Tropical Cyclone Contribution to Rainfall over Australia

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ABSTRACT

Tropical cyclone (TC) rainfall over the Australian continent is studied using observations from 41 TC seasons 1969/70 to 2009/10. A total of 318 storms, whose centers either crossed the coastline or were located within 500 km of the coast, are considered in this study. Mean seasonal (November/April) contributions by TCs to the total rainfall are largest along the northern coastline from 120°–150°E. However, the percentage contributions by TCs are greatest west of 125°E, with mean coastal values of 20%–40% and inland values of approximately 20%. Farther east, percentages near the coast are only around 10%, and even lower inland. Inland penetration by TC rainfall is generally greatest over western portions of the continent, associated with greater inland penetration of TC tracks. During the peak of the TC season (January–March), TCs contribute around 40% to the rainfall total of coastal regions west of 120°E, while during December, TCs contribute approximately 60%–70% to the total rainfall west of 115°E. Rain from TCs varies sharply between TC seasons, with some longitude bands receiving no TC rain during some seasons. For the 110°–115°E longitude band the TC rain contribution is quite inconsistent, varying interannually from 0%–86%. This has an impact on water supplies, with storage dams falling to low levels during some years, while filling to capacity during TC-related flood events in other years. These large interannual variations and their impacts underline why it is important to understand TC rainfall characteristics over the Australian continent.

1. Introduction

During each warm season in the Southern Hemisphere, from around November to April, approximately 12 tropical cyclones (TCs) are observed in the Australian region between longitudes 90° and 160°E (McBride and Keenan 1982; Dare and Davidson 2004; Ramsay et al. 2008). While it is well known that a TC’s strong winds inflict damage directly upon human infrastructure, causing economic losses and loss of human life (Sheets 1990; Elsberry 2002; Rappaport 2000; Blake et al. 2007), the heavy rainfall from TCs is also a destructive factor. When a TC makes landfall, it often brings torrential rains (Larson et al. 2005). These large rainfalls cause flooding (Burpee and Black 1989; Cerveny and Newman 2000; Kim et al. 2006; Atallah et al. 2007; Gao et al. 2009; Galarneau et al. 2010), flash flooding (Cry 1967; Kunkel et al. 1999; Wang et al. 2009; Nogueira and Keim 2010), and contribute to landslides and debris flow (Dong et al. 2010), as well as inundation of towns, and disruption to transportation, utilities, and communications (Elsberry 2002). Prior to Hurricane Katrina, Elsberry (2002) noted that inland flooding had become the predominant cause of deaths associated with hurricanes in the United States.

Rainfall from TCs also affects the agricultural community (Englehart and Douglas 2001; Knight and Davis 2007), bringing drought mitigating rains (Elsberry 2002; Nogueira and Keim 2010), and providing a significant portion of the water needed for food production (Lee et al. 2010), such as in Southeast Asia (Rodgers et al. 2000). Wendland (1977) noted that TCs make a significant contribution to the annual precipitation of locations such as Japan and the southeast United States. More specifically, 10% of Florida’s annual rainfall is contributed by TCs (Knight and Davis 2007), while annual contributions of 20%–40% for Taiwan and southeastern coastal China have been reported by Ren et al. (2006) and Lee et al. (2010). For the Southern Hemisphere TC season (November/April), Jiang and Zipser (2010) used Tropical Rainfall Measuring Mission (TRMM) data to show that 3%–4% of the South Pacific Ocean rainfall was due to TCs, with a corresponding value of 7%–8% in the southern Indian Ocean. Near the Western Australia
discussed in the following section. The method used to classifying rainfall as that associated with TCs, are discussed in the following section. The method used to identify TC tracks that potentially contribute rainfall to the Australian continent is explained in section 3. Total and TC rainfall amounts are presented in section 4. Variations in TC rainfall with distance inland from the coast are considered in section 5, followed in section 6 by a discussion of differences in rainfall between months. Interannual variability of coastal rainfall is considered in section 7, with consequences of TC rainfall discussed in section 8. Conclusions are made in section 9.

2. Data and method

Reanalyzed “best track” Australian region (90°-160°E) TC data from seasons 1969/70 to 2009/10, provided by the Australian Bureau of Meteorology’s National Climate Centre, were used to determine dates and locations of TC centers approaching and making landfall across the Australian coast. Rainfall observation points within 500 km of the TC center were classified as being associated with the TC. The 500-km radius was applied around the position of the TC’s center at each 6-hourly observation. Also included were the areas supposedly covered by a 500-km-radius storm as it moved between 6-hourly observation positions. The choice of a 500-km radius is consistent with the work of Cry (1967), Lonfat et al. (2004), Lau et al. (2008), Yokoyama and Takayabu (2008), Jiang and Zipser (2010), and Nogueira and Keim (2010). It also compares reasonably well with the 4° (~444 km) radius used by Rodgers et al. (2000, 2001), and with the 5° (~555 km) radius used by Larson et al. (2005), Kim et al. (2006), and Lee et al. (2010). Alternatively, McBride (1983) combined the use of a 6° radius with subjective assessment of satellite pictures, while Ren et al. (2006) assessed TC-related rainbands out to a distance of 1100 km, and Jiang et al. (2008) used a radius of 10° to capture extreme storm sizes. Kubota and Wang (2009) used a radius of 1000 km, while at the other extreme Shepherd et al. (2007) used 277 km and Chen et al. (2010) used 250 km.

The choice of a 500-km radius is further supported by Rodgers et al. (2001) who note that a 444-km radius includes eyewall and inner and outer rainbands, while Frank (1977) stated that strong upward vertical motions exist inside about 4° radius, but weak vertical motions beyond 6° radius. Also, Larson et al. (2005) conducted sensitivity tests using radii varying between 2.5° and 7.5°, and found that radii larger than 5° make relatively little difference to the TC rainfall values recorded.

Without carrying out the very time-consuming task of manually, and subjectively, examining several days of satellite imagery and rainfall observations for each unique synoptic and weather situation in which each TC was embedded during the 41-yr period being

(WA) coast they found that TCs contributed as much as 40%-55% of the seasonal rainfall, and up to 10% along the northern coastline of Australia. Using station data for five November/April seasons 1974/75 to 1978/79, McBride (1983) found values of 26% for Broome on the coast of WA, 16% for Darwin, and 27% for Townsville, Australia. The amount of rainfall produced varies greatly between storms (Cry 1967; Griffith et al. 1978; Corbosiero et al. 2009), from month to month (Larson et al. 2005; Knight and Davis 2007; Jiang and Zipser 2010), and between locations (Corbosiero et al. 2009; Knight and Davis 2009). Cry (1967) found that the TC contribution to total rainfall shifted geographically during the TC season in the United States, with Knight and Davis (2007) finding an eastward progression throughout the hurricane season. This progression may be explained by the relationship between major hurricanes and the positions of the polar jet stream and the subtropical high over the North Atlantic Ocean (Elsner et al. 2000; Knight and Davis 2007).

The TC rainfall generally decreases with distance inland from the coast, as TCs generally weaken after making landfall, with the storm’s inner core isolated from the warm, moist ocean surface (Cry 1967; Ren et al. 2006; Gao et al. 2009; Knight and Davis 2009). Despite this general weakening, it is possible for a TC to produce heavy rainfall much farther inland from the coast (Larson et al. 2005; Nogueira and Keim 2010). A remnant system may continue to produce rainfall inland for some days (Schwarz 1970; Atallah et al. 2007; Srock and Bosart 2009; Dong et al. 2010), or interact with other synoptic systems to enhance rainfall (Ross and Kurihara 1995; Bosart and Dean 1991), even at a remote location (Wang et al. 2009).

Given the above points, is it necessary to investigate rainfall associated with TCs to understand its contribution to climatological rain totals and its potential to cause flooding. The point that we consider in this study is the mean seasonal behavior of TCs around the Australian coast and their associated contribution to seasonal rainfall over the entire continent. This is important to understand for a very dry continent such as Australia (Haurwitz and Austin 1944; Sellers 1965) because TC rainfall may be a significant contributor to freshwater supplies for human communities, for agriculture, and for the health of ecosystems. The second point considered is the change in TC rainfall with distance inland from the coast. Two further points discussed concern monthly differences in coastal rainfall and the interannual variability of coastal rainfall.

The TC and rainfall datasets used, and the method for classifying rainfall as that associated with TCs, are discussed in the following section. The method used to
considered in this study, it is likely that the method of using the 500-km radius will result in a conservative estimate of TC-associated rainfall rather than an overestimate. For example, cloud bands and squall lines directly attributable to the storm, but located some distance from the TC’s center, may be neglected. The rain amount may also be underestimated because the TC’s history is based solely on best-track reports that do not account for the contribution made by remnants (Rodgers et al. 2001), or by reinvigorated remnants (Dong et al. 2010). However, the method used here does account for the rainfall directly falling from the inner core of the TC and its immediately surrounding rainbands.

In the current work we utilize a high-quality $0.05^\circ \times 0.05^\circ$ gridded rainfall product covering the Australian continent, based on an extensive network of rain gauges, as described by Jones et al. (2009). The domain of interest, within which the Australian continent is located, was initially subdivided into $5^\circ \times 5^\circ$ grid boxes (discussed in section 4). For each box, the areal mean rainfall was computed for each month for the period from 1 July 1969 to 30 June 2010 to provide the “all” rain amount, representing the total of non-TC and TC-associated rain. This analysis was repeated but only for those days on which a TC’s center was located within 500 km of the Australian continent, to account for all grid points of the rainfall product lying within 500 km of the TC’s center. This provided the “TC rain” amount.

3. Tropical cyclone observations

In the period 1 July 1969 to 30 June 2010 (41 TC seasons), 481 TCs were observed in the Australian region ($90^\circ$–$160^\circ$E). Of these, 318 (66%) were found to either cross or graze the Australian coastline, where graze means that a TC’s center was located within 500 km of the Australian continent, but did not cross the coastline. The TCs that crossed the Australian coastline numbered 205 (64% of 318) while there were 113 TCs (36%) that grazed the coastline. The tracks of the TCs that cross and graze the coast are composited in Figs. 1a,b, respectively. The numbers of TCs and rates per 6-month season are discussed below. For later reference, Fig. 1c contains 400- and 800-m terrain heights (gray and black, respectively) over the Australian continent. Note the Great Dividing Range extending along the east coast. Terrain over 400 m also exists over the central and western parts of the continent, but without the steep slopes very close to the coastline as seen along the east coast.

Observations of TCs within $5^\circ$ longitude bands across the Australian region are shown in Fig. 2a. While there may be multiple observations of the same TC within each band, each TC is counted once only within each band, but may be counted again for each different band in which it was observed. The all row of data in Fig. 2a
refers to all TCs, while the land row refers to TCs that crossed or grazed the Australian coastline and therefore may have contributed rainfall to the Australian continent. The percentage row considers the number of “land” TCs relative to all TCs. Corresponding rates per season of TC occurrence and land TCs within each 5° longitude band are shown in Fig. 2b, with percentage values from (a).

4. Rainfall from tropical cyclones

A 6-month period, inclusive from November to April, is used to represent the TC season. The all areal mean rainfall amounts for the 6-month period are expressed here as monthly mean values (i.e., totals over 6 months divided by 6). The largest values of monthly mean rainfall over the 6-month period occur north of 20°S (Fig. 3a). These rain amounts are mainly due to the contribution of the Australian monsoon (McBride 1987, 1998). North of 15°S the values are all in excess of 150 mm month⁻¹. Relatively large values close to 100 mm are found along the east coast of Australia during this 6-month period. Moist easterly winds flowing onto the east coast of the continent are largely responsible, with further enhancement due to orographic lifting of the air due to the Great Dividing Range (Fig. 1c). The remainder of the continent receives relatively much less rainfall during this period.

The largest values of monthly mean rainfall contributed by TCs during the 6-month season are found along the northern coastline between 120° and 150°E, with most amounts at the coast above 20 mm (Fig. 3b). Although these TC rain values may appear to be quite small compared with large rainfall amounts often observed falling from TCs, these are areal mean and monthly mean amounts averaged over a 6-month period, while the rain from a TC would, of course, actually fall over a small number of days.

The percentage of total rainfall contributed by TCs (Fig. 3c) places in context the data in Fig. 3b. Along the northern coastline from 125° to 150°E, TCs contribute approximately 10% of the total seasonal rainfall. However, west of 125°E, values along the coastline are above 20%. Even some distance inland the percentages over this western region are greater than those found along the northern coastline. Although TCs do produce more rain along the northern coastline than they do over the inland west, the percentage contributions reveal a different distribution for two reasons. First, the northern region (north of 20°S) receives monsoonal rainfall for several weeks during the 6-month period of interest, while TCs, no matter how intense, produce rainfall for a few days only, as they rapidly dissipate after making landfall. As such, TCs contribute generally around 10% of the total rainfall in the north, east of 125°E. Second, the inland west receives much less total rainfall (Fig. 3a) during this 6-month period than does the northern region. In this area, the rainfall contributed by TCs is...
therefore a relatively larger percentage than that found in the north. Consequently, the seasonal contribution made by TCs is a valuable source of water in the western region. However, the reliability of this source impacts the western region’s water supply. This is discussed further in sections 7 and 8.

5. Variation of TC rainfall with distance inland from coast

a. Rainfall remapped with respect to the coast

The rain falling from a TC generally decreases with distance inland, as discussed in the introduction. It may therefore be useful to investigate and quantify the variation in TC rainfall with distance inland from the coast. As TCs affect many thousands of kilometers of the Australian coast, from the northwest to the north, the Gulf of Carpentaria and the northeast, it is also useful to compare the inland variations in TC rainfall from the west to the east of Australia. To examine the variation in rainfall with distance inland from the coast, the original source data are remapped to a series of 50-km-wide strips located parallel to the coastline within each 5° longitude band, for coastlines north of 25°S (Fig. 4). Note that latitudes are not relevant in these diagrams; the data correspond to the longitude and to the distance inland from the coast as shown by labels on the axes, while the background map is included only as a guide to the location of the longitude and corresponding section of Australian coastline.

The use of the 50-km-wide areal strips parallel to the coastlines has resolved some spatial features in the rainfall distributions. For example, the total rainfall amounts at the northern coastline near Darwin (longitudes 130°–135°E) are 221 mm, falling to 191 mm, then 170 mm, with each 50-km-wide step inland (Fig. 4a). A general feature evident in Figs. 3a,b is the fact that rainfall decreases with distance inland. In Fig. 4a, this pattern is observed for all longitude bands except for those from 110° to 120°E, where there is some increase in rainfall from the coast to 150 km inland in the total rain data. This increase with distance inland is not present in the TC-influenced rainfall in Fig. 4b, showing that non-TC weather systems must be responsible for the increase. In Fig. 4a, the decreases in rainfall with distance inland over all longitude bands east of 120°E, during this 6-month season, are largely determined by the position of the northern Australian monsoon trough (McBride 1987). During active phases of the monsoon, the rain rates are large over northern Australia but decrease inland to the south, to the dry desert interior.

The location of the largest coastal (0–50 km) TC-influenced rain rate is within the 120°–125°E longitude range.
The climatological rainfall amounts contributed by TCs are greater within this band from the coast to approximately 250 km inland than they are for equivalent distances inland for other longitude bands over the continent. Values of the percentage contribution of TCs to the total rainfall (Fig. 4c) are approximately 2–4 times greater within the first 150 km of the coast for longitudes 110°–125°E (Fig. 4c, box A) than for the equivalent coastal percentages over longitudes 125°–155°E (box B), where values are close to 10%. It is also interesting that the values for hundreds of kilometers inland between longitudes 115° and 125°E (box C) are greater than the coastal values in box B. This occurs because total rain rates are relatively low in the western region compared with the rest of the continent (Fig. 4a). Also contributing to this feature is the relatively large concentration of TC tracks over the inland region between longitudes 115° and 125°E (Fig. 1a). These TCs have penetrated this inland region from the north and northwest. Note however that the TC rain rates (Fig. 4b) show the opposite relationship, with coastal (0–50 km) values east of 125°E greater than the western inland rain rates (115°–125°E, >150 km inland). Although percentages in box B (Fig. 4c) may not seem large, these values of around 10% are not minor because they are relative to the substantial monsoon rains. The coastal percentages in both boxes A and B are in good agreement with the findings of McBride (1983) and Jiang and Zipser (2010).

b. Where TC rainfall decreases to half of the coastal value

The distance from the coast at which the TC rain rate within each longitude band falls to half of its respective coastal value is shown in Fig. 5. Note that due to the geography of the Australian continent, longitude band 110°–115°E contains data covering only a relatively short distance inland, and is not considered here. The distance is found to be over 250 km west of 120°E, decreasing to values of around 150 to 200 km between longitudes 120° and 145°E. In contrast, over far eastern Australia, the rate of decrease in TC rainfall is more rapid, with rain rates falling to half of the coastal value at distances of less than 100 km inland east of 145°E. Overall, the value of this parameter decreases from west to east across the continent. This means that rain from TCs penetrates farther inland over the western portions of the continent compared with the east. As the storms moved inland near 115°–125°E they were able to produce rain, but this did not occur to such an extent over the east of the continent. The rapid decreases in TC rainfall and concentrations of TCs inland from the coast lead to increased rainfall inland for equivalent distances inland for other longitude bands over the continent.
rain with distance inland over the eastern longitudes may be due to the presence of the steep slopes of the Great Dividing Range (Fig. 1c). Not only does landfall isolate the TC from the ocean surface, but hills and mountains along the east coast may act as a physical barrier by adversely affecting the integrity of the storm’s structure. Knight and Davis (2007) have previously noted that mountains act as a barrier to the inland penetration of TC rainfall. Additionally, removal of moisture from the TC is enhanced due to orographic lifting as the storm encounters the mountain range. Although some TCs do move inland across the Great Dividing Range from east to west, TCs in the west do not encounter such a formidable barrier and are therefore able to penetrate farther inland (Figs. 1a,c), producing the climatological rain distributions shown in Fig. 5. Note that these are climatological results and do not necessarily represent the behavior of individual TCs. Also, these values have been normalized with respect to the climatological values of rainfall at the coast for each respective longitude band, and as such do not represent a direct comparison of rain amounts between longitude bands. Despite these points of caution, this analysis has identified large differences between the west and the east of the continent in terms of the inland penetration of TC rainfall.

6. Monthly variations in tropical coastal rainfall

In this section, monthly variations in TC contributions to rainfall in the 50-km-wide coastal band are investigated. Although TCs are generally observed in the Australian region during the months November to May, for clarity, the current investigation is limited to the climatological peak of TC activity, the five months from December to April. In Fig. 6a monthly rates of total coastal rainfall (along coastlines north of 25°S) are shown for all 5° longitude bands covering the Australian continent. The corresponding monthly rates of TC-associated rainfall are shown in Fig. 6b, with the percentage of TC rainfall contribution to the total rainfall shown in Fig. 6c. Numbers of TCs observed during each month within each 5° longitude band during the 41 TC seasons are also included (Fig. 6d).

The highest climatological amounts of rainfall along the majority of Australia’s northern coastline (Fig. 6a) occur during January and February, due to contributions...
by the monsoon (McBride 1987). The next highest amounts occur during March, then December, with smaller amounts during April. Rain amounts decrease westward from about 130°E for all months because the coastlines at these longitudes are located progressively farther south, away from the general location of the rains associated with the monsoon. In comparison, coastlines in the east at equivalent latitudes (20°–25°S) receive more rain than those in the west because of the onshore winds, associated with trade winds and an inland heat low. For all months, the smallest amount of coastal rain occurs west of 120°E.

Unlike the total rainfall amounts, the TC rainfall amounts (Fig. 6b) do not show such consistent and clear patterns between location and month. Along the most northern parts of the coastline (located from 120° to 150°E), the month contributing the largest TC rain amount varies with longitude, with three different months (January, February, and March) containing the peak rainfall values for the six northernmost longitude bands, as indicated by the arrows in Fig. 6b. The asterisk indicates the longitude band (130°–135°E) where there are local minima in both the January and February TC rain amounts. This corresponds with the local minima in the number of land-affected TCs for the same two months within the same longitude band (Fig. 6d, asterisk). Generally, the TC rain amounts and the number of TCs in each longitude band for each month show some agreement. The largest numbers of TCs that either cross or graze the coast occur during January to March between 115° and 125°E. There is a peak in the TC rain data for January and February at 120°–125°E, but a decline in values immediately to the west within the 115°–120°E longitude band. This decrease may be due to characteristics of individual TCs, or the probable decay of TCs as they move south into this region where, climatologically, SSTs decrease southward and wind shear increases. Over longitudes 125°–135°E, TC numbers and TC rainfall are both relatively suppressed during January and February. Interestingly, both TC numbers and TC rainfall are largest over these same longitudes during March.

Figure 6c shows that there is no clear preference during which month the greatest percentage of TC rainfall, relative to total rainfall, occurs over Australian coastlines east of 130°E, where values are generally 10%–15%. Percentages increase westward of 130°E, where the coastline is located farther south, because the large monsoon rainfalls are largely absent here, so that TCs contribute a relatively larger amount to the total rainfall. From 120° to 125°E, percentages are above 20% for the four months December to March. From February to March, TCs contribute around 40% to the rainfall total of coastal regions west of 120°E, while earlier in the TC season, (December and January) the percentages are above 50%. During December before the wet season generally begins, the presence of a TC means that any rainfall it contributes is likely to be a substantial fraction of the total; west of 115°E the value exceeds 70%.

During December, the number of crossing and grazing TCs is 5 (out of 41 TC seasons) for both the most westward and the most eastward longitude bands (Fig. 6d). The TC rain during December is also similar for these two longitude bands (Fig. 6b). However, the percentages of rain due to TCs are very different between these two locations because of the corresponding all rain differences (Fig. 6a). The all rain value is larger in the 150°–155°E band because of the onshore flow associated with easterly trade winds and the inland heat low (Skinner and Leslie 1999).

7. Interannual variability

Mean monthly rain rates for the 6-month period from November to April are collected for every TC season from 1969/70 to 2009/10. The interannual variability between TC seasons (November/April) is considered in this analysis, based on the coastal (0–50 km) areas within each 5° longitude band. The all rain rates are smallest over the far western longitudes (110°–120°E) and largest from 130° to 150°E (Fig. 7). Although there are some large interannual variations, the all rain rates east of about 120°E remain well above zero for every season. In contrast, the TC rain rates (Fig. 8) vary sharply between seasons, with some longitude bands receiving no TC rain during some seasons. For example, in the far west (110°–115°E) 17 of the 41 TC seasons analyzed receive mean monthly TC rain amounts below 1 mm. In the far east (150°–155°E) there are 18 TC seasons with virtually no TC rain, and they occur largely during the past 20 years. This feature is related to the number of TCs present in this region and may be associated with El Niño (Callaghan and Power 2011).

A consequence of the above interannual variations in TC rain is that the percentages of rain due to TCs also show great variation between TC seasons (Fig. 9). In particular, the percentages for longitudes 110°–115°E vary interannually from 0% to 86%. As the mean number of TCs that affect the coast per season is small (approximately 2–3 in any 5° longitude band; Fig. 2b), and TC motions are quite erratic in the Australian region (Dare and Davidson 2004), it is not surprising that interannual variations in TC rain are large. This large interannual variation has consequences for the water supply of some locations in the west. This is discussed further in section 8.
The data in Figs. 7–9 are summarized in Fig. 10, with mean seasonal rain rates and standard deviations of rain rates within each 5° longitude band. The thick lines in Fig. 10 represent the long-term mean seasonal data while the thin lines represent the standard deviations of the seasonal values shown in Figs. 7–9. For all rain (Fig. 10a), the smallest standard deviations and smallest rain rates occur west of 120°E. The largest standard deviation occurs in the 145°–150°E band, corresponding to the largest mean rain rate. Apart from in the west, the rain rates are much greater than the standard deviations for this all rain category. In contrast, for TC rain (Fig. 10b), the standard deviations and means are of similar magnitude, based on the large interannual variabilities seen in Fig. 8. For the percentage of rain contributed by TCs (Fig. 10c), there are fairly consistent values of mean and standard deviation of percentage across longitudes east of 130°E. Over the bands west of 130°E, the percentage of rainfall due to TCs increases westward up to about 40%. Accompanying this increase is an increase in standard deviation relative to the values farther east, corresponding to the large interannual variability in Fig. 9 for western longitudes. Although the western region receives a substantial amount of its rainfall from TCs, this supply is not consistent between seasons. Some consequences of this are discussed next.

8. Some consequences of TC rainfall in Australia

The large interannual variations in TC rain percentage for longitudes 110° to 120°E, discussed previously (Fig. 9), have consequences for the availability of water...
to residential, business, and industrial sectors in this region. For example, the Harding Dam in Western Australia, which supplies drinking water to 20,000 people, had dropped to 20% capacity before being filled by rainfall from TCs (Western Australia Water Corporation 2011). The fact that the supply had dropped to a level as low as 20% may be linked to the fact that although TCs contribute a substantial fraction of the total rainfall in this region, there are large fluctuations from year to year. Although the filling of the dam is a positive example, rain from TCs also cause floods and can, ironically, disable the water supply main at some locations, putting pipelines under meters of water and mud, and threatening supplies of drinkable water (Western Australia Water Corporation 2009, 2011). In terms of ecosystems and agriculture, rain from TCs is a valuable source of water for inland river systems, pastoral enterprises, rural dams, and for recharging groundwater supplies (Middelmann 2007).

Main population movements within Australia from the years 2000–10 were to the states of Queensland and Western Australia (Australian Bureau of Statistics 2011). These two states contain the northeast and northwest coasts of Australia, respectively, locations where rain from TCs makes a large contribution to the total (Figs. 3b,c). Middelmann (2007) also notes a growth in population along the northeast coast, a location where communities are exposed to TCs. Additionally, a rapid increase in mining activities in western regions of Australia not only exposes an increasing population to TCs, but also increases the financial exposure of mining industries. Crompton and McAneney

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**Fig. 8.** Interannual time series of the mean rate of TC rain observed within the 0–50-km coastal strip for each 5° longitude band, over the 6-month November/April period, expressed as the mean amount of rain per month (mm month⁻¹).
(2008) state that increasing costs of insured losses due to natural disasters in Australia are caused by demographic and societal changes. In recent decades there have been increases in the numbers of people and insured assets in vulnerable areas of Australia. It is therefore important to be aware of the characteristics and potential impacts of TC rainfall over the Australian continent.

9. Conclusions

Rainfall associated with TCs was studied using a high-quality $0.05^\circ \times 0.05^\circ$ gridded rainfall product covering the Australian continent, along with a dataset of TC tracks in the Australian region. Of the 481 TCs observed in the Australian region during the 41 seasons from 1969/70 to 2009/10, 318 storms crossed or grazed the coastline. Rainfall observed over the continent within 500 km of the center of each of the 318 TCs was considered as TC rainfall.

Mean seasonal (November/April) contributions by TCs to the total rainfall were largest along the northern coastline between $120^\circ$ and $150^\circ$E. However, in terms of percentage, the greatest contributions to the total rainfall by TCs were found west of $125^\circ$E, with values around 20% to 40% within 150 km of the coast, while farther inland values were approximately 20%. In contrast, percentages near the coast east of $125^\circ$E were around 10%. Although TC rainfall was larger over this eastern region than that to the west, the percentages were smaller because the overall total rain amounts were relatively much larger in the east, due to factors other than TCs, such as the monsoon. Also, in the west the total rain amounts are relatively small, with a large percentage of the rainfall associated with TCs.
To assess the change in TC rainfall with distance inland, for each 5° longitude band over the Australian continent, the distance from the coast at which the TC rainfall rate fell to half of its corresponding coastal value was computed. The largest distance found was 250 km west of 120°E. The distance generally declined eastward, to values of less than 100 km east of 145°E. In a climatological sense, these results indicate that there is less inland penetration of TC rainfall over eastern Australia compared with the west. This may be explained by the greater inland penetration of TCs over the western portions of the continent (Fig. 1a). The presence of hills and mountains along the east coast of Australia may also contribute to these findings, with the terrain retarding the inland movement of TCs. Additionally, rainfall may be enhanced nearer to the coast due to orographic lifting. These points lead to a more rapid decrease in TC rainfall with distance inland, relative to the situation over western Australia.

Along the majority of Australia’s northern coastline, the climatological rainfall rates vary depending on month, with the highest rates during January and February, followed by March and December, due largely to the monsoon. Along the Australian coastline east of 130°E, contributions by TCs to rainfall totals are generally 10%–15% for all months. During the peak of the TC season (January to March), TCs contribute around 40% to the rainfall total of coastal regions west of 120°E. During December, TCs contribute approximately 60%–70% west of 115°E.

The TC rain rates vary sharply between seasons, with some longitude bands receiving no TC rain during some seasons. TC rain rates and the corresponding percentages show great variation between seasons. In particular for the 110°–115°E longitude band, the percentage of rain due to TCs varies interannually between 0% and 86%. Although the western region receives a substantial amount of its rainfall from TCs, this supply is not consistent between seasons. This has consequences for supplies of water in a region where the population and mining activities have been increasing in recent years. It is therefore important to understand the characteristics of TC rainfall over the Australian continent.

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