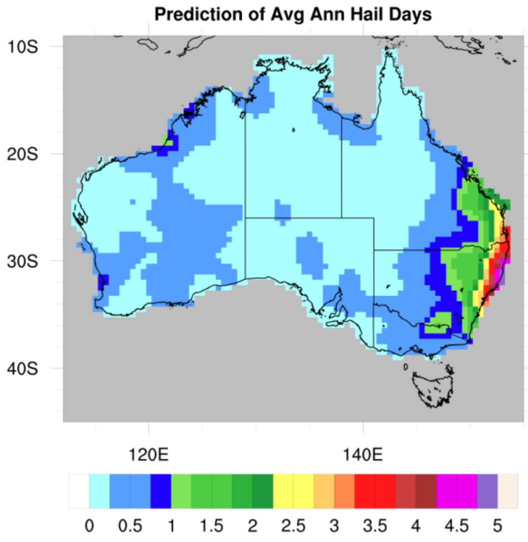

Fig. 6: Predicted average annual number of hail days per grid cell based on the linear model from Fig. 5.

Following the same process, a prediction of hail days is done based only on the occurrence of severe hail environments (no lightning considered). The spatial distribution is markedly different (Fig. 7), and it is essentially a smoothed version of the individual climatology of SHIP exceeding 0.5. The east coast maximum is more elongated without as much inland penetration. The northwest coast maximum is of equal magnitude as the east coast, and it has much greater spatial coverage than when both lightning and SHIP are considered. This climatology predicts much higher hail frequency on the northwest coast than the one in which lightning is also considered. This disagreement suggests that even though there is high individual frequencies of lightning and SHIP, they tend to not occur together as often as say the east coast. This could be related to an abundance of convective inhibition on high SHIP days.

Table 1: Comparison of reported and predicted average annual number of hail days for grid cells containing select cities. Asterisk indicates that a neighboring grid cell has a greater value.

Average Annual Hail Days		
City (Grid Cell)	**Reported**	**Predicted (Lightning & SHIP)**
Sydney, NSW	2.7	2.8
Melbourne, Vic	1.2	0.5
Brisbane, Qld	3.2	3.2
Perth, WA	0.5	0.8
Adelaide, SA	0.3	0.3
Gold Coast, Qld	1.1	3.5
Newcastle, NSW	1.1	3.5
Canberra, ACT	1.1	0.9
Townsville, Qld	0*	0.3
Darwin, NT	0*	0.2
Geraldton, WA	0*	0.4
Alice Springs, NT	0*	0.1

5. COMPARISON WITH OTHER STUDIES

While there has not been as much work on Australia severe thunderstorms as the United States, there are some studies with which to compare. Brooks et al. (2003) was not explicitly a hail study, but it did estimate global severe thunderstorm environment days from the NCEP/NCAR Reanalysis. Their results showed two maxima for Australia centered in southern Queensland and the border of Western Australia and Northern Territory, near the coast. They are displaced farther inland than the results here, possibly due to a much coarser model used. Similarly, Allen and Karoly (2013) was an Australia-only study using the ERA-Interim where locations of maxima in severe environments agreed largely with Brooks et al. (2003), although shifted to be positioned along the coasts. Our results are farther south for both maxima.

A global satellite-based hail climatology was produced by Cecil and Blankenship (2012) using

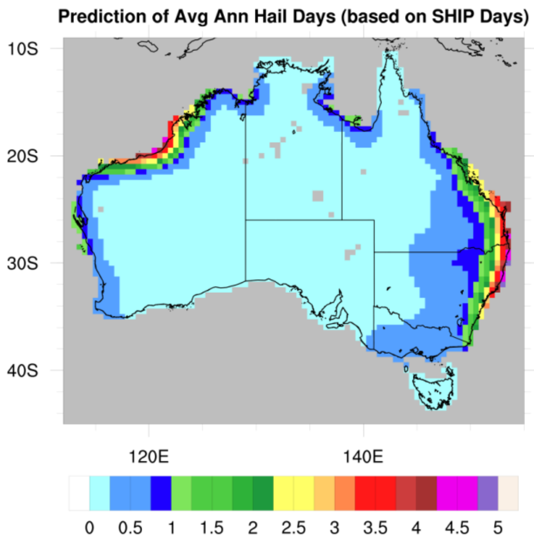

Fig. 7: As in Fig. 6 but predictive model is based only on the severe hail environments.

AMSR-E measured brightness temperature deficits. The same eastern and northwestern Australia maxima were found along with another on the southern coast of the Gulf of Carpentaria.

6. SUMMARY

Lightning data from the LIS and CFSR-based severe hail environments were used to create a hail climatology for Australia. This version predicts a maximum in hail activity along coastal New South Wales and southern Queensland, roughly between Sydney and Brisbane. The majority of reports occur around those cities, with a relative dearth in between. The predicted climatology suggests that there is significant underreporting in that area. This study provides a more complete view of hail risk for Australia, filling in gaps associated with a storm report only based view. This information potentially is useful to those interested in hail risk such as catastrophe modelers, insurers, urban planners, and climate scientists.

The results also suggest elevated hail frequency in a small region on the northwest coast, where there are no reports with which to verify. Since this is a tropical location at low elevation, it is difficult to believe that it is a region that experiences hail. Further work using freezing level as a control may yield improved results.

There are potential limitations to the data and method that may limit the results. First, the assumption that the intersection of lightning and severe hail environment relates to severe hail may be erroneous. This is probably not a bad assumption since severe thunderstorms are known to be related to instability and wind shear, which are incorporated into SHIP. Second, the reporting in the five major cities may not be accurate, which would negatively impact the model used to predict hail activity for the whole country. Third, since the satellite only makes a small number of passes per day, there is significant under detection of lightning. As mentioned the satellite does not trace the same path with each pass, so it was assumed that spatial differences would even out, allowing for relative magnitudes to be accurate between grid cells. If there are regional biases then there will be under and over predictions depending on the bias. This is seen with southern Victoria including the city of Melbourne. Since it is at or just beyond the edge of the sensor, the observed lightning activity is much less than what likely occurs. This causes under prediction of hail frequency there.

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