Chapter 2: METEOROLOGICAL HAZARDS

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2.1 Introduction

This chapter provides an introduction to meteorological hazards. It is divided into the different meteorological phenomena that affect the Perth region, including cool season storms, warm season thunderstorms, heavy rain and flooding, tropical cyclones, heatwaves and bushfires. A number of hazards such as hail, flooding or wind can occur as a result of more than one of these meteorological phenomena. The modelling of severe wind and riverine flooding is described for Perth in Chapters 3 and 4 respectively.

Cost of meteorological hazards

Table 2.1 shows the average annual cost of the four most costly meteorological hazards between 1967 and 1999 in Western Australia and Australia as a whole. The unpublished Emergency Management Australia database (EMA Track) has been used for the analysis and is biased by large events, such as the Sydney hailstorm (Bureau of Transport Economics (BTE), 2001). In Western Australia cyclones produce the largest average annual cost, with cyclonic activity focused in northern Western Australia. The damage from cyclones may be from flooding, severe winds or storm surge. However, the values shown in Table 2.1 considerably underestimate the damage, with a major cost of cyclones to the industry, which has not been included. The average annual cost from severe storms ranks it as the second most costly meteorological hazard in the state. Accounts of historical events illustrate the prevalence of severe storms in the Perth area, with severe winds in particular resulting in damage to buildings and infrastructure. Bushfires have also impacted the region, and have an average annual cost in Western Australia of $4–5 million, followed by flooding at a cost of about $3 million. Heatwaves, though not ranking in the top four meteorological hazards in terms of cost, can result in loss of life, particularly among the elderly.

Table 2.1: Average annual cost of meteorological hazards (Extracted from BTE, 2001)

		Average annual cost ($ million)		
Location	**Flood**	**Severe storm**	**Cyclones**	**Bushfires**
WA	2.6	11.1	41.6	4.5
Australia	314	284.4	266.2	77.2

2.2. Cool Season Storms

The storm threat

During the cooler months of the year the southwest of Western Australia experiences moist westerly winds that generally produce over 80% of the region's annual rainfall Cold fronts embedded in the westerly flow bring the rain and strong winds on an irregular cycle every few days. Each front is unique, varying with the strength of wind, and amount and distribution of rainfall.

Some of the more vigorous fronts produce severe wind gusts in excess of 90 km/h, or may spawn tornadoes. The level of threat to life and property may also be described in terms of wind strength. Damaging winds refer to wind gusts between 90 and 125 km/h, and destructive winds refer to wind gusts in excess of 125 km/h. These events are not necessarily accompanied by lightning, but they are still referred to as 'storms'.

It is possible to distinguish two general types of storm threats that cause severe winds during the cooler months:

- Strong fronts and intense lows that cause sustained gale-force winds and severe gusts over a widespread area, and
- Fronts that cause localised severe winds, including tornadoes.

Widespread severe winds

Although fronts frequently move over southwest Western Australia in the cooler months, only a few times each year do very strong cold fronts associated with deep low-pressure systems affect the region. These can cause gale-force winds and heavy rain over the southwest, including Perth. The more significant events also produce an increase in tidal levels known as a storm surge, and also large waves that can result in coastal erosion. Wind damage, such as fallen power lines, typically occurs over a wide area, with the potential to cause significant power outages and traffic disruption. Often fallen trees and branches cause much of the property damage. More severe damage, likely to be caused by destructive winds exceeding 125 km/h, is usually localised.

The wind event is more significant if the strong westerlies remain for extended periods. Usually this occurs when a low or series of deep lows moves slowly south of the state and generates multiple fronts maintaining a strong westerly airstream over the southwest. On 7–8 June 1981, for example, winds at Fremantle (recorded at a height of 60 m) exceeded 55 km/h for 36 hours.

A characteristic of major westerly events is the strong winds associated with downdrafts accompanying showers and thunderstorms. These winds are transported from higher levels to the surface, causing severe squalls of at least 90 km/h, but usually less than 125 km/h. Gusts may be quite localised, becoming more widespread if associated with showers on a front or pre-frontal line.

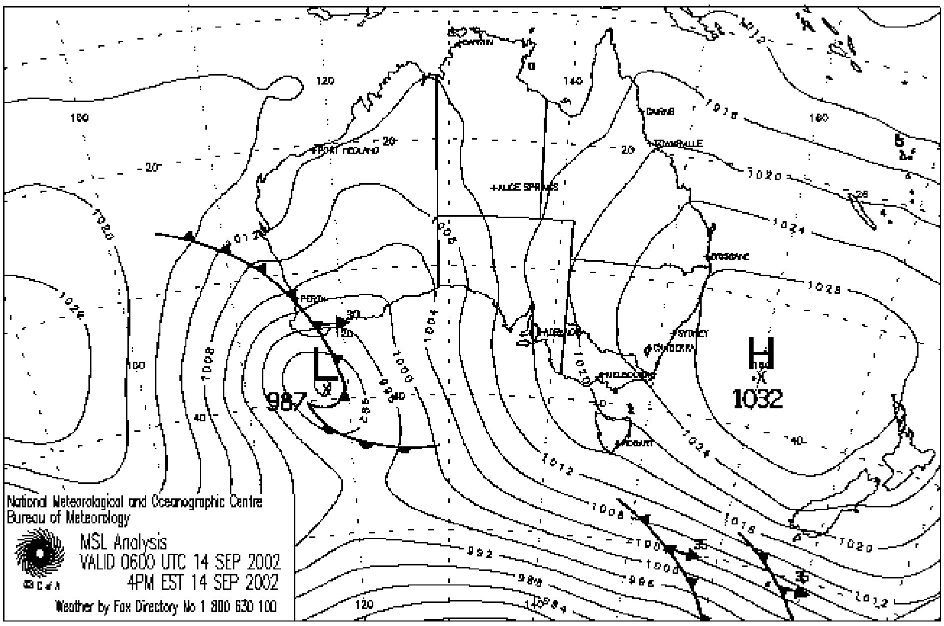

Figure 2.1: Mean Sea Level Pressure analysis showing a strong front extending through Perth to a deep low south of Albany, 14 September 2002

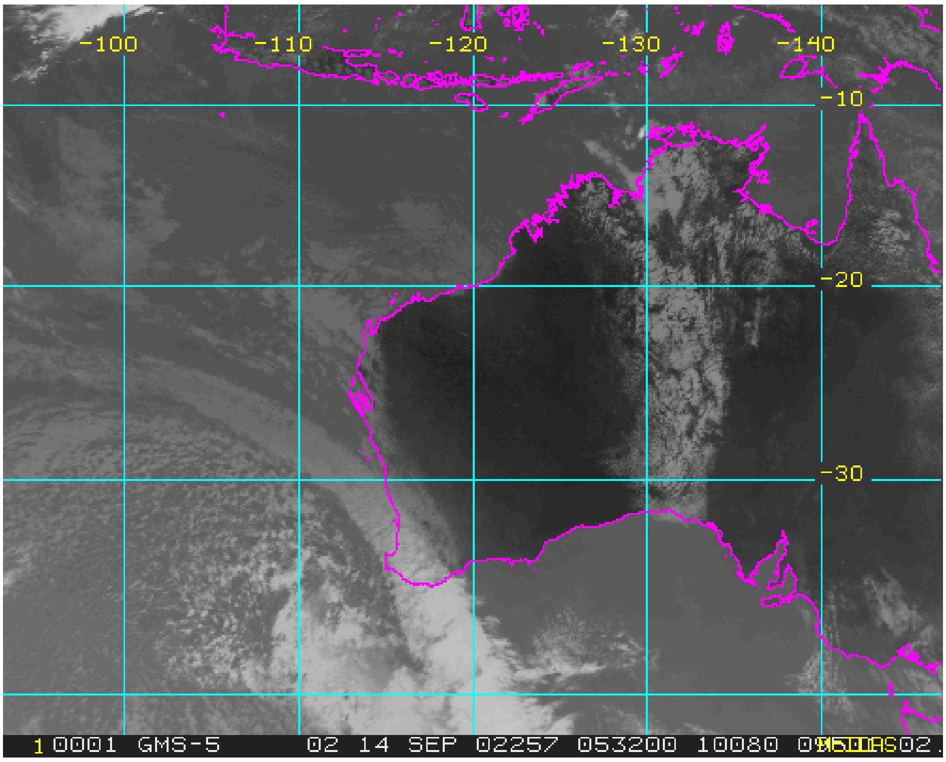

Figure 2.2: Satellite image of a strong front near Perth, 14 September 2002 (Courtesy of the Japan Meteorological Agency)

An example of a deep low and associated strong pressure gradient over the southwest is shown in the mean sea level pressure analysis of 14 September 2002 in Figure 2.1. The accompanying satellite image in Figure 2.2 shows the distinctive cloud band along the frontal boundary followed by the speckled cloud indicative of the cold airmass to the west.

Historical events

Winter storms have long been recognised as a major hazard of the area. The indigenous Nyungar people in the Perth region tended to move inland during the cooler months, partly to avoid the westerly gales. In June 1801, the French explorer Nicholas Baudin felt the full force of a winter gale as he rounded Cape Leeuwin *en route* to Rottnest Island. The early settlers were quickly made aware of the dangers of winter gales. The loss of the *Marquess of Anglesea* and damage to other vessels during a gale in 1830 threatened the existence of the colony, being described at the time as almost a ‘death blow to the infant colony’ (Bureau of Meteorology (BOM), 1929, p. 164). Winter gales posed a frequent threat to shipping, not only disrupting services but occasionally sending ships aground and sometimes wrecking ships completely. A list of some of the major winter storms of the last fifty years and their impact is shown in Table 2.2.

In more recent times, the event of 23 May 1994 ranks as one of the most significant wind storms experienced in Perth, causing an estimated $37 million damage (1998 dollars). Apart from two houses that were unroofed, most of the damage was of a minor nature such as damage to fences, with the average insurance claim only $700 (McCready and Hanstrum, 1995). The *Australian* (25 May 1994) reported that at least 600 homes in Perth had sustained some form of damage. Power outages were so widespread with more than 250,000 buildings affected, that it took almost a week to fully restore power to Perth homes. In addition to affecting businesses and homes, the loss of power affected pumping stations resulting in minor spills of raw sewage into the Swan and Canning Rivers from 29 pumping stations (*West Australian*, 25 May 1994). Two people on board a yacht were lost at sea off Jurien, north of Perth. Huge seas and above normal tides caused significant erosion to beaches, while parts of the Perth river foreshore were inundated. Fremantle recorded 25 wind gusts of at least 129 km/h, more than three times the number recorded for any other event since the 1960s.

Table 2.2: Notable deep winter lows causing gales during the cooler months

Date	Description
14 August 1955	Several westerly gale events caused massive coastal erosion on Perth's beaches. At Cottesloe not a vestige of sand was left anywhere along the seaward side of the main 120 m promenade, leaving exposed the underlying limestone.
19–20 August 1963	A strong front caused a wind gust of 156 km/h in Perth, the highest ever recorded in the Perth area. A suspected tornado demolished a factory in Scarborough just before midnight and the trail of damage extended through Doubleview and Innaloo.
8 June 1981	Strong, squally winds, accompanied by heavy rain, produced widespread damage about the southwest coast. Perth metropolitan area was littered with fallen trees and power lines and the debris from damaged buildings. Damage extended north to Geraldton, inland to Northam, and south to Harvey.
28–29 June 1983	This storm was responsible for widespread damage in the southwest, including the loss of two lives. Bad weather was blamed for a road crash fatality and an American sailor was crushed behind a ship's door in high winds. The storm downed trees and power poles, with blackouts lasting up to three days after the event. Roads were cut due to heavy rain. The damage bill for this storm was estimated to be greater than $1 million (1983 dollars).
22 September 1988	The storm caused extensive damage from Perth to Albany. Hundreds of roofs were damaged and several ripped off entirely, trees were downed, and power was lost to over 100,000 homes in the metropolitan area. Damage was sustained to about twenty boats in the Perth area after breaking their moorings. Severe damage was also done to Perth market gardens and vineyards. The cost was estimated (in 1991 dollars), to be $8 million (McCready and Hanstrum, 1995).
23–24 May 1994	The windstorm was one of the most destructive weather events to affect Perth, with a total damage bill of $37 million (1998 dollars). Several houses were completely unroofed but the majority of property damage was minor, most claims being for fence damage. Downed powerlines, mostly due to fallen trees and branches, caused widespread blackouts, leaving up to one-third of Perth without power at the height of the storm. Two people on a yacht off the coast from Jurien Bay were lost at sea. Huge seas and above normal tides caused significant erosion to beaches. Parts of the Perth river foreshore were also inundated. Swanbourne recorded a maximum gust of 143 km/h, while winds at Fremantle averaged 107 km/h over a 30-minute period.
16 May 2003	A deep low moved over the coast near Cape Naturaliste where the pressure fell to 982 hPa, one of the lowest pressures ever recorded in southern Western Australia. A storm surge of 0.8 m caused the highest tide ever recorded at Fremantle, about 0.5 m above the highest astronomical tide. The resulting flooding in low-lying parts disrupted traffic and undermined the foundations of a canal property near Mandurah. The high tides and heavy surf caused widespread beach erosion. Wind damage was general, although mostly minor. Rottnest Island recorded a gust of 117 km/h and Ocean Reef 115 km/h.

Frequency

A simple indicator of the intensity of fronts affecting the lower west coast is the pressure gradient from Geraldton to Albany. A 'storm event' can be defined when the pressure gradient exceeds 15 hPa. Although this does not always reflect the intensity of every system, it does provide an objective comparison between events since 1965, when three hourly pressure data was available from both Geraldton and Albany. This threshold generally correlates to gale-force winds on the coast and wind gusts exceeding 90 km/h. There have been exactly 100 such events over a 39-year period from 1965 to 2003, equating to about 2.6 per year. There have been eight major events when the pressure gradient has reached at least 20 hPa such as in May 1994. On average this equates to one major event every five years. The monthly frequency of storm events is shown in Figure 2.3. Seventy percent of events are relatively evenly distributed between the months of June and September, though storm events have been recorded as early as April and as late as November.

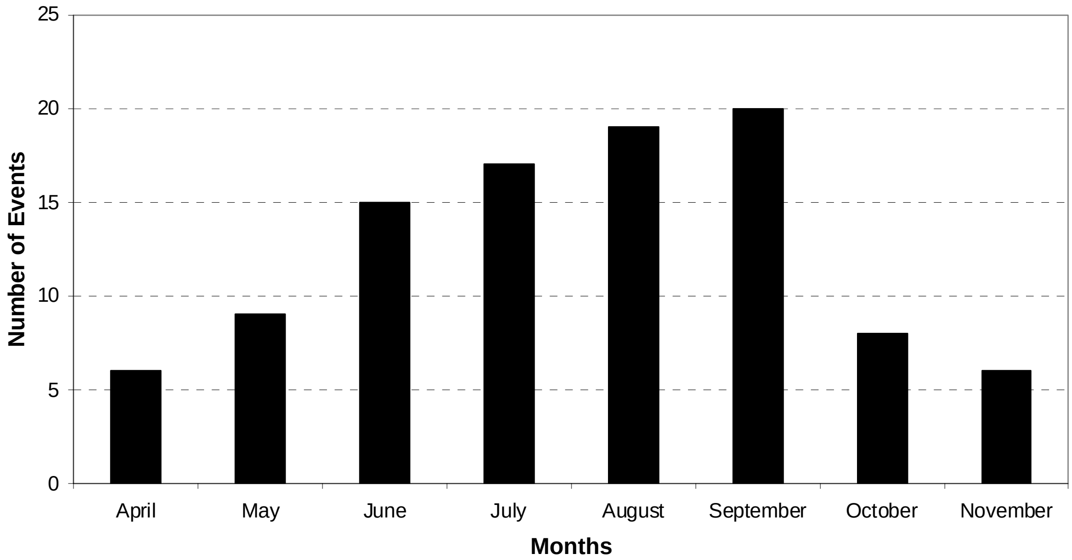

Figure 2.3: Monthly frequency of major winter storm events, 1965 – 2003. An event is defined by the occurrence of the Geraldton to Albany pressure gradient exceeding 15 hPa

Severe local wind storms

The most severe winds that occur in Perth are very localised, typically causing a narrow swathe of damage just tens of metres in width. Severe local wind storms (SLWS) can be divided into tornadoes and downbursts. It is often difficult to determine the exact cause of damage, particularly for weaker storm events. Where significant damage has occurred, indicating destructive winds in excess of 125 km/h, it can be easier to attribute the cause of damage to a tornado, colloquially called a 'cock-eyed bob' in Western Australia. Apart from the strong fronts, more moderate systems can also produce a SLWS, making these events particularly difficult to forecast. They typically occur with deep convective clouds on the frontal boundary, but may also occur on convergent lines ahead of the front, or in the cold air following the front.

SLWS are typically short-lived and move at speeds of up to 80 km/h with the associated front. Their narrow width and short path lengths, typically less than 5 km, means that they affect only small areas. They are relatively weak, usually only rating F0 (62–117 km/h) or F1 (118–178 km/h) on the Fujita tornado scale, based on extent and severity of damage. Damage reports and eyewitness accounts of these events indicate that damage varies considerably along the track. Some houses may be significantly damaged, while others of a similar construction nearby can escape any impact at all. Some reach F2 category (179–250 km/h), such as the Collie tornado in 1960.

Damage is often discontinuous along the track, suggesting that severe winds do not move evenly over the ground, especially when the terrain varies. Exposed elevated areas are more vulnerable to severe winds than sheltered parts on the leeward side of hills. Trees are often affected at different heights. Larger trees snapped off near the base indicate a much stronger wind than those with higher branches only broken off. A farmer described a tornado at Williams in 1959 passing over a flock of sheep without disturbing them. Fronts may spawn more than one tornado at a time. On 17 October 2002, a front of what appeared to be moderate intensity caused widespread localised damage across the South West Land Division with four tornadoes in the metropolitan area and several other confirmed tornadoes. It is likely that many more went unreported.

Cool season tornadoes are very different from those associated with severe thunderstorms in the warmer months, including those on the Great Plains in the USA. It is quite rare to have a report of a funnel cloud extending from the base of a cloud. Visibility is typically very low as it is usually raining heavily and they move at typical speeds of 60–80 km/h. Many people have reported hearing a sound like an approaching freight train or similar, which is a common description of tornadoes elsewhere.

Historical events

The earliest recorded probable tornado occurred during the early morning of 18 June 1842 at Australind, north of Bunbury. The *Perth Enquirer* reported a ‘wind storm’ that moved across the narrow strip of land between the sea and the Leschenault Estuary, creating a lane through the forest 300–400 yards wide and extending from the northwest to southeast across the Collie and Preston Rivers. In the centre of the path nothing was left standing but bare trunks of trees. The storm was accompanied by rain, hail and lightning and the wind turned from northerly on the 17th to the west southwest on the 18th.

The first observation of a probable tornado in the Perth area was reported by a Captain Wray on 4 June 1856. He described a ‘whirlwind’ that moved over Fremantle prison from northwest to southeast, accompanied by a loud hissing noise. The whole north boundary prison wall was laid flat, ‘turning over its foundations like a hinge’ (BOM, 1929).

One of the most intense tornadoes to affect southwest Western Australia swept through dense Jarrah forest at Lyall's Mill near Collie on 6 April 1960. The tornado cut a path averaging 240 m wide along a continuous 30 km track. Forestry officers estimated that the volume of felled timber was enough to provide a year’s work at a local mill. On 11 July 1964, a teenager was killed and several others injured when a tornado pushed a moving car off the road at Busselton (*Sunday Times*, 12 July 1964).

Closer to Perth, on 8 June 1968 a severe wind squall likely to have been a tornado destroyed 40 caravans and extensively damaged 24 cottages at Naval Base, south of Fremantle. The damage trail is shown in Plate 2.1. Plate 2.2 shows one of eight homes in Mandurah destroyed by storms which damaged more than 100 dwellings on 22 September 1993 (Hanstrum, 1994). The damage to an apartment building in Fremantle on 13 August 1999 is shown in Plate 2.3. The remains of a house after a reported tornado at Rockingham on 13 June 2001 are shown in Plate 2.4. The experience of a man who narrowly escaped death from the 12 August 1987 tornado in Mandurah is described in the *West Australian* (13 August 1987):

> *He heard the terrifying scream of ripping steel. He looked up and saw guttering, tiles and branches flying across the street. At one stage, a shed flew about 20 m over a house on the other side of the street. A flash of white rebounded off the side of one house and on to the roof of another. It was an aluminium boat…A 135 kg waste disposal bin from next door was picked up by the wind and smashed into the side of their house. It took several men to lift it back into place. The Bairds’ water tank was carried about 70 m, smashing through fences and a sign before coming to rest in bushland.*

Frequency

The occurrence of severe localised winds (including tornadoes) is much greater than is commonly thought. While most events occur in coastal parts between Perth and Albany, they have been recorded across the South West Land Division from Geraldton, Southern Cross and near Esperance. It is not coincidental that the highest number of reports comes from the most heavily populated parts of the coastal strip between Perth and Busselton. The highly localised nature of these events mean that those in remote bushland are likely to go unreported, making it very difficult to give meaningful statistics on frequency, especially in an area of low population density.

Coastal suburbs are more likely to experience a SLWS than those further inland, probably due to frictional discontinuity at the coast. A particularly high proportion of reports are from the Mandurah and Rockingham areas south of Perth. It has been conjectured that the change in coastline orientation makes these locations more susceptible to SLWS events than other parts of the Perth metropolitan area. The extra lifting and frictional effects of the Darling Escarpment suggest that the frequency of events should be higher near the escarpment than on the adjacent coastal plain but the extent of bushland near the escarpment makes this claim difficult to confirm.

Plate 2.1: Damage from the tornado at Naval Base, 8 June 1968 (Courtesy of the *West Australian*)

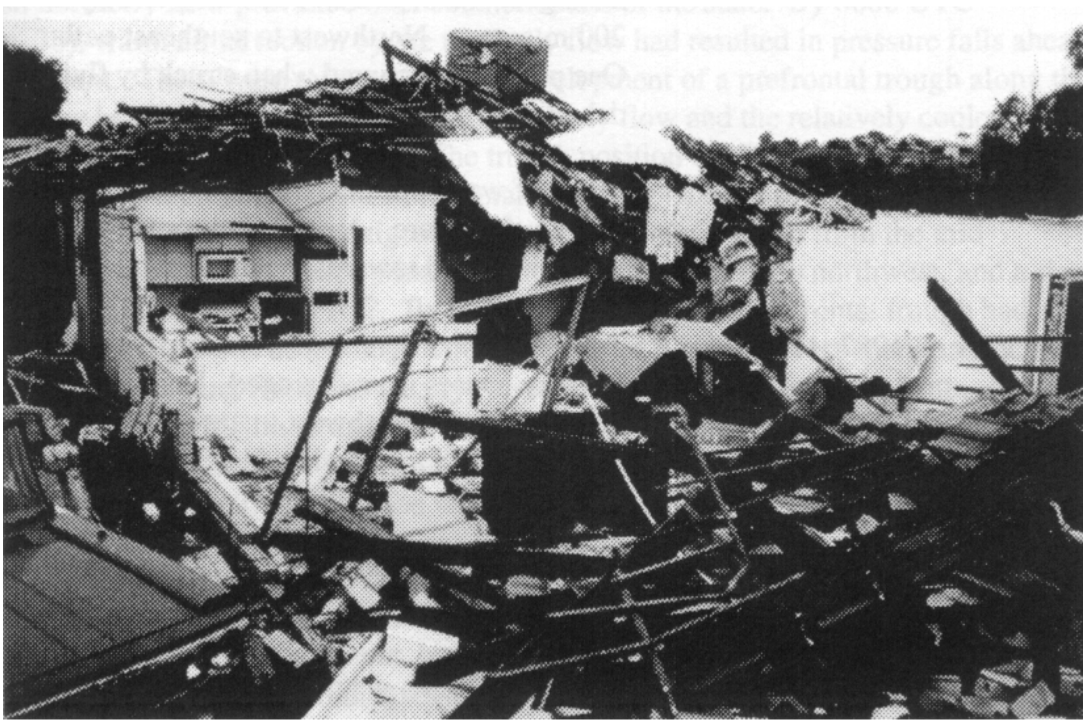

Plate 2.2: A house destroyed in Mandurah, 22 September 1993 (Courtesy of the *West Australian*)

Plate 2.3: Damage to apartments in Fremantle, 25 August 1999 (Courtesy of BOM)

Plate 2.4: A house destroyed by a suspected tornado in Rockingham, 13 June 2001 (Courtesy of the BOM)

SLWS have been reported between April and October. The earliest in any year that a storm has occurred has been on the 6 April (1960) and the latest on 31 October (2002). They occur most commonly in June. They can occur at any time of the day and there appears to be no higher concentration of occurrence at any particular time of the day.

Foley and Hanstrum (1990) analysed SLWS during the cooler months in the southwest of the State from 1958 to 1988. They identified 51 cases on 47 days in the 31-year period using newspaper clippings, averaging 1.6 per year. This included 33 cases in the Perth metropolitan area. However, they concluded the frequency of events along the Lower West coastal strip to be higher at 5.6 per year, after accounting for variations in reports due to population density. From 1993 to 2003 there has been an average of 5.5 reports per year in the region, a considerable increase in reports over the 1958 to 1988 study. In Perth there were 31 suspected tornado cases on 26 days in the eleven years to 2003, almost the same number as in the 31 years in the previous study. However, this increase is likely to be more attributable to an improved detection rate rather than an actual increase in frequency. Additionally there were many more SLWS when wind gusts exceeded 90 km/h but did not cause any known damage.

An alternative method of assessing the frequency of SLWS is to identify the atmospheric environmental features in which they occurred. In a study of 20 tornadoes in Western Australia and South Australia from 1994–96, Hanstrum *et al.* (1998) identified the critical environmental features for tornado development. This study has not only improved the ability to forecast such events but also assists in more objectively assessing the frequency of occurrence.

An unpublished study of observational records from 1967 to 2003 showed the frequency of potential tornado days to be about nine per year for Perth. Experience suggests that this is probably an overestimate of actual tornado days, especially when considering the incidence in just the Perth metropolitan area. Based on reports from 1993 to 2003, the average number of tornadoes in the Perth area seems to be in the order of three per year. However, the theoretical number of nine potential tornado days may more closely match the number of frontal events that cause severe wind gusts in Perth. An unpublished study of cold fronts from 1995 to 2003 showed that there were an average 9.5 events per year causing severe wind gusts in Perth. Of these, two to three were considered major fronts accounting for widespread minor damage, four caused local damage, and three events had no known damage although severe wind gusts were recorded. A description of some significant severe local wind squalls in Perth and the Southwest region is given in Table 2.3.

Rainfall

Although the aforementioned events causing severe winds can also cause periods of heavy rain, they do not represent the strongest rainfall-producing events. Cold fronts that generate slow-moving cloudbands extending into the tropics typically cause the heaviest cumulative rainfall. These are discussed in more detail in section 2.4.

Storm surge and coastal erosion

One of the consequences of sustained gale-force winds about the lower west coast is storm surge. Storm surge is a rise in the normal water level caused by strong onshore winds and reduced air pressure. The impact is greatest if the storm surge peaks near the time of high tide. This can result in the inundation of the river foreshore such as Riverside Drive near the Perth city centre and on the freeway just south of the Narrows Bridge. Low-lying coastal areas such as at Mandurah, Bunbury and Busselton are particularly vulnerable to inundation. Flooding is exacerbated when river levels are high because of heavy rains. More details on storm surge are provided below.

Coastal erosion results when the pounding of large waves generated by significant wind speeds combine with a storm surge. Every winter Perth’s beaches are temporarily modified due to the scouring of beach sand by strong winter storms. A strong westerly gale on 20 July 1910 caused damage to the Fremantle North Mole and the foundation of the Jandakot railway line (BOM, 1929). During the May 1994 event, significant coastal erosion occurred because of wave action, despite the storm surge peaking near the time of the normal low tide. The open water swell was estimated at 8–9 m. Storms in August 1955 badly damaged many of the beaches between South Beach and Sorrento. South of the jetty at Cottesloe Beach, 150m of foreshore were eroded back about 25 m during the storms. An extract from the *West Australian* (18 August 1955) describes some of the damage.

At Cottesloe not a vestige of sand is now left anywhere along the seaward side of the main 400 ft. promenade. The whole of the area is rugged dangerous limestone. The 12 ft. high wall of the promenade is firmly embedded in the limestone reef, but yesterday morning heavy seas were dashing high against it. A certain amount of undermining was going on. At the foot of the former jetty where the waves were heaviest a 4 ft. wide hole had been made in the promenade bitumen surface…The main damage at North Cottesloe has been the undermining of an 50 ton wartime beach observation post of concrete and steel and the collapse of the 30 ft. steel shark alarm tower… In Sunday's storm hundreds of tons of sand and big slabs of concrete were carried away from in front of the Swanbourne Nedlands Surf Club pavilion.

Table 2.3: Notable severe local wind squalls, including tornadoes

Date	Description
16 June 1954	Damage through Jarrah forest near Dwellingup to 200 m wide along 10 km track.
6 April 1960	Tornado through Jarrah forest near Collie, 240 m wide for 30 km. The estimated volume of timber useful for milling was enough for a year's work at the local mill.
15 June 1964	Tornado through the northeastern part of Mandurah caused extensive damage to houses and vegetation along a narrow track about 30–50 m wide. One person was injured by flying debris.
8 June 1968	A severe wind squall destroyed 40 caravans and extensively damaged 24 cottages at Naval Base. Eye-witness accounts do not describe a tornado, although damaging winds came from several directions.
9 September 1968	Thirty houses were unroofed at Kewdale.
21 June 1980	A tornado in Shoalwater Bay caused major damage to 38 homes and minor damage to another 60 in a 100 m wide strip along a 3 km path.
22 August 1983	In Fremantle a tornado damaged several hotels, 40 houses and two storage buildings. Eye-witnesses reported a 'whirlwind of sand and stones' in places and a 'spray of water' as it crossed the Swan River.
3 September 1983	About 50 houses damaged, some almost totally destroyed, along a path from Scarborough to Mt Lawley. Damage was worst on higher ground.
12 August 1987	A tornado, first observed as a waterspout at sea, damaged 70 houses along a 3 km path in Mandurah. One man was injured when his car was rolled over.
22 September 1993	Two tornadoes swept through Mandurah at 5 pm. The stronger one passed through Halls Head, destroying 8 houses and damaging a further 100.
15 July 1996	Tornado through Kings Park and South Perth. One house badly damaged and insurance claims, mostly for minor damage such as fences and ridge capping, totalled approximately $447,000.
25 August 1999	One person was injured in Fremantle when the roof blew off a block of flats
23 August 2001	Two separate lines of damage, up to 100 m wide, occurred in Kelmscott and Como. About ninety homes sustained damage, most because of roof damage done by fallen trees. Up to 10,000 homes were without power as lines were brought down.
13 June 2002	A tornado on a pre-frontal squall line moved through Rockingham at 2:40 am. The SES was called to 28 homes in the tornado's 50 m wide and 2 km long path.

Hail

During the winter months hail can occur in the cold airmass following the passage of a front. However, the growth of hail is much less than in summer thunderstorm clouds and the size is generally on the order of one centimetre or less, and not large enough to cause damage. Nevertheless, a large amount of small hail can block drains that can lead to water inundation to properties. Larger hail is more common in spring and the warmer months, and is discussed in more detail in section 2.3.

Thunderstorms and lightning

Despite cool season events being described as storms, only a minority of them actually cause thunderstorms and lightning. In Perth there are an average of two thunderstorms per month from May to July and one per month for the remainder of the year. One such lightning event cut all computers and telephones in the Royal Perth Hospital and subsequently put human life at risk (*West Australian*, 1 July 1996). The electrification process is weaker in cool season thunderstorms than those of the warmer months, so the number of lightning strikes is considerably lower between May and July than in the months of January to March.

2.3 Warm Season Thunderstorms

The thunderstorm threat

Compared to eastern and northern Australia, thunderstorms are infrequent in Perth during the warm season between October and April, occurring on average five to six times. Only a small number of these storms become severe enough to pose a serious threat to the community. The number of warm season thunderstorm days varies considerably from year to year, ranging from 14 in 1991–92, to just one in the 1990–91 and 1993–94 seasons.

Most storms develop in the afternoon when surface heating is greatest. A typical feature of the weather pattern in the warmer months is a low-pressure trough that extends from the Pilbara to southern parts of the state. Surface heating combined with convergence near this trough in the low levels of the atmosphere can trigger convection providing there is sufficient moisture. Figure 2.4 is a satellite image showing storms developing along the trough near the west coast.

Storms are more frequent to the north and east of Perth. Typically, a trough forms inland of the city, or moves inland during the day with the seabreeze prior to storms developing along it. On such days storm clouds can be clearly seen to the east of the city over the ranges. When the trough is near the coast they are more likely to form in the warmer air to the north and be steered to the southeast by mid-level winds. For these reasons the eastern hills areas such as Chittering and Gidgegannup have a higher incidence of warm season storms than other areas.

About 30–40% of Perth’s warm season storms occur in the early morning. They usually result from uplift forced by strong easterly winds near the surface rather than from surface heating. These storms are more difficult to forecast. They are not usually associated with severe weather phenomena, but when combined with other forcing mechanisms or tropical moisture, as happened on 8 February 1992, strong winds, hail and heavy rain can be produced.

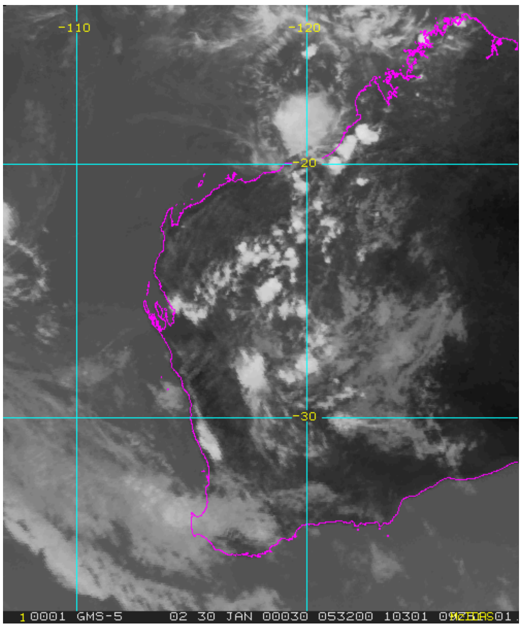

Figure 2.4: Satellite image showing thunderstorms developing near the west coast trough just to the north of Perth on 30 January 2000 (Courtesy of the Japan Meteorological Agency)

Most storm events are highly localised and do not affect large areas, in contrast to tropical cyclones and winter fronts. Individual thunderstorms typically extend over an area less than 10 km^2, move at

20-40 km/h, and last only a few hours. Multiple thunderstorm cells commonly form in any given situation so the overall area affected may be considerably greater. Figure 2.5 shows composite tracks of thunderstorm cells over 4 hours on 27 March 1995. Storms developing over a widespread area usually require abundant moisture inland, possibly associated with a tropical low or cyclone to the north. The satellite image in Figure 2.6 shows widespread storms over the southwest associated with a low off the Pilbara coast during the 22 January 2000 rain event. Some types of severe storms can last for several hours. Plate 2.5 shows low-level cloud indicating the approach of storms on 30 March 2003. On this day, 29 mm of rain was recorded in just 30 minutes at Perth Airport.

Although all thunderstorms pose a danger to life and property through lightning strikes, very few of Perth's thunderstorms reach 'severe' status. A severe thunderstorm is defined as producing one or more of the following:

- hailstones with a diameter of 2 cm or more;
- wind gusts of 90 km/h or greater;
- flash flooding; and/or
- tornadoes.

Table 2.4 is a list of notable warm season thunderstorms in the Perth region. There are several different types of severe warm season thunderstorms that affect Perth. Although quite infrequent, the supercell type storm can maintain an intense state for several hours. It has an organised structure of co-existing updraught and downdraught and can move in different directions to normal thunderstorms. Of particular concern to Perth are those that form to the north of Perth and move to the right of the typical southeasterly track. Therefore, rather than moving inland they move to the south or even southwest near the coast as shown in Figure 2.5. On 27 March 1995 and 14 January 2002, supercells caused large hail just north of Perth before moving offshore. These storms are capable of producing large hail, heavy rain severe wind gusts and even tornadoes. In January 1960, a tornado caused a swathe of damage in the Byford area. However, such events are rare in the metropolitan area.

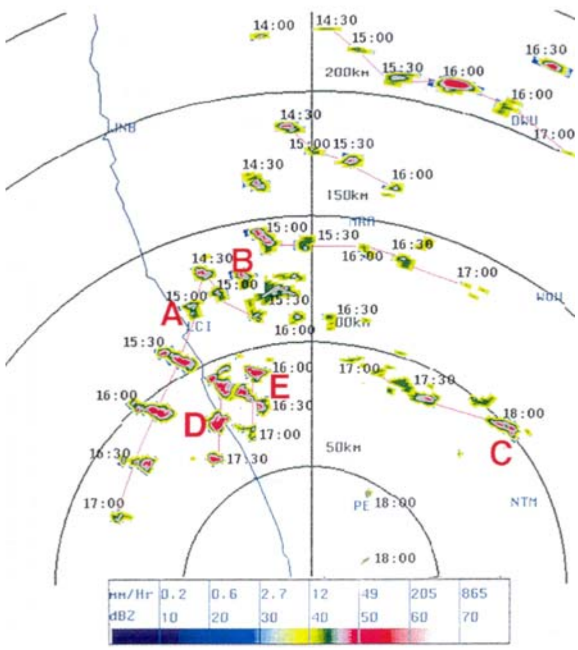

Figure 2.5: Composite tracks of thunderstorm cells over four hours (4–8 pm, 27 March 1995). Most cells move to the southeast but severe cells A and D split away and move to the south-southwest. Fortunately these were most severe after moving off the coast but cell D caused hail to 5 cm diameter near the coast

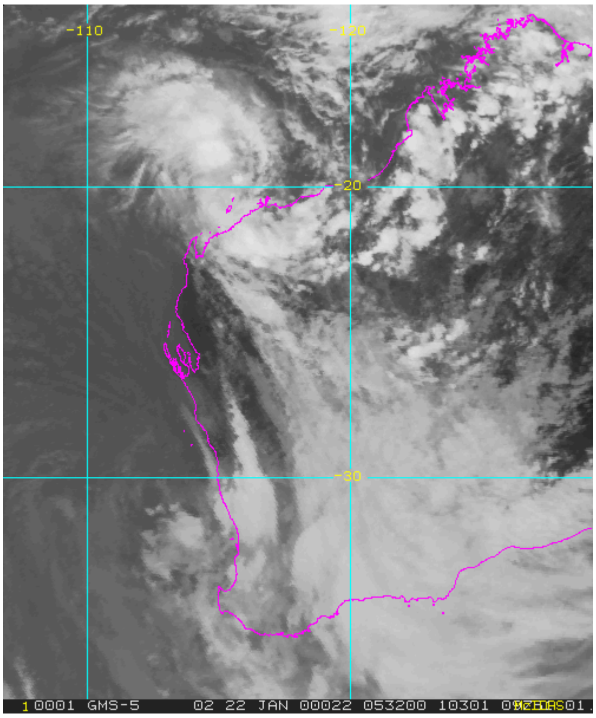

Figure 2.6: Satellite image showing thunderstorm area over the southwest during the 22 January 2000 rain event. A tropical depression off the Pilbara coast provided the moisture while an upper-level low off the west coast combined with a surface trough near the coast to cause widespread heavy rain (Courtesy of the Japan Meteorological Agency)

Plate 2.5: Photo of low-level cloud indicating the approach of storms on 30 March 2003 (Courtesy of Radek Doleki)

Severe wind gusts can also be caused by downbursts – a strong downdraught that reaches the surface. These are sometimes accompanied by heavy rain, but may also occur in the absence of rain when they are referred to as dry downbursts. For most of these cases the extent of the severe gusts is highly localised, so the term microburst is often used. In December 1991 a dry microburst was able to move a parked passenger aircraft at Perth Airport, while others have been known to unroof houses.

Table 2.4: Some notable warm season thunderstorms affecting the Perth region

Date	Description
1 January 1960	An afternoon storm that initially brought heavy rain and hail to the western suburbs produced a tornado at Byford, cutting a swathe of damage, mostly through bushland. Damage was minor, apart from one house unroofed.
20 February 1977	An afternoon storm caused severe winds, recorded to 113 km/h in the city. The winds created havoc on the Swan River, with one person drowning when a yacht capsized. In adjacent eastern and southern suburbs buildings were unroofed, caravans overturned and trees and power lines brought down.
2 January 1982	Golf-ball sized hail occurred in the northern suburbs.
7–8 November 1986	Overnight storms lasted for ten hours and caused some isolated strong gusts.
16 January 1991	A dry microburst, measured to 108 km/h, moved a parked passenger jet at Perth Airport, resulting in structural damage in excess of $1 million.
8 February 1992	Slow-moving storms caused Perth’s wettest day on record, with falls over 100 mm (Medina 231 mm). Strong winds and golf-ball sized hail damaged apartment blocks in Glendalough in the morning.
23 February 1995	An afternoon severe thunderstorm downburst caused damage amounting to over four million dollars in the eastern suburbs of Perth. A five-tonne demountable home was flipped onto the roof of another building and 30 one-tonne swimming pools were picked up by the winds and scattered about. Perth Airport recorded a gust of 115 km/h.
27 March 1995	A severe storm caused hail measured to 5 cm diameter at Woodbridge, north of Perth.
14 December 1998	Lightning killed a jockey at Ascot racecourse. Wind damage affected tens of properties in the southern suburbs while hail damaged vegetable crops.
22 January 2000	Slow-moving widespread storms caused heavy rain resulting in flooding. Perth registered 104 mm, its second highest daily fall.
18 November 2001	Overnight storms caused severe localised winds that damaged more than 25 houses in the northern suburb of Ridgewood (Wanneroo).
14 January 2002	A supercell formed north of Perth causing hail at Regans Ford, before moving offshore and striking Kwinana, shifting an oil tanker from its moorings and causing millions of dollars damage to the refinery.
29–30 March 2003	Storms overnight on the 29th and during the 30th caused power outages to 70,000 Perth homes at its peak and the SES received over 100 callouts for flood-related damage. Karragullen registered 40 mm of rain in 45 minutes.

Rainfall

While most thunderstorms are capable of producing heavy rain for a period during their mature phase, the amount of moisture in the lower levels of the atmosphere is usually a constraining factor for storms near the west coast. The continental airmass is usually significantly drier than that over the tropics or near the eastern Australian coast. Perth residents usually welcome rain from thunderstorms during the dry season, particularly if it brings some respite from the heat.

Although the natural environment of the coastal plain is not particularly prone to flash flooding, heavy summer rains have a major impact on a population unaccustomed to rain during the warm season. Sufficiently heavy rain that may cause flash flooding is rare and usually requires a moisture source from tropical origins or an unusual combination of features such as a slow moving low-level convergence zone and deep upper-level trough. On 8 February 1992 such a combination led to sustained heavy rainfall in the Perth region and flooding, particularly near the Darling Ranges. Perth registered its highest daily fall of 121 mm while Medina recorded 230 mm (see section 2.4).

Hail

Large hailstones (in excess of 2 cm diameter) are infrequent and are usually associated with supercell-type storms. Although hail size reports are often quite subjective there have been confirmed reports of hail greater than 3 cm in diameter in Perth. The largest reported hail was 5 cm, and fell at Woodridge, just north of Perth, on 27 March 1995.

Lightning

A significant consequence of summer thunderstorms is lightning. In Australia, lightning accounts for five to ten deaths and well over 100 injuries annually. In Perth, lightning-caused deaths are infrequent, with only one over the last decade. A roof tiler who narrowly escaped death after being hit by lightning described his ordeal to the *West Australian* (28 March 1995):

> *"I heard a crack, saw a big blue flash, then time just stood still", he said from his bed at Sir Charles Gairdner Hospital. "I was still on my feet but the top half of my body just folded over"…He told doctors he felt a sharp pain in his neck and ankle – the suspected entry and exit points of the lightning.*

Significant damage to electrical and communications equipment and appliances is common. Following lightning strikes in January 1999, for example, 900 fault calls were received by Telstra, amounting to almost $1 million in costs (*West Australian,* 25 January 1999). Lightning-ignited bushfires are a frequent problem, particularly if little rain occurs. On 22–23 December 2002, lightning ignited dozens of fires in the metropolitan area, creating havoc for fire agencies. Plate 2.6 illustrates the spectacular show that can be created by lightning. Lightning illuminates the 'shelf' cloud of the severe thunderstorm that caused damage in the northern suburbs.

Plate 2.6: A spectacular lightning show on the night of 18 November 2001 (Courtesy of Radek Doleki)

2.4. Heavy Rain and Flooding

Frequency of heavy rainfall

Perth is not commonly associated with heavy rain and flood events particularly in recent decades. Nevertheless, there is sufficient historical evidence to suggest that the flood risk in Perth is real and serious and the potential impact made worse by the lack of events in recent memory.

Table 2.5 shows the frequency distribution of daily rainfall by month using composite data from the official Perth site from 1880 to May 2004. The heaviest rainfall occurs in June and July. Of the 78 events when daily rainfall has exceeded 50 mm, half occurred in June and July, and only 15%

occurred in the months from September to March. However the two highest rainfall amounts occurred in February (121 mm on 9/2/1992) and January (104 mm on 22/01/2000).

Table 2.6 shows the peak daily rainfall for the ten highest rainfall events in the Lower West District. This district is approximately centred on Perth, extending for about 150 km in a north-south direction and 50 km inland. While most of these rainfall events occurred from May to July, the top three events occurred in either February or March. The number of sites recording more than 100 mm during the same event is also shown. However, it should be noted that the number of sites recording rainfall has gradually increased over time.

Table 2.5: Frequency analysis of daily rainfall at Perth, 1880–2003

Rainfall	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Total**
0	3518	3223	3377	2827	2169	1590	1577	1721	1975	2490	2923	3326	30716
0.1 to 5	305	259	427	624	905	966	1023	1095	1088	931	638	419	8680
5.1 to 10	27	37	58	157	324	398	506	457	370	233	95	59	2721
10.1 to 15	12	14	36	77	181	258	276	256	143	91	33	19	1396
15.1 to 20	5	11	15	40	119	186	183	136	93	51	11	13	863
20.1 to25	3	7	7	23	73	117	127	85	35	23	15	4	519
25.1 to 30	0	2	8	12	42	72	75	63	26	9	2	2	313
30.1 to 35	0	1	3	8	30	65	51	26	10	9	1	0	204
35.1 to 40	1	0	2	3	26	43	18	14	3	3	2	0	115
40.1 to 45	1	1	2	2	12	13	18	9	3	1	0	1	63
45.1 to 50	1	0	0	2	11	22	4	5	2	1	0	1	49
50.1 to 55	1	1	1	1	7	7	3	3	2	0	0	0	26
55.1 to 60	0	0	0	1	3	5	5	1	0	1	0	0	16
60.1 to 65	0	1	0	1	1	2	3	2	0	0	0	0	10
65.1 to 70	0	0	0	2	2	3	3	0	0	1	0	0	11
70.1 to 75	0	0	0	0	0	1	0	2	0	0	0	0	3
75.1 to 80	0	0	1	0	1	2	1	0	0	0	0	0	5
80.1 to 85	0	0	0	0	0	0	0	0	0	0	0	0	0
85.1 to 90	0	1	0	0	0	1	1	0	0	0	0	0	3
90.1 to 95	0	0	0	0	0	0	1	0	0	0	0	0	1
95.1 to 100	0	0	0	0	0	1	0	0	0	0	0	0	1
100.1 to 105	1	0	0	0	0	0	0	0	0	0	0	0	1
105.1 to110	0	0	0	0	0	0	0	0	0	0	0	0	0
110.1 to 115	0	0	0	0	0	0	0	0	0	0	0	0	0
115.1 to 120	0	0	0	0	0	0	0	0	0	0	0	0	0
120.1 to 125	0	1	0	0	0	0	0	0	0	0	0	0	1
No. of days	3875	3559	3937	3780	3906	3752	3875	3875	3750	3844	3720	3844	45717
No. of years	125	126	127	126	126	125	125	125	125	124	124	124	125.17
Rainfall > 25 mm	5	8	17	32	135	237	183	125	46	25	5	4	822
Rainfall > 50 mm	2	4	2	5	14	22	17	8	2	2	0	0	78

Table 2.6: Highest ten daily rainfall events in the Lower West District

Peak rainfall for the event (mm)	Site of peak rainfall	Date of event	No. other sites recording > 100 mm for the same event
230.0	Medina	9/2/1992	20
196.3	Bindoon	9/3/1934	17
190.5	Wannamal	16/02/1955	15
164.8	Rockingham	11/06/1945	8
159.2	Serpentine	29/7/1987	22
155.8	Mundaring	30/07/2001	13
154.7	Rottnest Is	21/06/1984	2
145.8	Karnet	26/06/1967	7
138.9	Highgate	10/06/1920	8
137.0	Lupin Valley	2/05/1953	6

Heavy rainfall events are not confined to a 24-hour period. Intense rainfall of short duration can result in flash flooding; causing gutters and drains to overflow in five to ten minutes. Perth's sandy soils on the coastal plain and relative lack of topography diminish the impact of heavy rain. Also, Perth's infrastructure is not designed to cope with very heavy rainfall, especially when compared to tropical locations. Every year there are reports of properties becoming inundated due to short-term heavy rain. On 30 March 2003, for example, the State Emergency Service responded to over 100 requests for flood-related damage when a thunderstorm caused 29 mm of rain in half an hour at Perth Airport.

To assist in hydrological design procedures the frequency analysis of rainfall data can be indicated by derived intensity–frequency–duration (IFD) design rainfall curves. IFD curves for Perth are shown in Figure 2.7. These show the rainfall rate for periods ranging from 5 minutes to 72 hours, which correspond to average recurrence intervals (ARI) ranging from 1 year to 100 years. The ARI of 2 years, for example, corresponds with 20 mm of rainfall in one hour, and an ARI of 50 years corresponds with the occurrence of 40 mm of rainfall in one hour.

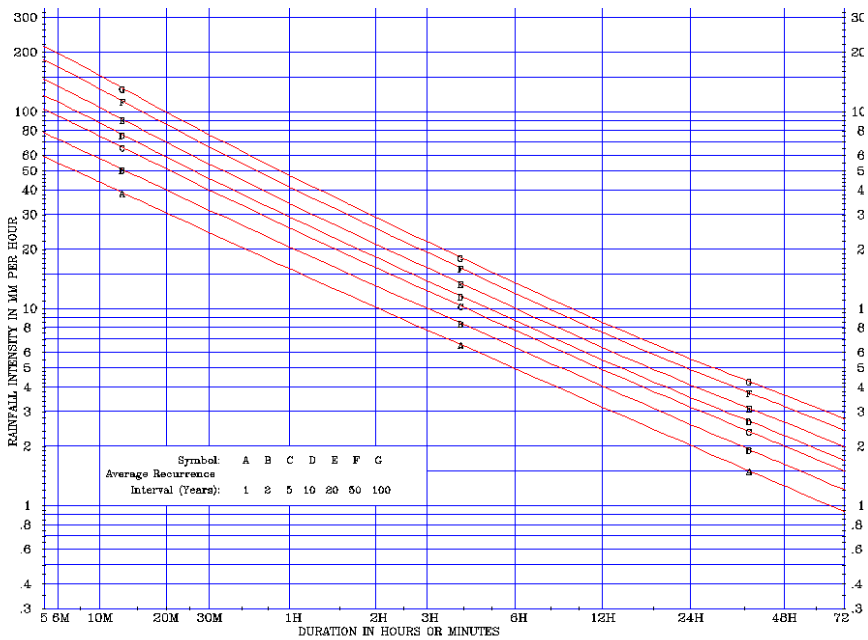

Figure 2.7: IFD curves for Perth

Mechanisms

Heavy rainfall in the Perth region can be caused by a range of meteorological mechanisms, but are usually associated in some way with one of the following patterns.

- A mid-latitude low and cold front embedded in the westerlies (see winter storms).
- The most typical pattern for heavy rain is for a front to interact with a tropical moisture source to produce a band of cloud stretching from the northwest to southeast as shown in Figure 2.8 (July 2001). A slow-moving low to the south or southwest can result in this rainband causing extensive heavy rain or even a succession of rainbands as several fronts sweep across southern Western Australia. These rainbands have the potential to cause widespread rain although it is common for particularly heavy rain to occur in a strip owing to strong convergence in a northwest to southeast orientation.
- A tropical low or cyclone off the west coast and moving south (see section 2.5).
- Thunderstorms (see section 2.3).

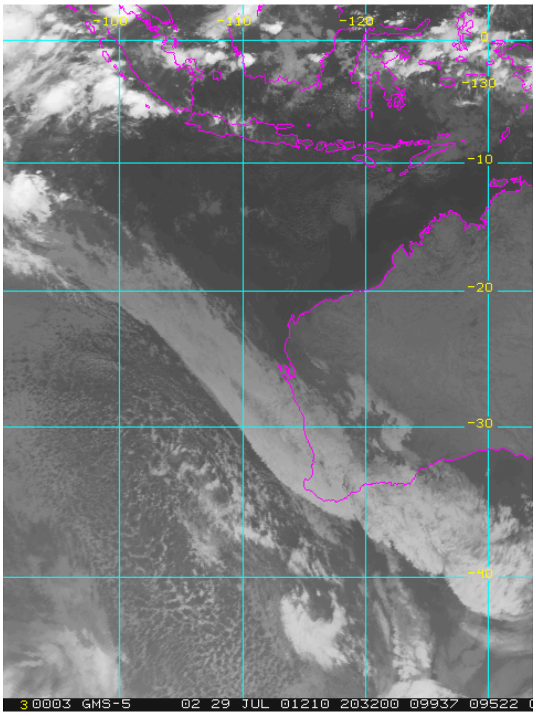

Figure 2.8: Satellite image of a rainband responsible for heavy rain in Perth in July 2001 (Courtesy of the Japan Meteorological Agency)

Flooding

Typically, flooding occurs in one of these forms.

- Localised flash flooding as a result of heavy rain over a short period.
- Inundation of low-lying land after prolonged rain. Improved drainage has reduced the risk of flooding in these areas that were once prone to seasonal flooding.
- Flooding caused by a rise in river height on the Swan and Canning Rivers. Although uncommon, major river floods have the most significant impact on Perth.
- Inundation of low-lying coastal areas by high tides caused by storm surge.

A heavy rain event does not automatically result in a sufficient rise in river levels to flood surrounding areas. While properties may be affected by flash-flooding, more significant flooding on the Swan and Canning Rivers is associated with heavy rainfall over prolonged periods. This is demonstrated in Figure 2.9 which shows rainfall over a 70-day period for four different rain and flood events in 1926, 1945, 1963 and 2001. The rainfall event in July 2001 recorded the heaviest daily rainfall at 99 mm. However, this event did not produce a major flood in Perth as just 184 mm fell in the previous seven weeks. Major floods did occur in 1926, 1945 and 1963 as heavy rain over the proceeding period had already raised river levels. In 1945 a total of 842 mm of rainfall fell over a 70-day period compared to just 184 mm prior to the 2001 event.

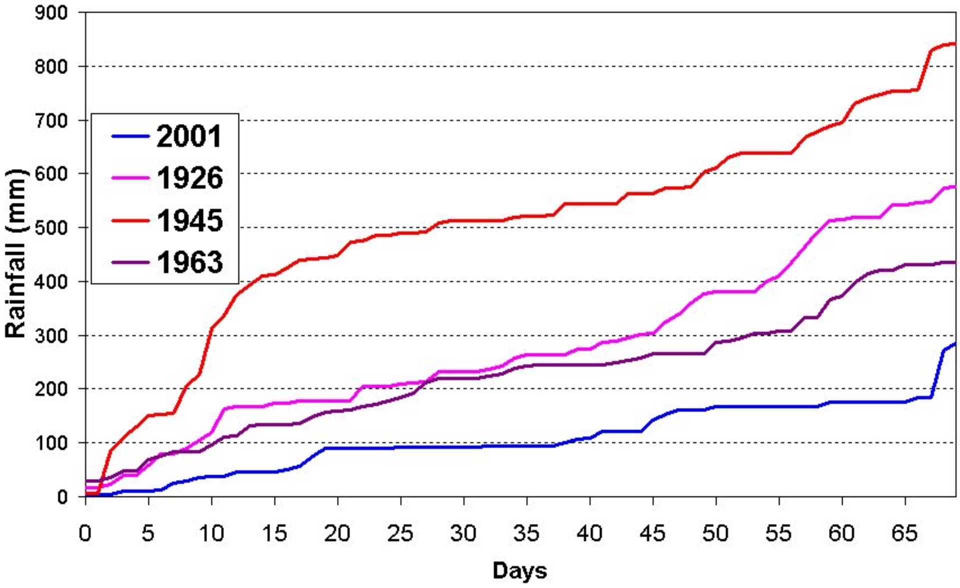

Figure 2.9: Rainfall over 70 days for the major floods in 1926, 1945 and 1963, and the rainfall event of July 2001 showing the importance of accumulated rainfall

Indeed rainfall can be important as much as 12 months prior to the event. The 1963 flood, for example, influenced the consequences of rain the following year. The Collie flood in 1964 (see Plate 2.7a and b) was rated as a one in 80 year event, yet the rainfall that fell was only rated as a one in 20 year event.

The requirement for preceding rain events to saturate the catchment and raise river levels provides an explanation as to why flooding on the Swan River is primarily a winter-time phenomenon. Those uncommon warm-season rainfall events generally do not cause major floods on the Swan River because of the river's capacity to discharge large volumes of water when existing river levels are low. This is not the case for some other towns such as Moora and Greenough that are located on smaller river catchments more susceptible to short-term heavy rain. Rainfall associated with tropical cyclone *Elaine*, for example, flooded the town of Moora in March 1999.

Very exceptional rainfall events can however cause flooding on large river catchments such as the Swan River. In March 1934, the Swan River reportedly rose 5.8 m in less than eight hours at Guildford in response to heavy rain (134 mm in just four hours at Clackline) associated with a tropical cyclone. In January 1982, 250 mm of rain fell in association with tropical cyclone *Bruno*, resulting in a flood with a 100 year ARI on the Blackwood River in the Southwest.

Plate 2.7 (a): Medic St, Collie, August 1964 flood (Courtesy of the Collie Camera Club)

Plate 2.7 (b): Medic St, Collie, not in flood (Courtesy of the Collie Camera Club)

Even if summer rain events do not cause a major flood on the Swan River, they can still cause considerable damage and disrupt activities in the city. The impact of one such event is illustrated by the newspaper headlines relating to rainfall on 22 January 2000 (Figure 2.10).

Figure 2.10: The heavy rainfall event of 22 January 2000. While not causing a major flood on the Swan River, the event did considerable damage and disrupted activities in the city

Historical trends

Historical rainfall patterns in the southwest have been the subject of intense study in recent times owing to a sustained reduction of annual rainfall in the last 40 years. Studies associated with the Indian Ocean Climate Initiative (IOCI) showed that heavy rainfall events decreased both in frequency (the number of events) and intensity (the amount of rainfall in each event), particularly since the 1960s (Haylock and Nicholls, 2000). Using the Manjimup site south of Perth, the ARI for daily rainfall of 50 mm increased from 1.5 years (0.0018 AEP) in the 1930–65 period, to 7.5 years (0.0004 AEP) in the 1966–2001 period (IOCI, 2002). Such changes are less dramatic in Perth, but nevertheless the number of heavy rain events has decreased noticeably. Figure 2.11 shows the frequency at 15 year intervals of daily rainfall exceeding 50 mm for Perth since 1883. This highlights the sudden decrease in heavy rainfall events in the 1960s.

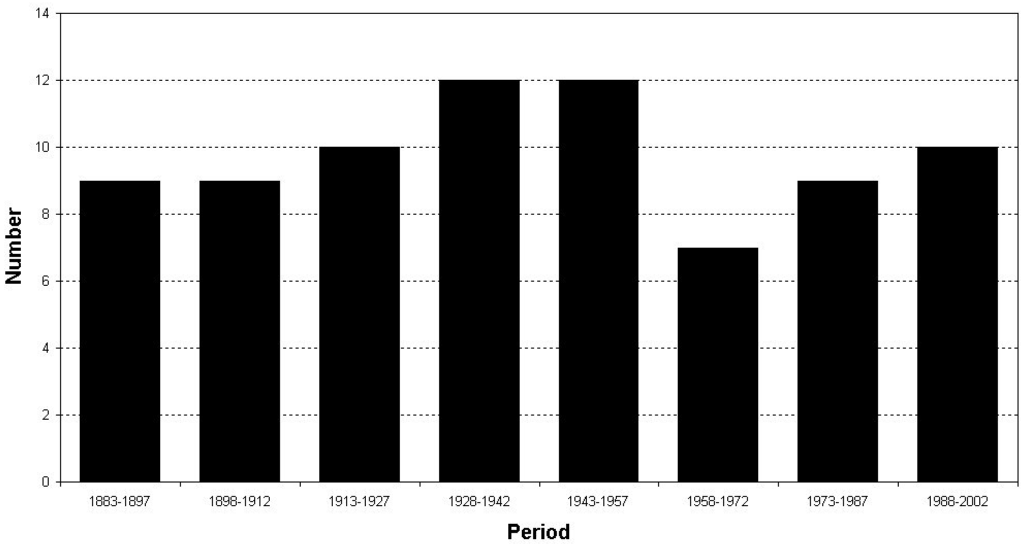

Figure 2.11: Frequency of daily rainfall exceeding 50 mm at Perth in 15 year intervals 1883–2002

This drier period agrees with the flood record on the Swan River where the last major floods occurred in 1963 and 1964. Although there have been significant individual rain events in the last forty years they have not caused major floods. The most serious of these was in July 1983, when heavy rain over the Swan-Avon catchment flooded the upper Swan Valley and threatened some properties in Bassendean and Guildford.

Storm surge

Sustained strong westerly or northwesterly winds can cause a build up of water on the coast that is referred to as storm surge. This enhances the water level above the normal tidal variation. This includes water levels on the Swan River subject to tidal variation so that parts of the river foreshore may be inundated near high tide. A storm surge also exacerbates flooding on the coastal plain by not allowing the river water to escape out to sea. The extent of flooding in Perth is dependent upon:

- the intensity of the surge itself which relates to the strength and duration of onshore winds;
- the timing of the peak surge in relation to the predicted high tide; and
- existing river levels from rainfall in the catchment area.

Most storm surge events are associated with sustained westerly gales caused by intense lows and cold fronts in the cool season (refer section 2.2). During the 23 May 1994 storm, the tidal elevation measured at Fremantle showed a storm surge of 0.98 m. Fortunately the potential for more serious and extensive flooding was not realised, as the peak surge occurred near low tide. A strong westerly gale on 20 July 1910 caused damage along the west coast to as far north as Geraldton. The Fremantle North Mole was damaged while on the Swan River all the surrounding low-lying lands and many of the jetties were submerged. More recently, gales associated with a low passing near Busselton on 16 May 2003 caused a storm surge of 0.8 m at Fremantle at close to the time of high tide as shown in Figure 2.12. The actual tide was 0.5 m above the highest astronomical tide and significant coastal erosion occurred. Plate 2.8 shows water overflowing onto Riverside Drive near the city centre. Fortunately existing river levels were low owing to dry conditions in the previous months, otherwise flooding would have been significantly worse.

Wave action adds to coastal erosion. Intense winter lows to the south generate significant swells. During the May 1994 storm the open-water swell was estimated at 8–9 m.

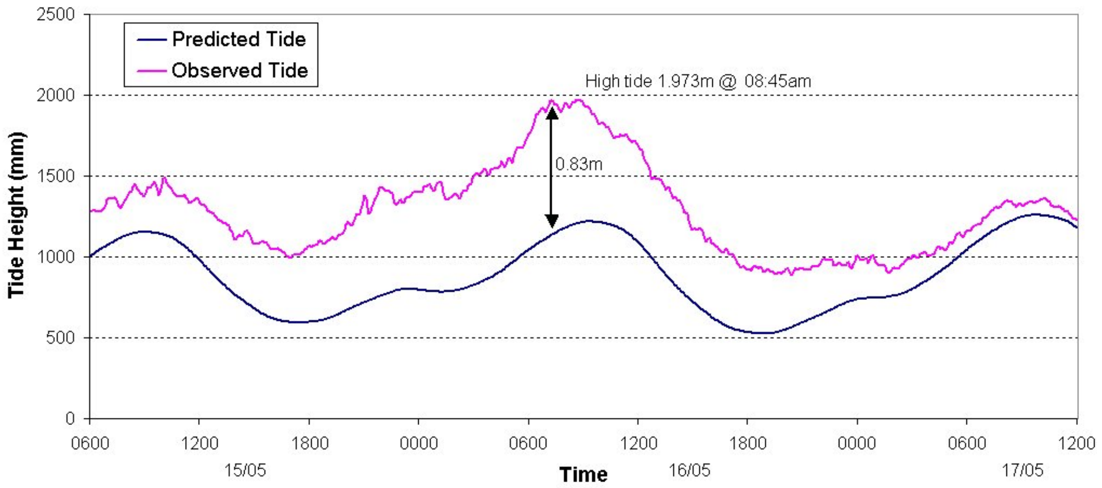

Figure 2.12: Actual tide above the predicted tide at Fremantle, 15–16 May 2003, showing the impact of a storm surge during a cool season westerly storm (Data courtesy of DPI)

Plate 2.8: The effects of the storm surge on Riverside Drive, 16 May 2003 (Courtesy of Lee Evelegh)

In addition to cool season events tropical cyclones can also cause storm surges in Perth. Cyclone *Alby* (refer to section 2.5) in April 1978 generated northerly gales responsible for large waves and a storm surge, which caused substantial coastal erosion along the Lower West coast. At Fremantle the surge was about 0.6 m, causing a high tide of 1.8 m, about 0.5 m above the highest astronomical tide. Very dry conditions and northerly, rather than westerly winds negated the flood potential on the Swan River. Low-lying areas further south on the coast at Bunbury and Busselton, more prone to a northerly surge, were flooded.

2.5 Tropical Cyclones

Tropical cyclone threat

Although an infrequent occurrence in the Perth region, tropical cyclones have historically been the most significant weather hazard in the southwest. In April 1978 cyclone *Alby* resulted in five deaths and caused coastal erosion, destructive winds the equivalent of the strongest of winter fronts, and conditions conducive to the spread of devastating wildfires.

The region off the northwest Australian coast is a prolific breeding area for tropical cyclones, producing about four to five cyclones each year on average. The vast majority of these storms dissipate well to the north of Perth, but a small number maintain considerable intensity as they travel south, despite moving over cooler water and into a generally less favourable environment.

Media and public interest usually diminishes when a cyclone begins to lose its tropical cyclone characteristics and the intensity is downgraded as it moves south. However, occasionally a decaying tropical cyclone interacts with a cold front and evolves into an intense, fast-moving system. These systems can produce a range of destructive phenomena: from intense rainfall, storm surges and large waves resulting in coastal erosion and inundation, to damaging winds and hot, dry conditions conducive to the spread of bushfires. The sudden onset of these phenomena tends to intensify their impact on a population more accustomed to benign weather conditions through the warmer months. The infrequency of these cyclones, combined with the accompanying changes in structure and motion as they move south, makes them a difficult forecasting problem.

Cyclones in the southwest can move at speeds greater than 70 km/h, in contrast to their average speed of 10–15 km/h in the north. The structure of the cyclone changes as it accelerates so that the regions of dense cloud and heavy rainfall are displaced towards the right quadrants of the system (when looking along the direction of the track), leaving the left quadrants largely free of significant cloud. As a result, the heaviest rainfall, for example, would occur when a cyclone crosses the coast near, and to the north of Perth, as in March 1934.

The strongest winds associated with these fast-moving systems occur in the left quadrants where the clockwise rotating winds are augmented by the system's translational speed. The cloud-free squally winds from the north or northeast are a recipe for severe dust storms and an extremely dangerous environment in which fires can engulf the countryside with frightening speed. The wildfires associated with cyclones in February 1937 and April 1978 typify this potentially devastating weather scenario.

The change in structure described above is known as 'extra-tropical transition'. This process is observed in other tropical cyclone basins around the world and can result in a re-intensification of the system even though it loses tropical cyclone characteristics. A study by Foley and Hanstrum (1994) showed that accelerating tropical lows were associated with intensifying cold fronts that moved to the northeast towards the tropical low. This 'capture' process and the resulting weather is shown schematically in Figure 2.13 and described in the section on cyclone *Alby* (see below).

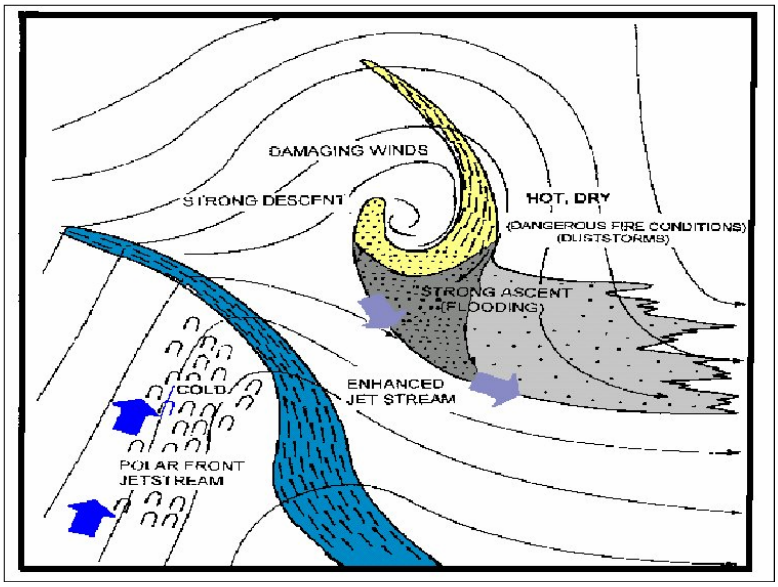

Figure 2.13: Schematic diagram showing features of a tropical cyclone undergoing extra-tropical transition (Foley and Hanstrum, 1994)

Climatology

During the 95-year period from 1910 to 2004 there were a total of 14 tropical cyclones that either caused gales or wind-related property damage in the Perth region. Decaying cyclones that caused heavy rain but not gales are not included in this number. The annual frequency of occurrence is 0.15: about equivalent to one every 6–7 years. Interestingly, there have been no cyclone events between 1992 and 2004. This has probably increased the level of complacency in the population regarding the risk of a cyclone impact. There is considerable variation in decadal occurrence within the 95 year data period. Given the small number of events, a much longer data set is required before meaningful conclusions can be made in trends of occurrence.

Cyclones affecting the lower west coast have occurred between the months of January and May and tend to occur later in the cyclone season than those in the tropics, peaking in March. Indeed, over 70% of the cyclones affecting Perth have occurred in March and April.

Figure 2.14 shows the tracks of significant cyclones affecting the Perth region. The majority originate from north of the Pilbara coast. They initially move to the southwest, and then move to the south, then to the southeast. Some of these cyclones have affected large parts of the west coast. The 1956 cyclone moved down the west coast causing considerable damage along the way. On rare occasions, cyclones such as *Marcelle* (1973, not shown) have originated from further west in the Indian Ocean and affected the west coast. The tracks of cyclones prior to the introduction of weather satellites in the 1960s should be treated with caution. A common factor between the cyclones is the increase in speed as they move southwards. By the time they reach Perth they can be moving at speeds in excess of 70 km/h.

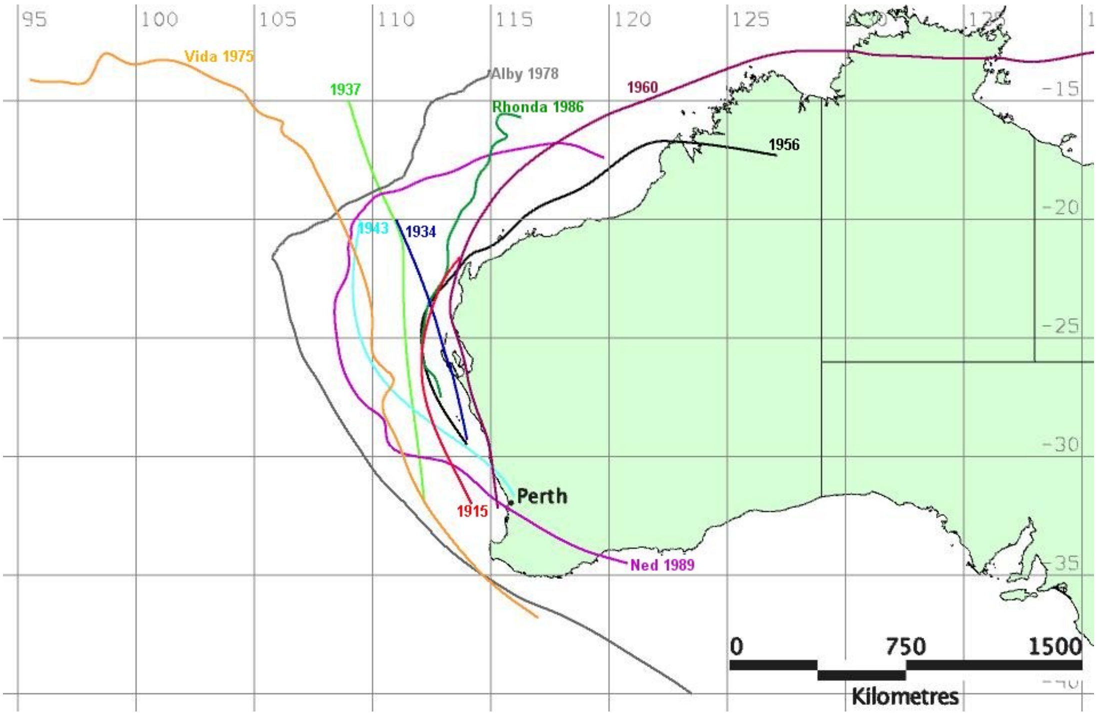

Figure 2.14: Tracks of cyclones causing gale-force winds in Perth

Historical events

Table 2.7 shows the list of major cyclones that have affected Perth since 1830. While it is difficult to compare the severity and impact of these events, cyclone *Alby* in 1978 is arguably the strongest in terms of winds in Perth (see below). The convention of giving names to cyclones only began in 1964.

One of the early accounts of strong winds in Perth and in Western Australia was believed to be the result of a tropical cyclone which occurred on 11 April 1843. This is the first cyclone event recorded for the fledgling Perth colony which transcended all experience of previous weather during the warmer months. The following account of the event is taken from *Results of Rainfall Observations made in Western Australia* (BOM, 1929):

> *Perth was visited by a most terrific gale from the northwest, amounting to a full hurricane. Strong gales from this quarter have frequently occurred during the winter months; but this gale was unusually severe, although it lasted for such a short time. It set in about 6 p.m., and lasted until nearly 10 p.m., when it gradually lulled. The gale was so sudden and tremendous as to force the 'Success' to drift ashore with two anchors down.*

Table 2.7: Description of significant tropical cyclone events near Perth

Date	Description of impact
11 April 1843	A 'terrific' northwest gale lasting four hours struck the Perth area, then moved southwards to Bunbury, where the tidal surge in excess of 4 feet drove two large vessels aground.
10 March 1872	A storm described as being of 'unprecedented severity' occurred. The destruction of property in Perth was considerable and many trees were levelled.
27 February1893	A fierce gale blew at Geraldton and Fremantle. Several boats, including the *Alastar* and *Flinders,* broke their moorings and were damaged.
26 February 1915	A storm moved southwards on the 25th from Onslow towards Perth at a speed estimated at 50 mph. There was extensive damage to property along the track. At Midland Junction, near Perth, a child was killed and several others were injured when the Swan Mission dormitory collapsed.
9-10 March 1934	Perth recorded 77 mm and Toodyay 191 mm of rain as flooding caused damage across Perth and the Wheatbelt. The Swan River at Guildford rose 5.8 m in less than 8 hours, causing considerable damage to unharvested grapes.
10 February 1937	Widespread property damage occurred across the southwest of the state, particularly south of Perth. Many boats were damaged at Rockingham but many more were damaged further south, and the Busselton jetty was extensively damaged. The storm surge forced people to evacuate in parts of Mandurah and Bunbury. Severe bushfires were reported from the forest areas, most notably from Denmark and Walpole. Hundreds of acres of forest, pasture and fruit trees were destroyed by fires and stock losses were great. Widespread severe duststorms over the Wheatbelt reduced visibility to just a few metres in parts.
15 March 1943	A cyclone crossed the coast near Lancelin causing extensive damage along a narrow band from Lancelin to the southeast wheatbelt. Buildings were unroofed, telegraph poles were blown down and roads were blocked by falling trees.
4 March 1956	Buildings and property were damaged in parts of the southwest including Geraldton and Perth. Shipping was battered in Geraldton Harbour and the Perth to Geraldton highway was blocked by numerous fallen trees.
27 March 1960	Many small boats were blown ashore and damaged. Perth recorded winds to 113 km/h. Many centres in the Wheatbelt reported damage to outbuildings, wheat silos and homestead roofs.
20 March 1975	During cyclone *Vida,* winds of 128 km/h and 109 km/h were recorded in Fremantle and Perth respectively Many properties were damaged including St George's Cathedral and the Perry Lakes Stadium. At Rockingham a 7 m yacht sank, a 6 m cabin cruiser was destroyed and many other craft were damaged.
4 April 1978	Cyclone *Alby* passed close to Cape Leeuwin causing a period of gale-force north to northwest winds. Five lives were lost. Damage to property was widespread and most severe in the region between Mandurah and Albany. Widespread fires and severe duststorms reduced visibility to less than 100 m over a large area.
21-22 February 1986	The remains of cyclone *Rhonda* crossed the coast near Perth causing heavy rain (131 mm at Greenmount). Flooding, albeit minor, was widespread across Perth. Over 100 traffic crashes were attributed to the wet conditions.
1 April 1989	Cyclone *Ned* crossed the coast near Rockingham. Rottnest and Fremantle reported wind gusts of more than 100 km/h between 6 and 7 am. Only minor damage was reported on land.

While further cyclones affected Perth in 1845, 1867 and 1871, possibly the next most severe summer storm experienced occurred on 10 March 1872.

> *In Perth a storm of unprecedented severity occurred on the 10th March. About 7 am heavy rain fell, and from then for about five hours the gale raged with unabated fury. At noon the barometer read 29.20 inches, and the wind blew from east northeast. The destruction of property within the city was considerable, chimneys having been blown down and trees levelled to the ground. Telegraph*

> *communication was cut off between Perth and Fremantle, also beyond Guildford, and between Pinjarra and Bunbury. The town hall of Perth and the Colonist's Hospital were greatly damaged. Several cottages were blown down but no lives were lost.*
>
> *At Fremantle the port was visited by the most extraordinary weather that had been witnessed for some considerable time at that period of the year. The wind was so terrific that huge stones were lifted a distance of several feet from the ground.*
>
> (BOM, 1929)

A storm in February 1915 broke in the early hours of the morning. Strong winds, heavy rain, lightning and thunder continued for approximately an hour resulting in building and roof collapse, trees being felled, and the death of a young girl. The following account in the *West Australian* (27 February 1915) describes some of the impact:

> *A two storey brick building near the corner of Aberdeen and Lake streets, tenanted by Mr Thompson, sewing machine merchant, collapsed like a pack of cards when the full force of the elements caught it… St Patrick's Mission hall, a wood and iron structure, capable of accommodating 200 persons, was reduced to a shapeless heap of wood and iron…*
>
> *A remarkable happening occurred at the Boonomic Stores, Hay Street. At a certain moment during the disturbance the air pressure about the shop windows must have been so intense that two or three of the great panes of glass moved a fractional part of an inch from their brass fames. Through the tiny cracks so caused the force of air setting like a powerful suction pump, drew the edges of a number of feather boas and pieces of silk and satin. When the air pressure ceased the panes resumed something like their former position. Yesterday curious crowds gathered to view the sight of feathers and satin protruding through and wedged tightly in the window cracks…*
>
> *The most serious damage was occasioned at the Native and Half Caste Mission in Middle Swan. The new dormitory about 50 ft. x 18 ft., built of brick, and erected only about two years ago at a cost of something like 500 pounds, collapsed like a pack of cards, and a number of inmates were pinned down by the fallen masonry and timber… Of the girls who were still in bed when the structure fell, one about nine years of age, was found to be beyond all human aid. She had been struck on the head and shoulder by a heavy jarrah beam and the skull was fractured… Seven of the inmates are now confined to their beds as a result of the injuries received. In three cases, the injuries are serious, but in none are they considered dangerous.*

Tropical cyclone *Alby*

Tropical Cyclone *Alby* passed close to the southwest corner of Western Australia on 4 April 1978, killing five people and causing widespread but mostly minor damage to the southwest. The damage bill was estimated to be $39 million (2003 dollars). One man was blown from the roof of a shed and a woman was killed by a falling pine tree. Another man was killed when a tree fell on the bulldozer he was operating and two men drowned at Albany when their dinghy overturned. Storm surge and large waves caused coastal inundation and erosion from Perth to Busselton. Fires fanned by the very strong winds burned an estimated 114,000 ha of forest and farming land.

Track and intensity

A low developed on 27 March well north of the state, some 800 km north-northwest of Karratha. It moved slowly to the southwest and steadily intensified, peaking on 2 April with an estimated central pressure of 930 hPa (category 4 intensity) about 850 km west northwest of Carnarvon (refer to the track shown in Figure 2.16). The satellite image at 6 pm (Figure 2.17 (a)) shows a well-developed eye and banding structure – distinctive features of a strong tropical cyclone. *Alby* subsequently turned to the south-southeast and accelerated from about 10 to 25 km/h by midnight on the 3 April at a distance 750 km west northwest of Geraldton. At about this time the satellite image (Figure 2.17b) showed a weakening in the eye and banding structure around the centre and a broad mass of cloud to the south ahead of a cold front approaching from the southwest. This pattern indicates that *Alby* was changing into an extra-tropical system.

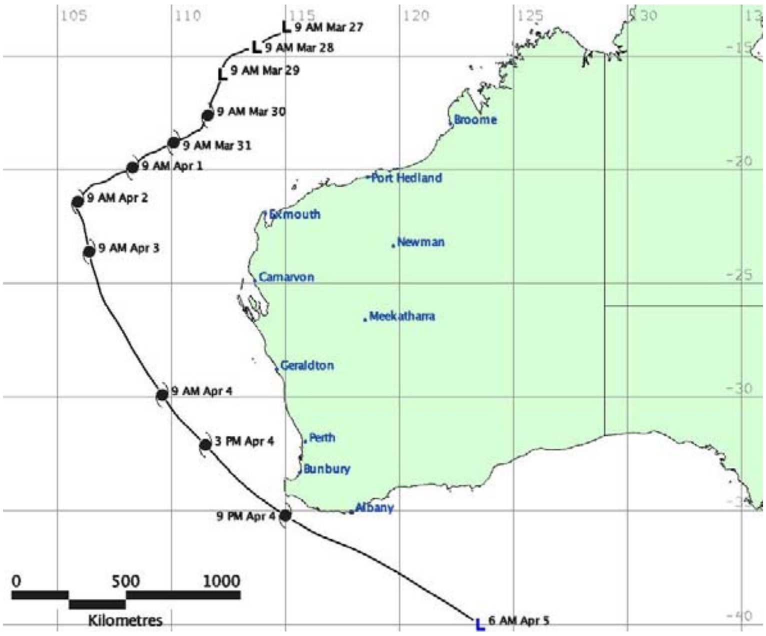

Figure 2.16: Track of cyclone *Alby*

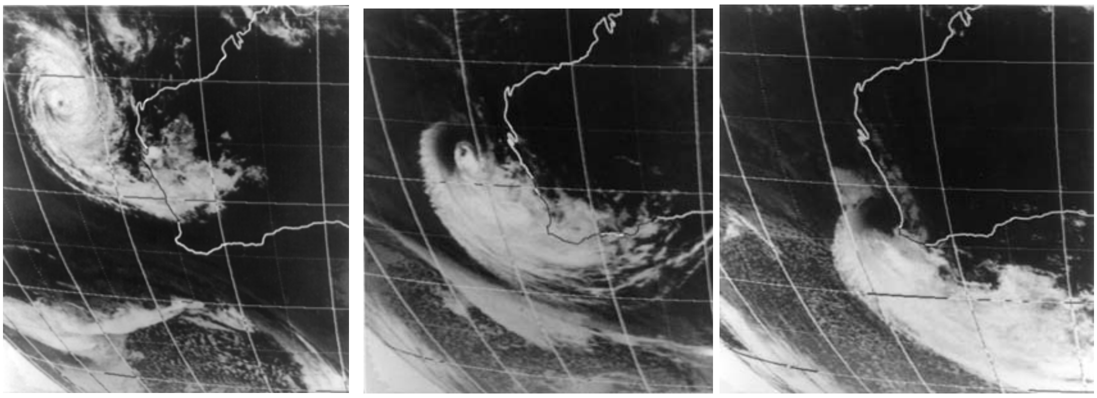

Figure 2.17a–c: Infra-red satellite imagery showing cyclone *Alby* as it moved from the tropics to the mid-latitudes; (a) 6 pm, 2 April; (b) 2 am, 4 April; and (c) 5 pm, 4 April 1978 (Courtesy of the Japan Meteorological Agency)

On 4 April *Alby* continued to accelerate, captured by strong upper-level northwest winds. The satellite image at 5 pm (Figure 2.17c) showed a complete absence of storms near the centre and the eastern half of the cyclone virtually devoid of cloud. The front had merged with the broad mass of cloud south of the centre. This pattern is very different from that associated with a mature tropical cyclone, yet it was still estimated as a category 3 system with a central pressure of 960 hPa. By 9pm *Alby* reached its closest approach to the mainland, about 60 km south of Cape Leeuwin, and was moving at a speed of 80 km/h to the southeast. The centre of the system was 250 km southwest of Perth at its closest. The centre became difficult to locate on the 5 April as it moved south of 40°S.

Table 2.8 shows the maximum gusts recorded around Perth on 4 April. The Fremantle gauge recorded the highest gust at 143 km/h. Winds increased abruptly on the 4th as *Alby* accelerated closer. Gales commenced in Perth City at 2:30 pm, and the maximum gust of 130 km/h was the third highest gust recorded at a city site in the record from 1942 to 2003. At Fremantle gales lasted for almost seven hours, while winds exceeded storm force (90 km/h) for four hours.

Table 2.8: Maximum wind gusts recorded around Perth, 4 April, 1978

Location	Highest gust (km/h)	Time (WST)
Pearce	113	16:50
Perth Airport	98	16:53
Perth City	130	16:50
Fremantle	143	15:55

Impact

Wind damage was extensive, with the greatest damage occurring in the coastal area south of Perth between Bunbury and Albany. There were no reports of houses being completely destroyed but partial roof damage occurred in Perth as described in *The West Australian* (5 and 6 April, 1978):

> *A car showroom in Queen Victoria Street, Fremantle, was partly demolished during the storm… Roofing iron from the sheds was blown several hundred metres to Leach Highway and walls of the unroofed sections caved in. Part of Henry Street Fremantle, was closed off after glass windows of a disused warehouse blew into the street. Parts of an iron and timber warehouse opposite were blown into the street below.*

> *An aluminium roof was whipped off the home of Mr and Mrs W R Hyams of Riverview Place, Mosman Park, and continued on an upward destructive path to damage a further six houses. Pieces of the roof were scattered over a wide area in Saunders Street, which is about seven metres above the wind damaged house. A piece of the roof was found 400 m away. Most of the roof fell on the property of Mr and Mrs D Robinson of Saunders Street, cutting off a chimney part of their roof, falling across Mr Robinson's car and slicing through several trees.*

Existing fires (normal end-of-harvest burn-off) combined with fires started on that day, and exploded into wildfires with measured rates of spread of between 5– 10 km/h. This resulted in an estimated 114,000 ha of forest and farming land being burned. The strong winds and dry conditions produced extensive dust storms that reduced visibility over a large area of the southwest on the afternoon of the 4th. The deposition on power lines of dust and, in coastal areas, of salt, eventually caused a failure of the electricity distribution system. Perth and all the area between Geraldton and Albany and east to Southern Cross were without power. The *West Australian* (6 April 1978) described the results:

> *Power supplies are still disrupted and more than 2000 fire fighters last night were still battling at least 70 fires… Insurance companies say the destruction caused by Tuesday's storm could cost many times the $20 million damage inflicted on Port Hedland by cyclone Trixie in 1975. The metropolitan area and nearly every town from Geraldton to Albany has suffered extensive damage… some Perth people had been without power for 30 hours last night… At one stage all five power stations supplying the grid system were out. There were problems when water and sewage treatment plants and pumping stations went out of action with the power failures. Liquid disposal tankers were called to sewerage pumping stations. The general manager of the Metropolitan Water Board, Mr F Armstrong, said that service reservoirs had met the demand for water but some people in high level areas had been temporarily inconvenienced.*

Large waves and a storm surge generated by the northerly winds caused substantial coastal erosion between along the Lower West coast, particularly in the Geographe Bay area. Low-lying areas at Bunbury and Busselton were flooded, forcing the evacuation of many homes including the Bunbury Nursing Home. Plate 2.9 shows floodwaters through the streets of Bunbury.

Plate 2.9: Flooding in Bunbury (Courtesy of *West Australian*)

An approximate 1.3 m surge at Busselton caused the tide to peak at 2.5 m, about 1 m above the highest astronomical tide. The Busselton Jetty was severely damaged. At Fremantle there was a storm surge of about 0.6 m, causing a high tide of 1.8 m, about 0.5 m above the highest astronomical tide. While this was not sufficient to cause flooding in Perth it did combine with large waves to scour beaches, as shown in Plate 2.10. A large number of small craft were also damaged. By contrast there was little rainfall during the event. Perth did not record any rainfall and the heaviest rainfall in the southwest was less than 40 mm. An extract from the *West Australian* (6 April 1978) describes some of the damage from cyclone *Alby*:

> *Heavy damage along metropolitan beaches became evident yesterday as Perth began clearing up after the storm. Local councils' surf clubs and individuals face many thousands of dollars worth of damage. Long time residents described the damage as the worst in living memory. The metropolitan coastline was altered dramatically by the storm. The Floreat Surf Life Saving Club was left teetering on the brink of a seven metre drop to the beach. The sea had swept in as darkness fell on Tuesday night taking a four metre bitumen road and five metres of beach approach with it. Further south along the coast which was littered with roof tiles and smashed boats, the storm completely destroyed the Cottesloe Surf Life Saving Club's boat house and ambulance room. The Vice-President of the club, Mr R Redfern, said that at least $30,000 worth of boats, skis, boards and reels had been swept out to sea and dumped in splinters on the beach… Councils with ocean or river frontages will face the highest repair bills because of erosion. Most ocean groynes from City Beach south were damaged and the PCC has already tentatively estimated the cost of repairs on its beachfront at $10,000.*

Plate 2.10: Coastal erosion on Perth's beaches (Courtesy of *West Australian*)

2.6 Heatwaves

The heatwave threat

Heatwaves are probably the most under-rated weather hazard in Australia, essentially because they are viewed as a ‘passive’ hazard in contrast to the more widely studied catastrophic hazards such as tropical cyclones and earthquakes. According to Coates (1996), heatwaves kill more people than any other natural hazard experienced in Australia. In a study on the consequences of heatwaves, Andrews (1994) reported that in the period between 1803 and 1992, at least 4,287 people died as a direct result of heatwaves. This was almost twice the number of fatalities attributed to either tropical cyclones or floods over much the same time frame. In the United States, heatwaves are the second greatest cause of human mortality resulting from a natural hazard, killing more people than hurricanes, tornadoes, lightning and floods combined. Only low winter temperatures have killed more people. Recent heatwaves that caused a large number of deaths include Brisbane in January 2000, when 22 people died, and New York City in 1980, when 1,600 deaths were attributed to a heatwave and economic losses totalled 15 billion dollars.

In Western Australia a total of 392 deaths have been caused by excessive heat between 1807 and 1994, compared to 1,250 in New South Wales. This equates to a death rate per 100,000 of 0.68 in Western Australia, ranking second to South Australia (1.14) and above New South Wales (0.41). Heat-related fatalities in Australia are decreasing. Between 1973 and 1992 the heat-related fatality rate per 100,000 has declined to just 0.06 in Western Australia.

In addition to the official statistics, there are many more heatwave-associated deaths that are caused mainly by heart disease and strokes, particularly in the elderly. Not all heat-related deaths occur on days of extremely high temperatures, however, suggesting that other factors in addition to maximum temperature are significant in influencing mortality.

The impact of heatwaves extends further than just mortality rates. High temperatures are linked to:

- increased hospital admissions relating to heat stress, dehydration, or as a result of heat exacerbating existing conditions;
- increased rates of certain crimes, particularly those related to aggressive behaviour such as homicide;
- increased number of work-related accidents and reduced work productivity; and
- decreased sports performance.

An extract from the *West Australian* (21 February 1995) illustrates the effect of a heat wave in Perth:

> *Perth’s heatwave caused record power consumption and overstretched the ambulance service yesterday… A spokesman said the demand was caused by elderly people collapsing and having heart problems in the stifling heat. There were also many more assaults and brawls than normal in the early hours of Sunday when Perth sweltered through the hottest February night for ten years. Ambulances were called out 70 times, compared with an average of 30… Royal Perth and Sir Charles Gairdner hospitals reported treating people for dehydration, severe sunburn and heat exhaustion. Many people who came in with other illnesses also complained that the heat was making their problems worse.*

High temperatures can also cause significant economic losses through livestock/crop losses and damage to roads, railways, bridges, power reticulation infrastructure and electrical equipment (EMA, 1998). Heatwave conditions also significantly increase demand for electricity to power domestic air conditioners, water consumption and retail sales of cold drinks. During a heatwave in February 2004, the power supply was unable to cope with demand, resulting in power outages across Perth.

In assessing heatwaves as a natural hazard, consideration should also be given to the interaction of high temperatures and population vulnerability, which is a result of both the social and physiological systems. The distribution of heat-deaths is complex, the most vulnerable being the elderly, the sick and infants living in low socioeconomic urban areas during early summer heatwaves. Physiological adjustments primarily include acclimatisation to high temperatures, which is an issue for the increasing number of tourists arriving from the northern hemisphere winter.

The vulnerability of the population has decreased through the development and use of air-conditioners, better housing design, more suitable clothing, a trend towards more people working indoors, education and temperature forecasts for seven days in advance. Offsetting this, the percentage of elderly people in the population has increased, with those aged 65 and over comprising 11.2% of the population in Western Australia in 2001.

Defining heatwaves

There is no universal definition of a heatwave although in a general sense it is a prolonged period of excessive heat. The difficulty in defining a heat wave in Australia has been in establishing an appropriate heat index with an acceptable event threshold and duration, and relating it to the climatology of the area under investigation. Various heat or thermal comfort indices have been developed to evaluate heat-related stress combining air temperature and humidity, and in some cases, wind and direct sunlight. Two of the most widely used indices are the apparent temperature work of Steadman (1984) and the Relative Strain Index, RSI, derived by Belding and Hatch (1955) and discussed in the Goldfields–Eucla climatic survey (BOM, 2000).

High temperatures in the Perth area typically correspond to low humidity values because the prevailing east to northeasterly winds originate from the dry inland parts of the state. A study of temperatures at Perth Airport at 3 pm indicates that for temperatures exceeding 35ºC, the relative humidity exceeds thirty per cent on about 10% of occasions. Also, for the same air temperatures, the apparent temperature exceeds the air temperature on only 12% of occasions. While more humid conditions can exist when the air temperature is closer to 30ºC and can provoke some degree of discomfort, such days are not generally associated with heatwave conditions. As a result, for Perth the air temperature alone can provide a reasonable measure of heat stress.

Heatwave risks

The level of heat discomfort is determined by a combination of factors:

- meteorological: air temperature, humidity, wind and direct sunshine;
- cultural: clothing, occupation and accommodation; and
- physiological: health, fitness, age and the level of acclimatisation.

Heat stress makes us feel uncomfortable not so much because we feel hot, but rather because we sense how difficult it has become to lose body heat at the rate necessary to keep our inner body temperature close to 37ºC. The body responds to this stress progressively through three stages.

- **Heat cramps**: muscular pains and spasms caused by heavy exertion. Although heat cramps are the least severe stage they are an early signal that the body is having trouble with the heat.
- **Heat exhaustion**: typically occurs when people exercise heavily or work in a hot, humid place where body fluids are lost through heavy sweating. Blood flow to the skin increases, causing a decrease of flow to the vital organs. This results in mild shock with symptoms of cold, clammy and pale skin, together with fainting and vomiting. If not treated the victim may suffer heat stroke.
- **Heat stroke**: this stage is life threatening. The victim's temperature control system, which produces sweating to cool the body, stops working. Body temperature may exceed 40.6ºC, potentially causing brain damage and death if the body is not cooled quickly.

(Information from American Red Cross: http://www.redcross.org/)

Heatwaves in the Perth area

Perth's summer patterns follow a typical sequence. A ridge of high pressure south of the state combines with a deepening trough off the west coast to direct east to northeasterly winds over the Perth region. This pattern causes rising temperatures over successive days. The trough then moves inland, allowing early seabreezes along the coast resulting in a cool change. A new ridge then develops to the south producing southeasterly then easterly winds and the sequence begins again. Prolonged spells of hot days occur when this pattern is slow moving, the high being maintained south of the state and the west coast trough remaining off the coast. On such occasions, the east to northeasterly winds prevent the early arrival of the seabreeze and cause temperatures well above the average. Figure 2.18 shows a typical heatwave weather chart from March 2003. Tropical cyclones off the west or northwest coast can also help to maintain the trough offshore resulting in high temperatures in southern Western Australia (see section 2.5). These days are usually associated with hazardous fire weather conditions (refer to section 2.7).

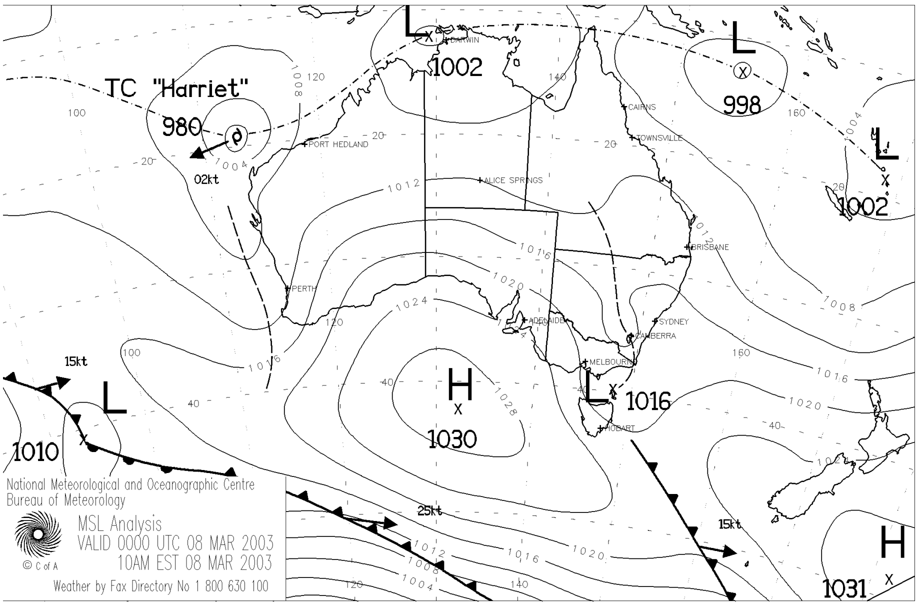

Figure 2.18: Mean Sea Level Pressure analysis of a typical heatwave pattern in Perth. A large and slow-moving high south of Australia combining with a tropical cyclone off the Pilbara coast maintains hot northeast winds in Perth

The occurrence of sequences of maximum temperatures of 35ºC or greater and 40ºC or greater at Perth Airport over 59 summers (1944–45 to 2003–04) is shown in Table 2.9. There have been 185 occasions where maximum temperatures of 35ºC or greater were recorded on at least three successive days, about three times per summer on average; and 15 occasions when at least three successive days have occurred on which maxima reached 40ºC or more, about once every four years on average.

Table 2.10 lists notable heatwaves showing data from Perth and Perth Airport. One of the greatest heatwaves occurred from 20 January to 6 February 1956, when for 17 consecutive days the maximum temperature at Perth Airport remained above 32ºC and averaged 38.8ºC. For five consecutive days maxima remained above 40ºC. The hottest summer on record was in 1978 when the temperature averaged 34ºC over 64 days from January to March.

Sequences of three successive days with maxima of 35ºC or greater have begun in all months between November and March, inclusive. Longer sequences of days with maxima of 35ºC or greater have been largely confined to the period from late December to mid-March.

Table 2.9: The occurrence of sequences of heatwaves at Perth Airport (1944–45 to 2003–04)

Duration of Sequence (days)	Maximum Temperature 35ºC or greater	40ºC or greater
3	91	11
4	39	2
5	23	1
6	18	1
7	4	
8	3	
9	2	
10	3	
11	1	
12	0	
13	1	
Total	**185**	**15**

Table 2.10: Notable heatwaves in Perth

Date	No. of days	Perth[1] Average Temp. (°C)	Perth[1] Highest Temp. (°C)	Perth Airport Average Temp. (°C)	Perth Airport Highest Temp. (°C)	Comments
16–27 January 1920	12	36.6	41.6			
3–11 February 1933	9	40.2	44.6			
20 January – 5 February 1956	17	37.1	43.7	38.8	43.7	Eight days over 40ºC at airport
29 December 1961 – 13 January 1962	16	36.0	40.5	37.1	41.6	
29 December 1964 – 5 January 1965	8	39.1	41.2	39.9	42.1	Six consecutive days over 40ºC at airport
29 January – 5 February 1975	8	36.9	40.4	38.5	42.4	
11–23 February 1975	13	37.1	40.9	36.4	40.9	
3 January – 7 March 1978	64	33.2	44.7	34.0	44.2	Perth's hottest summer ever
5–17 February 1985	23	36.5	43.7	37.5	43.4	
6–22 February 1988	17	35.8	39.0	36.6	40.8	
27–31 January 1991	5	39.1	45.8	40.5	46.0	
19–23 February 1991	5	39.1	46.2	40.5	46.7	Perth’s highest temperature on record.
1–16 February 1996	16	36.5	42.4	37.5	43.2	
24 December 1999 – 7 January 2000	15	35.8	39.3	36.2	40.4	
21 February - 6 March 2001	14	34.7	39.7	35.3	40.1	

Note: [1] The station of Perth has undergone many changes throughout the observational record. The Perth station was moved from West Perth to East Perth in 1967, and then to Mt Lawley in 1993.

The primary environmental influences on day-time temperature variations across the greater Perth area are the ocean, the Darling Scarp, the Swan River estuary, and the nature and extent of urban development. The greatest single factor is proximity to the coast, because of the impact of the seabreeze on temperatures. Perth's reliable afternoon seabreeze, commonly referred to as the ‘Fremantle Doctor’, provides cooling relief from the east to northeast winds on hot summer days. The breeze initially arrives on the coast then progressively extends inland, often decreasing the temperature on hot days to below 30ºC within a few hours from onset. The degree of cooling varies according to the initial temperature, the time of onset and the strength of the seabreeze. Seabreezes typically take several hours to extend from the coast to the foothills, although there is significant variability in its movement inland. During very hot periods the seabreeze is delayed until at least mid-afternoon, and may not reach the coast at all on some days. On those days coastal suburbs may experience higher temperatures than elsewhere.

Figure 2.19 shows temperatures from a number of Perth sites during the heatwave from 1–16 February 1996. In general the temperatures follow the same behaviour day to day, however on any one day temperatures vary between sites. The highest temperatures tend to occur at Pearce and Gosnells. On most days, the coastal site of Swanbourne has the lowest temperature reflecting the influence of the earlier seabreeze. The difference in temperature between Pearce and Swanbourne can be up to 9ºC on some days. On other days (e.g. 2nd, 7–9th, 11th and 13th February), when the seabreeze is very late or does not reach the coast at all, Bickley, located in the hills, has the lowest recorded temperature, reflecting the influence of altitude on temperature.

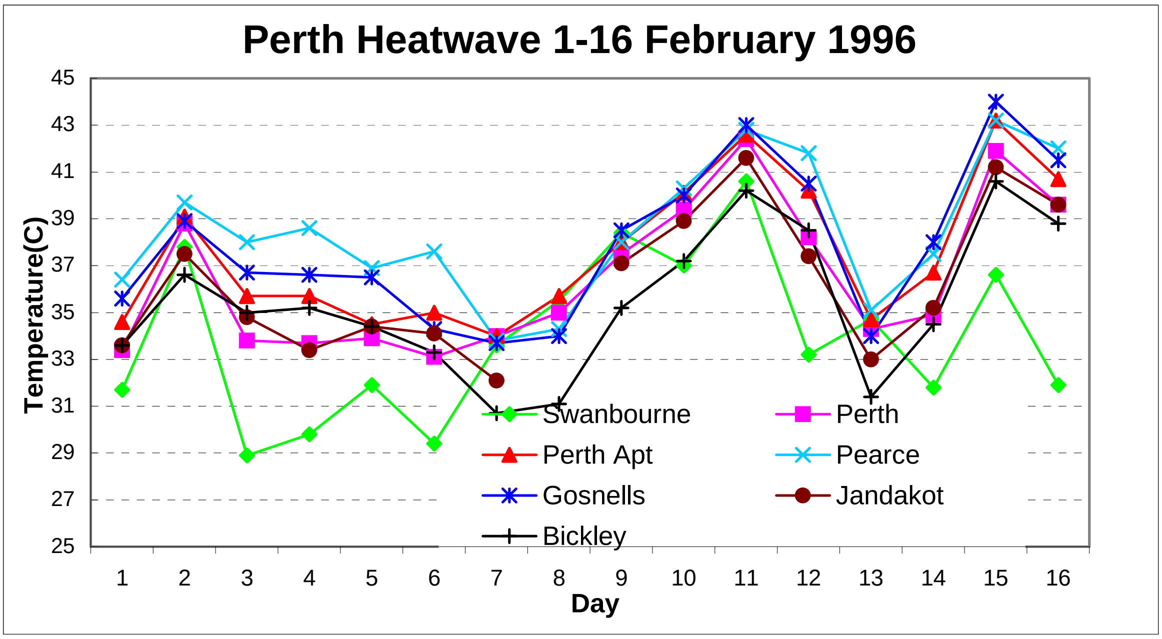

Figure 2.19: Maximum temperatures at Perth sites during the February 1996 heatwave

Trends and future projections

In contrast to the decline in the number of heat-related fatalities, the temperature record suggests an increase in the number of hot days in the Perth area. Summer maximum temperatures are estimated to have increased at the rate of over one degree per 100 years using data between 1950–1998. Collins *et al.* (2000) determined a slight increase in the frequency of heatwave events (at least three successive days of temperatures 35ºC or greater) at Perth Airport of 0.4 events per decade from 1957 to 1996.

Concern has been expressed at the possibility of temperature rises as a result of human-induced changes to the climate system. Current computer modelling by the CSIRO of the effect of an enhanced greenhouse effect on temperatures in the summer months suggests an increase in the number of days of 35ºC or greater at Perth from 15 to between 16 and 22 by 2030 and 18 to 39 by 2070. It is likely that the number of successive days of high temperatures would also increase.

2.7 Bushfires – a meteorological perspective

The bushfire risk

The rate of spread of fires is strongly associated with the weather conditions at the time. In Perth and about the lower west coast the fire risk is greatest from summer through autumn, when the moisture content in vegetation is low. Summer and autumn days of high temperatures, low humidity and strong winds are particularly conducive to the spread of fires. Indeed temperature, relative humidity, wind speed, and the curing rate of vegetation can be combined into a fire danger index (FDI) that is the basis for the fire danger rating (Low, Moderate, High, Very High and Extreme) included on forecasts. In Western Australia the FDI used is the Revised Grasslands Fire Behaviour Meter which is based on the CSIRO-modified McArthur Mk IV Grassland Meter.

Perth's most susceptible area to bushfires is the forest areas in the hills suburbs. These are prone to strong morning easterlies that can fan existing fires. These easterlies can also be enhanced by topographical variations such as the Helena Valley. Other areas of bushland in Perth are also vulnerable to wildfires and can threaten neighbouring residential areas if they catch fire. On one afternoon in January 1989 a wildfire burned 45% (120 ha) of Kings Park.

The fire threat is increased when thunderstorms develop; producing lightning that causes ignition for fires. This is particularly the case when thunderstorms cause little or no rain, as is sometimes the case on hot days.

Fire weather climatology

Table 2.11(a and b) shows the monthly frequency of the five fire danger ratings for Perth Airport (1993–2004) and Bickley (19972004). These ratings are based on the highest FDI calculated each day and assumes a curing rate of 100%. The maximum number of Very High and Extreme days occurs in January. The calculated FDI values are higher than actual values in December because the curing rate early in the season is less than 100%. The annual number of such Very High to Extreme days is considerably higher at Perth Airport (31) than at Bickley (3) because the summer temperatures on the coastal plain away from the coast are higher than in the hills. The frequency of Very High to Extreme days decreases towards the coast on the coastal plain because of the seabreeze effect. Despite the curing rate being 100% in autumn, the fire danger rate declines because of lower temperatures and lower wind speeds on average.

Table 2.11(a): Perth Airport Fire Danger Ratings (1993–2004)

Month	Low	Moderate	High	Very High	Extreme
January	0.1	0.2	24.3	4.7	1.6
February	0.0	0.4	21.9	5.2	0.8
March	0.1	0.6	26.5	3.3	0.6
April	0.3	3.8	24.9	1.0	0.1
May	0.1	11.1	19.1	0.6	0.1
June	0.9	12.7	16.1	0.3	0.0
July	0.7	13.5	16.3	0.4	0.1
August	0.1	11.9	18.5	0.5	0.0
September	0.1	8.1	21.0	0.4	0.4
October	0.2	1.5	27.7	1.4	0.1
November	0.3	0.3	26.2	2.3	0.9
December	0.0	0.3	23.8	5.1	1.9
Year	**2.8**	**64.3**	**266.3**	**25.3**	**6.6**

Table 2.11(b): Bickley Fire Danger Ratings (1997 –004)

Month	Low	Moderate	High	Very High	Extreme
January	0.7	2.0	27.8	0.3	
February	0.4	1.3	26.1	0.4	0.0
March	1.4	5.3	23.1	0.4	0.7
April	0.6	14.7	14.6	0.1	0.0
May	3.0	19.6	8.4	0.0	0.0
June	4.9	19.6	5.5	0.0	0.0
July	5.7	18.8	6.5	0.0	0.0
August	2.5	22.0	6.5	0.0	0.0
September	0.8	19.3	9.7	0.2	0.0
October	2.6	16.2	12.1	0.0	0.2
November	0.0	7.6	22.4	0.0	0.0
December	1.1	2.9	26.3	0.6	0.1
Year	**23.8**	**149.2**	**189.0**	**2.0**	**1.2**

Extreme fire weather conditions in the Perth region typically occur with strong easterly or northeasterly winds associated with a strong high to the south of the state and a trough offshore as shown in Figure 2.20(a). Easterly winds represent about 60% of extreme fire weather days (events) compared to less than 5% associated with southerly winds. This is in contrast to Geraldton where winds on 40% of extreme events are southerly and at Albany and Esperance where winds on over 75% on extreme events are northerly. About 15% of Perth events occurred in a westerly flow following the passage of a trough. This number increases inland from the west coast where the westerly or northwesterly winds can be strong and gusty while temperatures initially remain high with the trough change. The eastward movement of the trough is shown in the sequential mean sea level pressure charts in Figure 2.20(a–b).

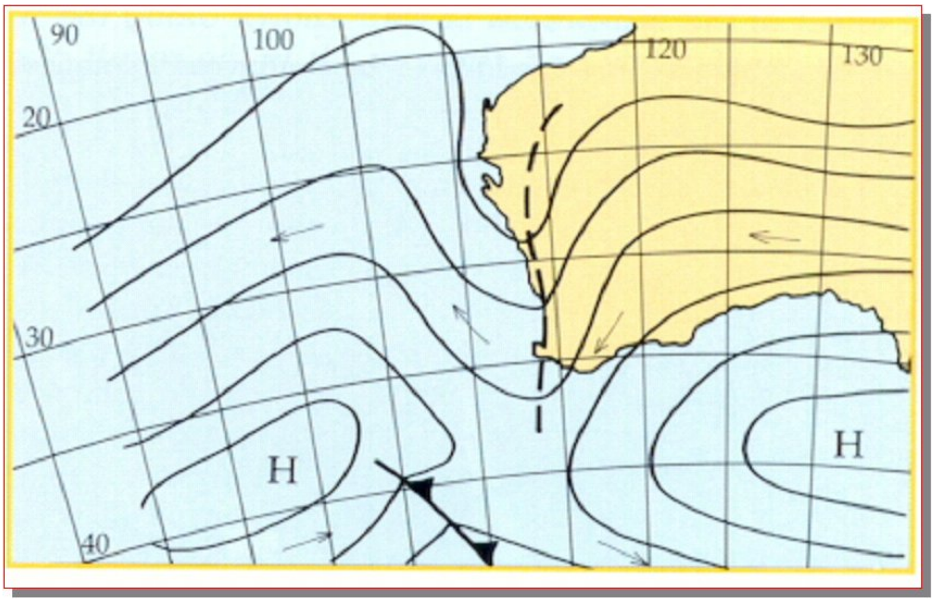

Figure 2.20(a): Mean Sea Level Pressure chart showing a typical day of hazardous fire weather. A high south of the continent directs east to northeasterly winds towards a trough near the west coast. Such days in Perth are typically very hot and dry

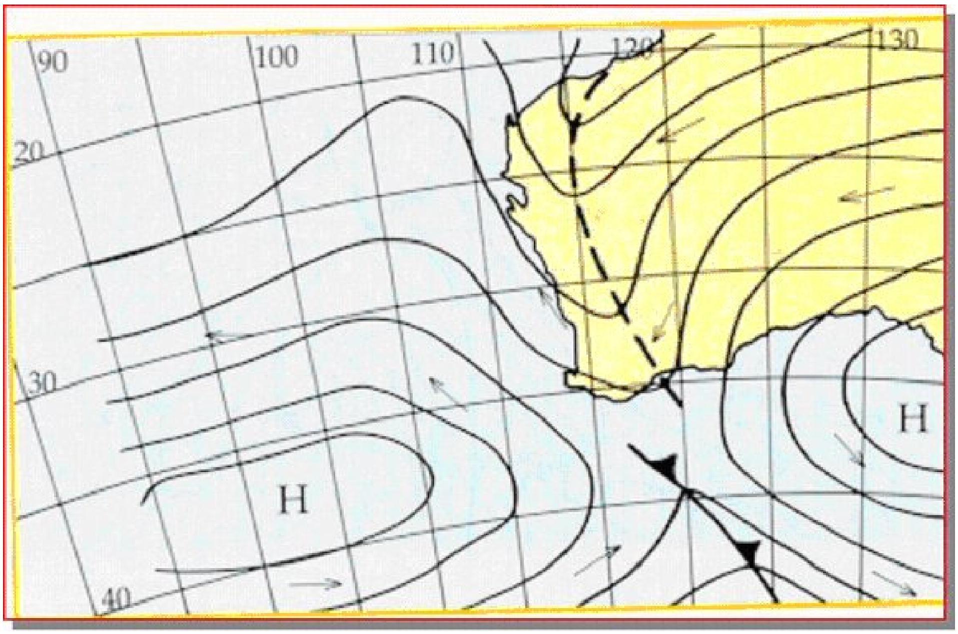

Figure 2.20(b): Mean Sea Level Pressure chart representative of the following day. The eastward mobility of the highs to the south helps to move the trough inland of the west coast resulting in significantly cooler conditions about the west coast

Very dangerous fire weather conditions often follow a sequence of hot days and easterly winds that culminate in the deepening of the trough near the coast and movement inland. The presence of a tropical cyclone off the Pilbara coast often helps maintain the trough offshore for longer than is normal. Such conditions occurred in January 1961 when the temperature at Wandering exceeded 40ºC on eight of the ten days from the 15th to the 24th. Strong winds associated with the trough passage on the 24th also coincided with thunderstorms that ignited fires east of the city and a major fire completely engulfed Dwellingup (Plate 2.11 and below).

Plate 2.11: The charred remains of Dwellingup after the devastating January 1961 bushfire (Courtesy of *West Australian*)

Tropical cyclones can cause a major fire threat in the southwest as demonstrated in February 1937 and again in April 1978 (cyclone *Alby*). Although tropical cyclones are normally associated with driving rain, destructive winds and storm surges, ones that accelerate into the mid-latitudes off the west coast can cause strong winds without rainfall over land (to the east of its track). The co-location of very strong winds and dry conditions creates a dangerous environment for wildfires to spread rapidly.

Some significant historical events in the Perth region

On 24 January 1961, a prolonged hot spell culminated in a very hot day and strong, gusty northwesterly winds associated with a trough change. Many fires that had been ignited by lightning in the previous week flared during the day and one fire front burned through Dwellingup, destroying 132 homes and a number of other buildings (Plate 2.14). Fortunately there were no serious human casualties. The situation was described by the *West Australian* (24 January 1981) as follows:

> *About 8.30 pm on Tuesday January 24, 1961, hundreds of terrified people watched helplessly as fire engulfed and destroyed most of Dwellingup, a timber milling town 100 km south of Perth. A short time before they had hurriedly abandoned their homes with only the clothes they wore. They watched a petrol station blow up, houses and motor vehicles explode into flames seconds after being abandoned and flames jump hundreds of metres ahead of the main front, fanned by 120 km/h winds. Some people jumped into a well to escape the inferno and workers trapped at a forestry mill lay face down on the ground and took turns spraying water on each other…*
>
> *Miraculously no one was killed or seriously injured. But about 800 people were left homeless and scores of people were treated for smoke inhalation and eye complaints. When the damage had been tallied up, 132 houses had been destroyed, as well as the hospital, two saw mills, two service stations, three general stores, offices, outbuildings and 74 motor vehicles. The value of the damage was estimated to be about $10 million - $50 million on today's [1981] values.*

Smoke from fires burning in the hills near Keysbrook and in the hills near Perth blanketed the city. Due to the poor visibility, Perth Airport was closed to light aircraft and at Fremantle shipping traffic had to be tracked by radar (*West Australian*, 24 January 1961).

On 4 April 1978, pre-existing fires were fanned by gale-force winds as cyclone *Alby* accelerated down the west coast. The Bushfires Board reported 78 fires in the area south of Eneabba to Lake Grace. These burnt over 31,000 ha and had a total perimeter of 470 km. Falling trees killed two people during fire fighting operations.

On 1 December 1979, a large bushfire near Mandurah cut power lines resulting in a power blackout. Perth lost one-third of its power, causing residents to swelter in 37° heat. The havoc it caused is described by the *Sunday Times* (2 December 1979):

> *A major power failure plunged Perth and the South West into chaos for several hours yesterday. The blackout, caused by a bushfire near Mandurah, cut both transmission lines between Perth and Bunbury, as most of the State sweltered in near century heat. At one stage, the entire metropolitan area and the South West were blacked out. State Energy Commission (SEC) officials worked for several hours to restore power and boost output from Kwinana and South Fremantle power stations. Late yesterday the two Bunbury transmission lines were still out as a huge bushfire raged out of control 8 km east of Mandurah. SEC engineers took to the air in an attempt to determine the point of the failure. They were flying along the transmission lines from the southern terminal at Cannington to Bunbury. The blackout hit Perth and the South West at about 12.30 pm bringing disruption to thousands of homes, hospitals, emergency services and sporting fixtures. It caused havoc in the racing world as the Ascot races were forced on to emergency power and 37 TAB shops were closed down. The SEC shifted the power load around the metropolitan area in a bid to ease the disruption. It was 3 pm before power was restored to most areas. The SEC's marketing manager, Mr Don Saunders, said the two transmission lines from Bunbury were cut suddenly at 12.30 pm. At that point Perth lost a third of its power. The total load for Perth is 600 megawatts and we lost 200 megawatts, he said.*

On 8 January 1997, bush fires at Wooroloo and Wundowie destroyed 16 homes and part of the Wooroloo Prison Farm. Other losses, including sheds, fencing, livestock, vehicles and stored fodder, contributed to a total cost well in excess of $12 million (Bushfires Board of Western Australia, 1997).

More recently, a bushfire burnt through 2,000 ha of scrub and damaged six homes in Perth's northern suburbs in early February 2001. Less than two weeks later this was followed by a bushfire which burnt through 1,000 ha of scrub in Perth's northeastern suburbs and threatened several homes and the Perth International Telecommunications Centre (*West Australian*, 15 February 2001).

2.8 Summary

The Perth region is subject to a range of meteorologically related hazards: winter storms, summer storms, floods, tropical cyclones, heatwaves and bushfires. Of these, cool season storms are the most frequent hazard and on average have the greatest economic impact. Strong fronts cause winds of gale-force intensity near the coastal fringe of the southwest producing mostly minor damage over a wide area. Damage is typically associated with roof damage and to power lines. These fronts may also spawn severe localised winds, including tornadoes. Winds may be strong enough to unroof houses although such damage is fortunately confined to small areas.

The meteorological hazards that have individually had the greatest impact on Perth have been floods and tropical cyclones. If Perth was to experience floods of the magnitude of those in 1862, 1872, 1917, 1926 or 1945, then the economic impact would be on the order of many tens of millions of dollars. However, Perth's average annual rainfall has decreased in the last 40 years, lessening the risk of a flood of such magnitude. Possibly Perth's single greatest meteorological event was cyclone *Alby* in 1978, when damage was estimated at $39 million (2003 dollars). Strong winds damaged properties and fanned bushfires, while a storm surge and large waves caused massive coastal erosion and flooding in low-lying areas.

Although summer thunderstorms storms are much less common in Perth than in most other Australian cities, there is the potential for them to be as severe as the Sydney hailstorm in 1999 that caused over $2 billion damage. Fortunately such a storm has not impacted Perth. Heatwaves, although viewed as a 'passive' hazard, kill more people than any other meteorological phenomenon. However, the impact of heatwaves has been reduced by factors such as increased use of air-conditioners, better housing design and greater awareness of the risk.

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