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Short Communication

Contribution of tropical cyclones to extreme rainfall in Australia

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ABSTRACT: The contribution by tropical cyclones (TCs) to extreme rainfall in Australia is examined using daily rainfall measurements from over 2000 rain gauges. Analyses focus on the period beginning with regular satellite monitoring of TCs (1969/1970) through the year 2012/2013 and consider daily and multi-daily annual maximum rainfall series. Our results indicate that TCs play a prominent role in extreme rainfall over much Australia, with more than half of the highest annual rainfall events associated with these storms over the coastal regions and in particular over Western Australia. Moreover, the TC fractional contribution to extreme rainfall increases as we focus on the largest rainfall events, with approximately 66–100% of annual maxima in excess of 100 mm (~4 inches) over Western Australia associated with TCs at over one third of the locations. Given the well-established controls on Australian TC activity by the El Niño–Southern Oscillation (ENSO), we also examined the relationship between extreme rainfall associated with TCs and ENSO using logistic regression. A larger probability of having an annual rainfall maximum related to TCs occurs during La Niña years, consistent with enhanced Australian cyclogenesis during these phases of ENSO. We also highlighted regional differences in the link between ENSO and extreme rainfall events, highlighting the stronger connection along the coastal areas and in particular over Western Australia.

KEY WORDS tropical cyclones; Australia; rainfall; extremes; ENSO

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1. Introduction

The rainfall associated with landfalling tropical cyclones (TCs) can be a curse – because these events are associated with torrential rainfall causing flooding and landslide (e.g. Wang *et al.*, 2009; Dong *et al.*, 2010; Ren, 2014; Villarini *et al.*, 2014a) – or a blessing because they can provide moisture vital for agriculture (e.g. Kam *et al.*, 2013). Heavy rainfall associated with TCs is projected to increase by up to 20% (e.g. Knutson and Tuleya, 2004; Knutson *et al.*, 2010, 2013) in a warmer climate, with a concomitant increased flood risk associated with these events. Villarini *et al.* (2014b) examined the response of TC rainfall to idealized global-scale perturbations: the doubling of CO_2, uniform 2 K increase in global sea surface temperature (SST), and their combined impact. Globally, they found an overall reduction in TC rainfall on the order of 5% under the CO_2-doubling scenario and an increase on the order of 10–20% associated with a 2 K increase in global SST. Similar results were obtained by Scoccimarro *et al.* (2014) who used the same experiments as Villarini *et al.* (2014b) but focused on landfalling TCs.

In this study, we examine the contribution of TCs to extreme rainfall in Australia. Using a high-resolution gridded rainfall product and focusing on the 1969/1970 to 2009/2010 period, Dare *et al.* (2012) found that TCs contributed the most to the November to April rainfall totals (~20–40%) west of 125°E and within 150 km of the coast and also observed differences in terms of TC-rainfall inland penetration between eastern and Western Australia. Dare (2013) examined the TC contribution to the seasonal total rain volume across Australia and found it to be positively correlated with the total time spent by TCs over land and the area that they covered. Moreover, this study found some evidence for larger (smaller) TC contributions to the total seasonal rain volume during La Niña or neutral (El Niño) years. Lavender and Abbs (2013) examined the role played by TCs in explaining trends in Australian rainfall, finding little influence over the 1970–2009 periods. By using a 1° × 1° rainfall product, they also focused on TC contributions to extreme precipitation (defined as rainfall above the 99th percentile), and indicated that these storms are responsible for over 40% of extreme rainfall over northwestern Australia. Ng *et al.* (2014) also focused on northwestern Australia and, for the 1970–2009 period, found results similar to Dare *et al.* (2012) and Lavender and Abbs (2013), but also highlighted large seasonal variations in TC contributions.

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Jiang and Zipser (2010) and Prat and Nelson (2013) used satellite-based rainfall estimates over a much shorter period of time (1998–2006 and 1998–2009, respectively) to examine TC contributions to the rainfall at the global scale (see also Hamada *et al.*, 2014). The results in terms of spatial distribution for Australia are similar to those found in the abovementioned studies, even though the fractional contribution tends to be smaller in these global-scale studies, possibly because of the shorter time period or uncertainties in the rainfall estimation derived from satellites.

Based on this brief review of the most recent literature, it is clear that TCs play a prominent role in influencing seasonal rainfall totals. It is less clear, however, what role they play in terms of extreme rainfall. In addition, more research is needed to determine where and to what extent extreme rainfall from TCs is more likely during El Niño or La Niña years, and what parts of Australia are more influenced by the El Niño–Southern Oscillation (ENSO).

Therefore, our main research questions are:

1. What fraction of the maximum daily rainfall is associated with TCs? The focus will be on 1-, 2-, and 3-day annual maxima.
2. Is there a higher probability of annual maximum rainfall associated with TCs during El Niño or La Niña years? What are the Australian regions that are more influenced by this climate phenomenon?

The manuscript is organized as follows. Section 2 presents the data and a discussion of the methodology. Section 3 describes the results of our analyses, followed by Section 4, which summarizes and concludes the article.

2. Data and methodology

Analyses will focus on the Australian TC seasons from 1969/1970 to 2012/2013 because of potential issues with TC detection prior to the introduction of satellite measurements and are based on daily rainfall observations from the Global Historical Climatology Network (GHCN; e.g. Peterson and Vose, 1997). Resorting to point measurements (rain gauges) rather than gridded values was also suggested by Ng *et al.* (2014) and aids in capturing the details associated with rainfall distribution around the centre of circulation of these storms. We only include stations with complete data (a year is considered complete if there are observations for a minimum of 330 days) over at least the 1969–2000 period, and we do not allow a gap larger than 2 years over the complete period for a station. A total of 2402 rain gauges satisfy our requirements, with more than 2200 stations with valid data over any TC seasons from 1970 to 2000 (Figure 1). The number of stations decreases over time, but there are over 2100 stations in 2005 and over 1000 in 2013.

In computing the annual rainfall maxima, we consider a year including the months from September to August of the following year (e.g. the annual maxima for 1970 are based on the daily measurements from September 1969 to August 1970). Within each year, we consider the largest 1-, 2-, and 3-day rainfall values. We examine heavy rainfall associated with TCs by complementing the rain gauge measurements with the best track data compiled by the International Best Track Archive for Climate Stewardship (IBTrACS; Knapp *et al.*, 2010). These data include the latitude and longitude of the centre of circulation of the recorded storms, maximum sustained wind, and minimum central pressure every 6 h during the storms' lifetime. We associate an annual maximum with a TC if the centre of circulation of the storm is located within 5 decimal degrees from the rain gauge (among others, consult Dare *et al.* (2012) and references therein) and if the annual maximum is concurrent with the passage of the storm plus or minus 1 day.

We examine the relation between the occurrence of an annual rainfall maximum associated with a TC and

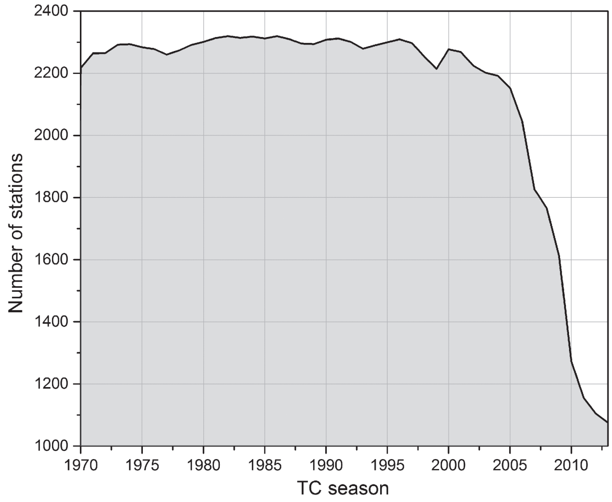

Figure 1. Plot showing the number of stations over the period 1969/1970 to 2012/2013.

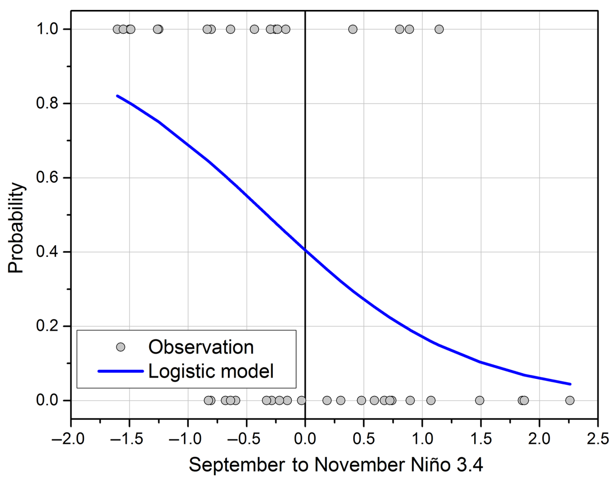

Figure 2. Plot showing the use of logistic regression at one location. The binary data identify whether an annual maximum daily rainfall value is associated with a TC (value of 1) or not (value of 0). The predictor is the value of Niño-3.4 index averaged over the September to November period.

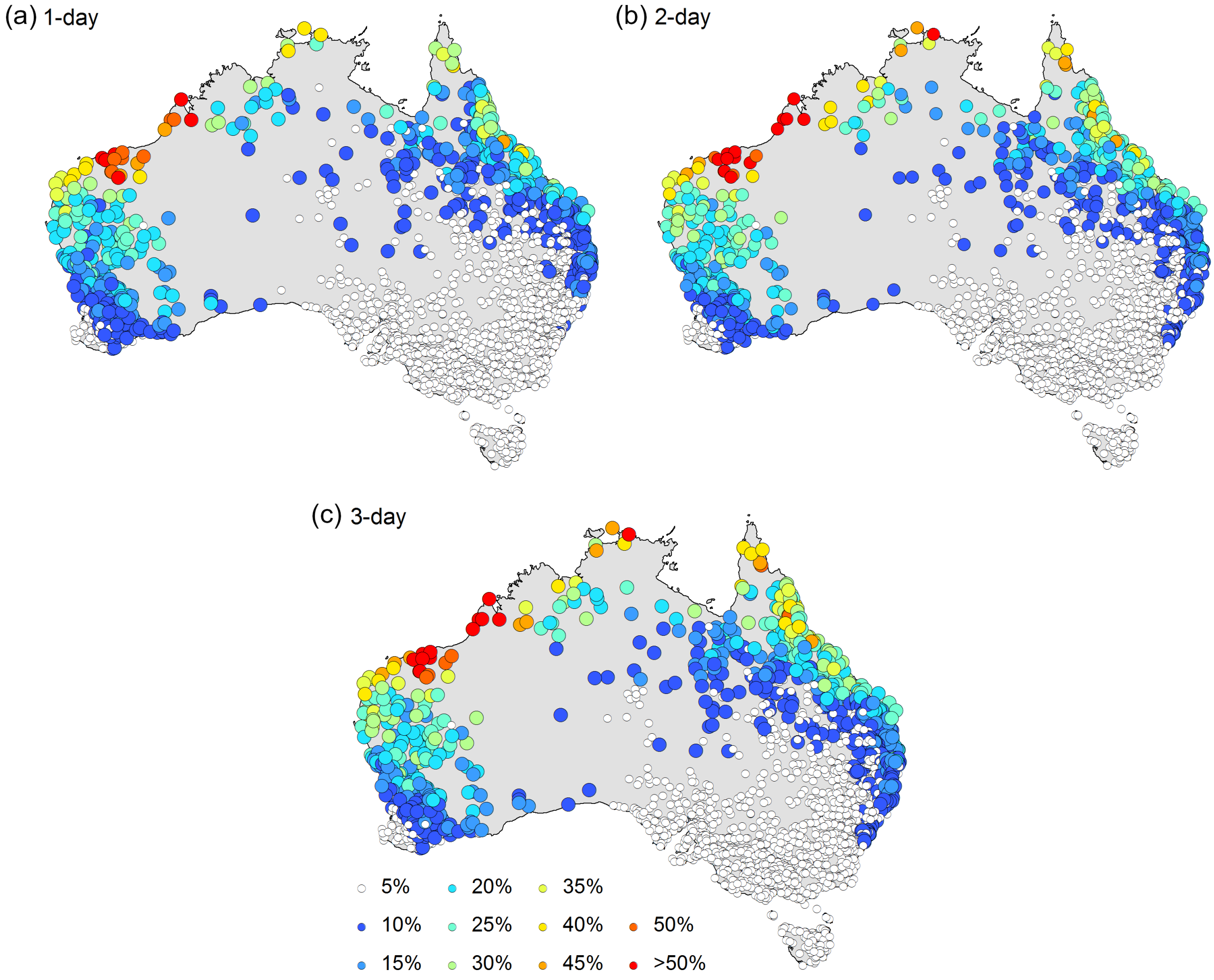

Figure 3. Maps showing the contribution of TCs to 1-, 2-, and 3-day annual maximum daily rainfall.

El Niño/La Niña using logistic regression (e.g. Dobson, 2002). As such, we are modelling a binary response variable (1 or 0 depending on whether or not the annual rainfall maximum is associated with TCs) in terms of ENSO states:

$$\log\left(\frac{\pi}{1-\pi}\right) = \beta_1 + \beta_2 x \quad (1)$$

where π is the probability of a 'success' (i.e. annual rainfall maximum associated with a TC), β_1 and β_2 are the two parameters to estimate, and x represents the ENSO state for which we use the Niño-3.4 index because Ramsay *et al.* (2008) found that it has a high negative correlation with November to April TCs in the Australian region (i.e. more TCs during La Niña years). We consider 3-month averages of this index from September to November to February to April. We fit the logistic model only for those stations that have at least five annual maxima (i.e. five 'successes') associated with TCs. Figure 2 shows the results of the logistic regression applied to one rain gauge. There is a tendency to have a larger number of 'successes' (annual maxima associated with TCs) during La Niña years compared to 'failures' (no annual maxima associated with TCs) which are more frequent during El Niño years.

3. Results

Figure 3 shows the contribution of TCs to 1-, 2-, and 3-day annual rainfall maxima. Northwestern Australia is the area with the largest TC fractional contributions, with values in excess of 50% indicating that more than half of the annual maxima are derived from TCs. In all of northern Australia coastal regions, TCs are responsible for ~30–50% of the annual maxima, with these values tending to decrease with distance south and the influence of these storms decreasing with distance inland (e.g. Dare *et al.*, 2012; Ng *et al.*, 2014). Although at any given latitude, eastern Australia presents smaller fractions than does Western Australia, overall, the spatial patterns for the three different durations (1-, 2-, and 3-day events) are similar. Therefore, these results provide empirical evidence that TCs are major agents of heavy rainfall over Australia, but also highlight regional differences.

Next, we accounted for these rainfall values (Figure 4) by computing the fraction of annual maxima exceeding 25 mm (~1 inch; Figure 4(a)–(c)), 50 mm (~2 inches; Figure 4(d)–(f)), and 100 mm (~4 inches; Figure 4(g)–(i)), and relating them to TCs. For the lowest threshold (25 mm), the picture is very similar to the results in Figure 3. However, from the 25-mm to the 50-mm

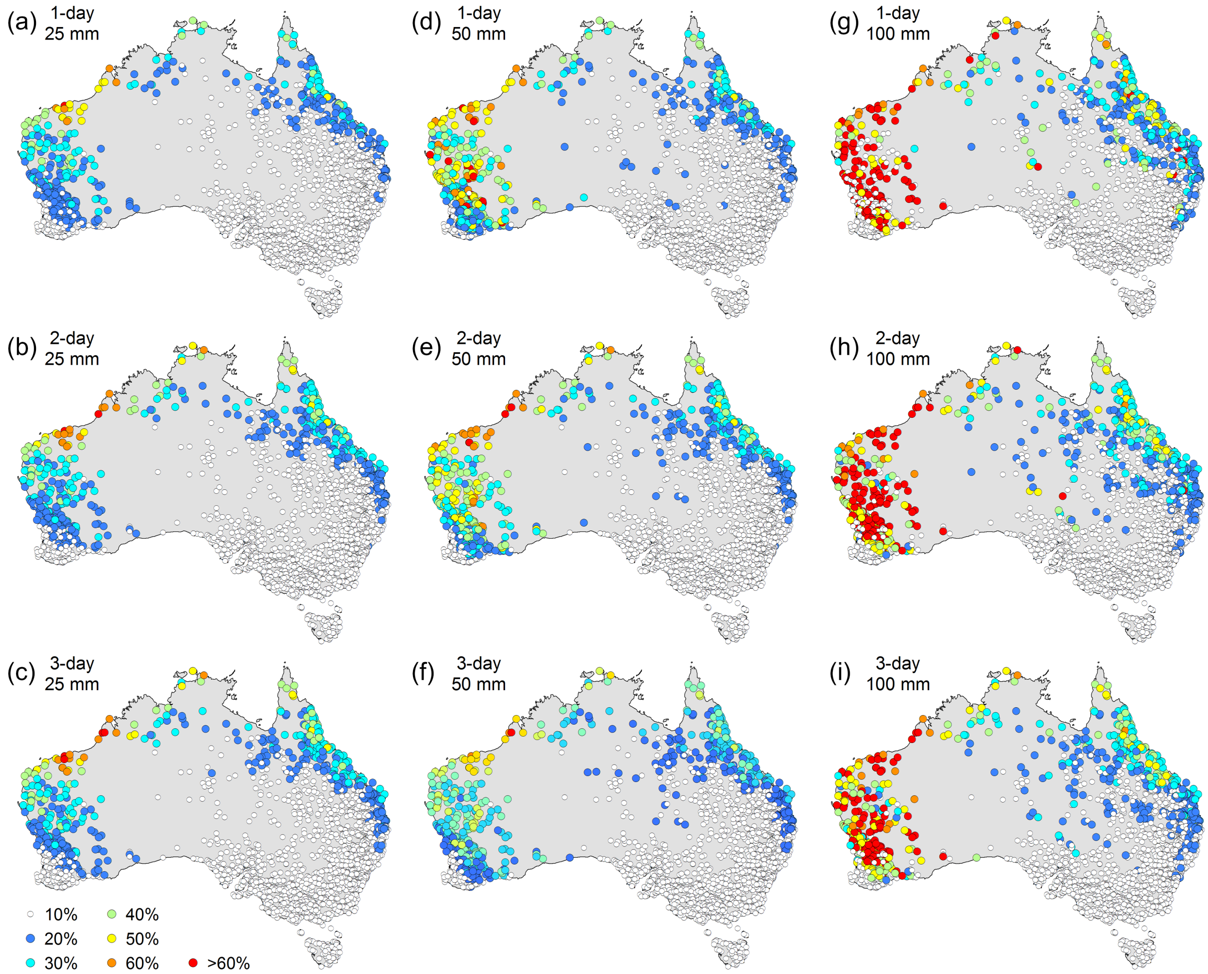

Figure 4. Maps showing the contribution of TCs to 1-, 2-, and 3-day annual maximum daily rainfall exceeding 25 mm (a–c), 50 mm (d–f), and 100 mm (g–i).

thresholds, the fractional contribution of TCs increases, a trend particularly evident in northwestern Australia, where about 50% of the annual maxima in excess of 50 mm are TC-related. The role played by TCs is even more marked when we focus on annual maxima exceeding 100 mm: more than 60% and, in some cases, all of the annual maxima in Western Australia are associated with TCs, with the TC fractional contribution being larger overall across Australia. Not only does this finding indicate that TCs are responsible for a large fraction of annual maxima, but it also suggests that the most intense rainfall in Western Australia is due to TCs.

We examine the relationship between maximum rainfall, TCs, and ENSO using logistic regression as described in the previous section. In estimating the β_2 coefficient at each location and rainfall duration, we consider two elements: its sign and p value. Negative (positive) values of this coefficient indicate a larger probability of an annual rainfall maximum during La Niña (El Niño) years. Our expectation based on the literature (e.g. Ramsay *et al.*, 2008; Dare *et al.*, 2012) is for negative coefficients. Our results in Figure 5 agree with this expectation because negative coefficients are overall five to six times more frequent than the positive ones. Almost all of the stations for which the β_2 coefficients are statistically significant at the 5 and 10% levels show negative coefficients, indicating that there is a higher probability of having TCs causing an annual rainfall maximum during La Niña years. Overall, these results are rather insensitive to the Niño-3.4 averaging window. Moreover, the 2- and 3-day annual maxima have a larger number of statistically significant coefficients, indicating that the link between ENSO and TC maxima is stronger for multi-day events.

The results in Figure 5 provide an aggregate view, but do not allow discerning spatial patterns. This information is provided in Figure 6, where we map the results in Figure 5. Large areas are characterized by a coherent signal including most of the western and to a lesser degree eastern Australian coastal regions that are more susceptible to TC-rainfall maxima during La Niña years. The strongest signal tends to be along coasts and to weaken with distance inland. While these results are in many cases not statistically significant, we can still consider them ‘scientifically significant’ in the sense that they highlight regions with a spatially coherent signal. Northern Australia tends to be La Niña dominated, even though the signal there is weaker than the majority of areas further west. Similar conclusions but of opposite sign (El Niño dominated) are valid for

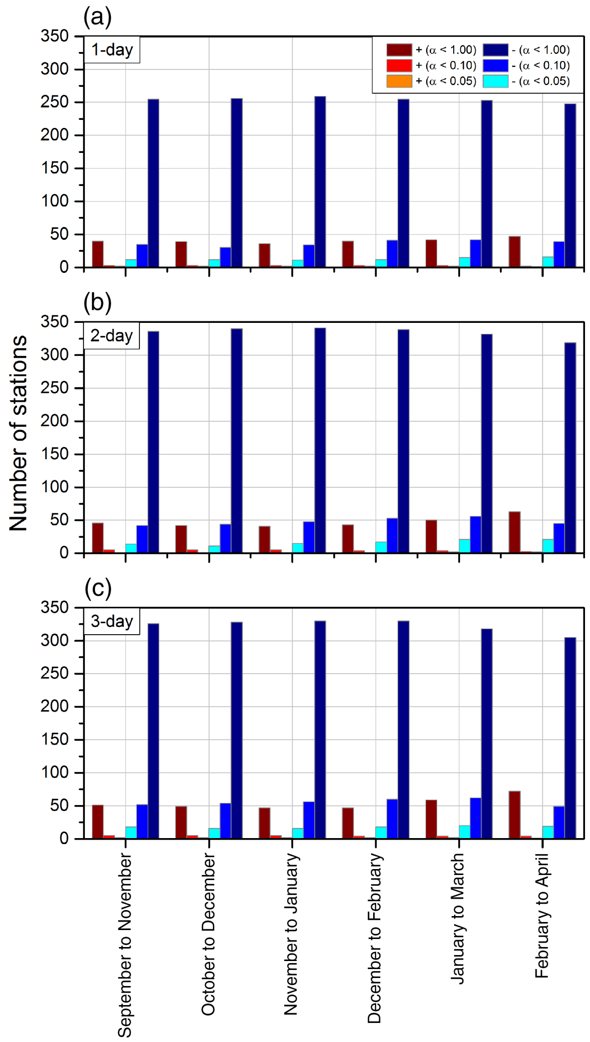

Figure 5. Number of stations for which there is a positive or negative relationship with ENSO [via the Niño-3.4 index; negative (positive) Niño-3.4 index values correspond to a La Niña (El Niño) state]. Results are based on logistic regression, and are for different rainfall durations, averaging months of the Niño-3.4 index and significance levels.

locations around the Gulf of Carpentaria and Cape York, where there is a tendency for positive (albeit generally not statistically significant; see also Klingaman *et al.*, 2013) values of the coefficients in the logistic regression model.

4. Summary and conclusion

This study examined the contribution of TCs to extreme rainfall in Australia. The results, which are based on daily rainfall measurements by more than 2000 rain gauges over the 1970–2013 TC seasons and which considered daily and multi-day rainfall maxima highlight that TCs play a major role over most of the Australian coastal regions. Northwestern Australia is the most susceptible to these events, with more than half of the annual maxima in this region related to TCs. We also highlighted that the contribution of TCs to extreme rainfall increases as we focus on more extreme rainfall values; the vast majority of annual maxima in excess of 100 mm (~4 inches) over Western Australia can be associated with TCs. Lavender and Abbs (2013) examined the connection between TCs and extreme precipitation (defined there as precipitation above the 99th percentile) and found similar patterns (e.g. larger contributions in Western Australia). Their values, however, were overall smaller, likely due to the use of 1° pixel rather than point measurements (see also discussion by Ng *et al.*, 2014). Some of these offsets could also be attributed to different definitions of extreme rainfall, even though our results suggest that the fractional contribution of TCs is larger for higher rainfall thresholds (Figure 4).

We also highlighted the relationship between TC annual maximum rainfall and ENSO. Our results indicate that overall there is an increased probability of having a TC annual maximum rainfall during La Niña rather than El Niño years. This relationship is particularly apparent along the coastal regions and over Western Australia, with the impact of the ENSO state on extreme rainfall tending to decrease with distance inland. Our results are consistent with Dare *et al.* (2012) who found indications that larger TC contributions to the total seasonal rain volume tend to occur during La Niña years. However, different from Dare (2013), we are not stratifying ENSO in three phases (La Niña, El Niño, and neutral), but rather we are considering Niño-3.4 as a continuous predictor. Moreover, the quantity (annual rainfall maxima associated or not with TCs) and regression framework (logistic regression) are approached differently. Finally, not only do we provide an aggregated view of the results, but we also show the areas that are more strongly linked to the ENSO phase. Therefore, there is mounting evidence that TCs are expected to contribute more to the total seasonal rain volume and extreme rainfall during La Niña rather than El Niño years. Because our results indicate that there is not a strong sensitivity to the Niño-3.4 averaging period, this information could be used to examine the predictability of extreme TC rainfall over Australia, potentially leading to the development of a system for improved preparedness against these events.

One of the limitations of this as well as the other recent studies of Australian rainfall is the relatively short record of highly reliable observational data. Longer records would allow a more robust characterizing of the role played by these storms and a framing of these results in a larger context, particularly for the examination of the role played by ENSO. La Niña conditions tend to increase the probability of annual maxima associated with TCs, even though the results are statistically significant for only a limited number of stations. Longer records (including paleoclimate reconstructions focusing on the nexus between TCs and ENSO state; e.g. Denniston *et al.*, 2015) would increase our confidence in these results. Based on these results, we conclude that TCs play a major role in shaping the upper tail of the heavy rainfall distribution over large Australian regions. Given that rainfall associated with TCs is projected to increase (e.g. Knutson *et al.*, 2010) and because of the sensitivity of TC rainfall to global forcings (e.g. Scoccimarro *et al.*, 2014; Villarini *et al.*, 2014b), it is possible that TCs will play an expanding role in Australian precipitation over the 21st century.

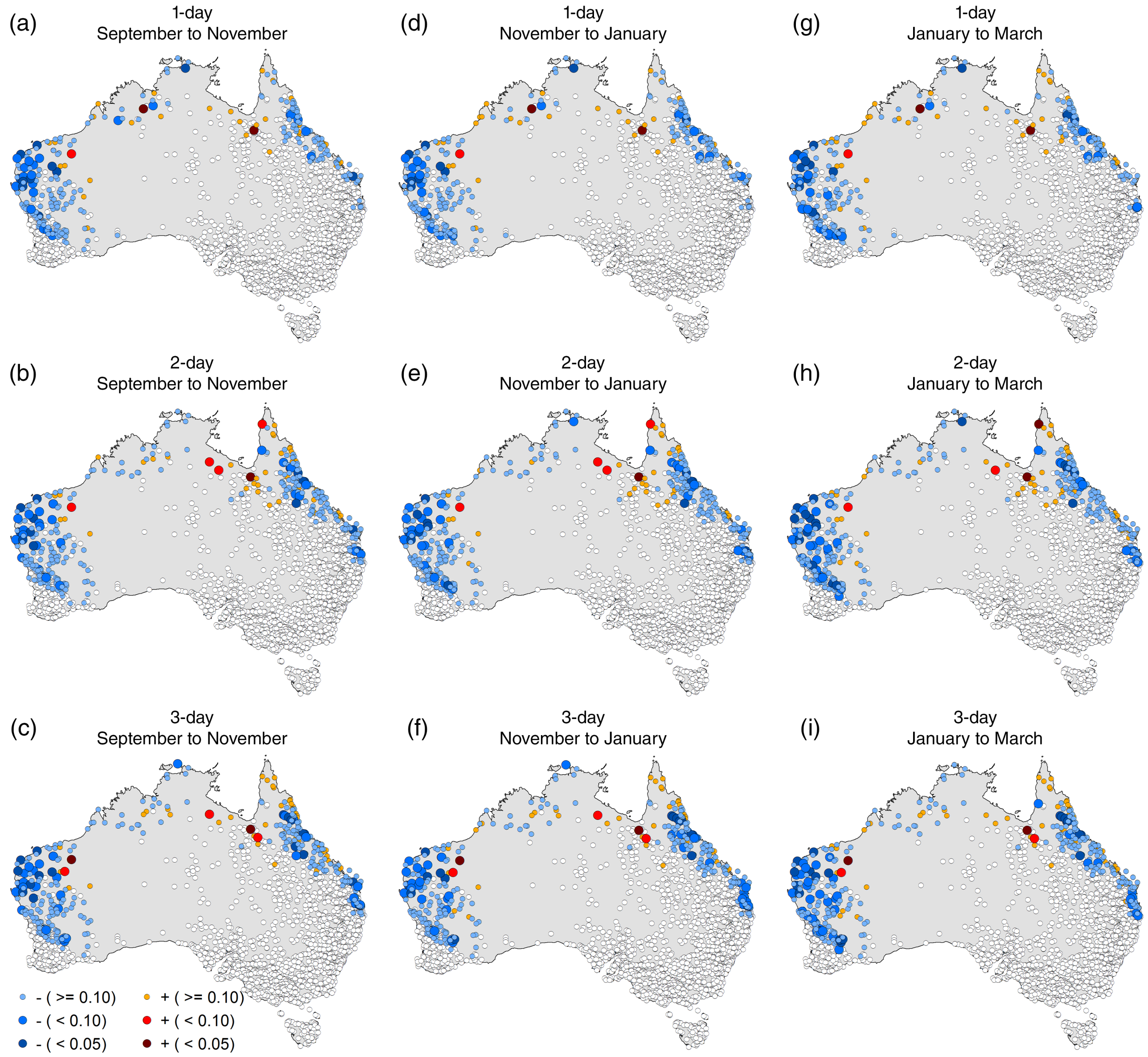

Figure 6. Map showing the location of the stations for which there is a positive or negative relationship with the Niño-3.4 index. Results are based on logistic regression and are for different rainfall durations, averaging months of the Niño-3.4 index and significance levels. The white circles indicate locations for which the logistic model was not fit (less than five TC annual maxima).

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