CHAPTER 2

MANAGING CROPPING SYSTEMS IN VARIABLE CLIMATES

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Rainfall variability and its interaction with land management has shaped Australian agriculture since the beginning of European settlement over 200 years ago. In less than a century European settlers had transformed much of Australia's natural landscape. Extreme climate events can dramatically affect farm level productivity, but can also affect the entire Australian economy. It can even influence macroeconomic indicators such as international wheat prices, employment or the exchange rate (White, 2000). In some regions, extreme climate events combined with factors such as overgrazing have resulted in major long-term resource degradation (McKeon *et al.*, 1990).

High rainfall variability is the major source of dryland yield fluctuations. Rainfall amount and distribution through the growing season are critical, with rainfall distribution becoming more important on soils with low plant available water holding capacity or in years when starting soil moisture levels at planting are low. Decadal scale climate variability has encouraged expansion of crop production into normally drier areas, only for it to retreat when a series of good years came to an end (e.g. the upper north of South Australia in the late nineteenth century. Peanut production which developed in southern Queensland during the above average summer rainfall conditions of the 1950s to 1970s, resulted in unrealistically high yield expectations for the changed climate patterns of the 1980s and 1990s (Meinke and Hammer, 1995). The resultant cropping systems of today are generally resilient, and capable of absorbing some of that variability - without immediate disastrous results. A typical example is dryland winter and summer cropping in the north eastern cropping region of Australia (central NSW to central Queensland) where water is stored in the heavy clay soils over fallow periods. This water is then used by the next crop grown and acts as a buffer against possible, low in-season rain. Another example is the wheat/pasture/grain legume rotations in southern Australia that remain profitable even under adverse climatic conditions (i.e. prolonged droughts or water logging).

To remain economically viable in an internationally competitive market, Australian farmers have to devise management options that can produce long-term, sustainable profits in such a variable environment. With declining prices and terms of trade, farmers have had to increase productivity and the level of inputs, but this has made them more vulnerable to losses in bad seasons. Hence, there is an increasing requirement for farmers to have a sound understanding of the sources of rainfall variability, their degree of predictability, and objective tools to assess management options in agronomic, economic and environmental terms. Demonstrating the effect of climate variability must not be confused with either the real or potential impact of a forecast. Effective applications of climate information, including climate forecasts, depend on factors such as the type of forecast provided and its suitability for influencing specific decisions.

This chapter initially outlines the basics of the Australian climate, including the physical causes and consequences of climate variability and its predicability. The chapter then describes how farmers, agribusiness, commodity traders and policy makers can use this information to make better-informed decisions.

AUSTRALIAN CLIMATE SYSTEMS, CLIMATE VARIABILITY AND CLIMATE FORECASTING

Australia has one of the most variable rainfall patterns in the world. Experiences such as the 'wet' decade of the 1970s in Eastern Australia (Russel, 1981), the drought impacts associated with the 1982 and subsequent El Niño events, and the prolonged drought in north-eastern Australia during the early 1990s, have led to considerable advances in oceanography, atmospheric sciences and climatology. This resulted in a much better understanding of the causes of this variability, and the scientific understanding gained provides a basis on which to assess likely future climate patterns, be they for the coming season, for the next decade or for future generations.

For agriculture, the question remains: how can we use such information profitably? While our natural environment is well adjusted to variability in rainfall patterns, our agricultural practices – often because of economic pressures, but sometimes also due to ignorance about possible alternatives – are not necessarily best attuned to such a fluctuating climate.

As this chapter shows, many of the successful applications of such information are based on our understanding of the El Niño/Southern Oscillation phenomenon (ENSO). Although ENSO explains a significant proportion of Australian climate variability (and future work will further refine current applications), knowledge of other climate drivers might also have considerable potential to improve agricultural systems performance. Hence, in order to understand how agricultural decision-making can be improved through understanding of existing climate variability, it is important to appreciate some of the basic principles and the key drivers of the Australian climate system. These are outlined in the first part of this chapter.

Broadscale climate drivers - the General Circulation

The climate of Australia is controlled by the earth's *General Circulation*, which is driven by differences in heating between different parts of the globe. Foremost among these is the difference between the tropical low latitudes, which receive abundant solar heat radiation, and the polar high latitudes, which receive relatively little. This heating imbalance creates a flow of heat from low towards high latitudes - but one complicated by numerous factors, such as the earth's rotation, the distribution of land, ice, and ocean, and differences in ocean temperatures.

The low latitude Hadley circulation

Generally, in tropical latitudes the heating of the earth and adjacent atmosphere creates low pressure at sea level, and rising motion. The rising motion condenses abundant moisture usually present in the tropical atmosphere into intense showers and thunderstorms, which heat the atmosphere further, by converting *latent energy* stored in moist air to heat energy (a process called *latent heat release*).

At a height of around 20km the air stops rising, because at that level, the *tropopause*, temperature begins to rise with height - a situation that inhibits further rising motion. Unable to ascend further, the air turns poleward – i.e. southward in the Southern Hemisphere - and at around latitudes 25-30ºS, sinks back towards the earth's surface, 'piling up' atmospheric mass. In this way the quasi-permanent *high pressure systems* of the globe, which make up the *subtropical ridge (STR)* are formed. Sinking air and high atmospheric pressure inhibit rainfall. Because the STR coincides with Australia's location, this largely explains why the bulk of Australia experiences low rainfall (the average annual rainfall over Australia is just 457 mm per year).

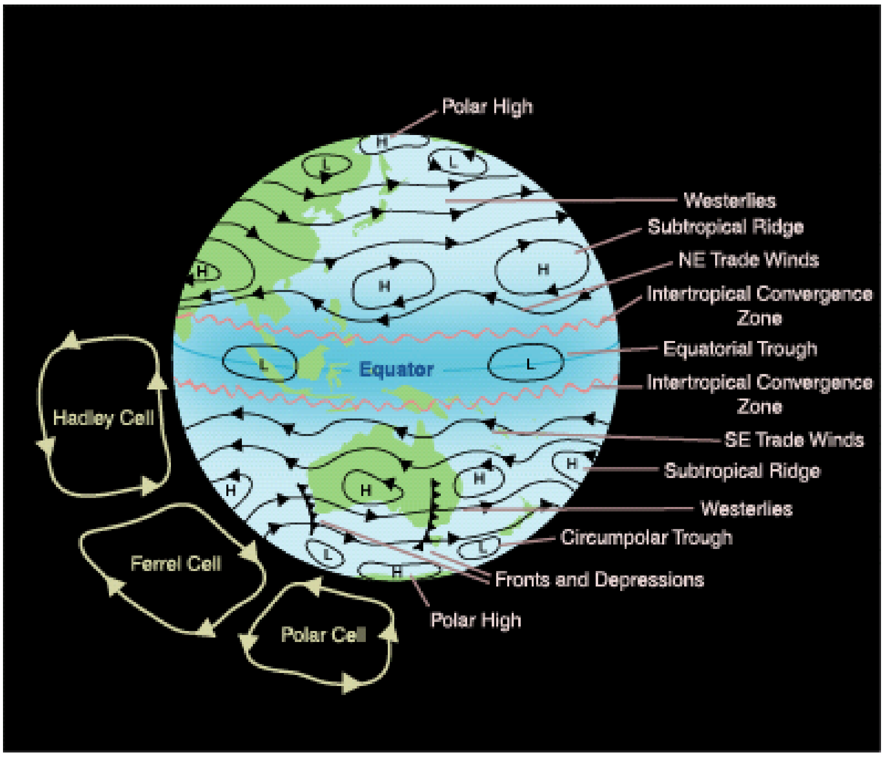


Figure 2.1 Depiction of the general circulation, showing the main circulation features and wind belts referred to in the text. The Ferrell cell in the diagram is formed from ascent in the vicinity of the circumpolar trough and descent in the subtropics. This schematic corresponds roughly with the transition seasons (autumn, spring): the main features extend southward in the southern hemisphere summer and northward in the southern hemisphere winter.

An equatorward low-level ‘return’ flow between the STR and the low pressure area near the equator completes a circuit between the tropics and subtropics known as the *Hadley cell.* The strength of this cell varies around the globe, and also with season. The rotation of the earth exerts a force on moving airstreams known as the *Coriolis Force*, which deflects equatorward-moving airstreams to the west, and poleward-moving airstreams eastward. For this reason, the equatorward low-level flow of the Hadley cell in the southern hemisphere is not southerly, but south-easterly, and the belt between the STR and equatorial trough is the domain of the *south-easterly Trades* (the northern hemisphere counterpart is the north-easterly Trades). The area of low pressure and disturbed weather separating the two equatorward-flowing Trade wind belts is termed the *Intertropical Convergence Zone (ITCZ)***.** The Hadley cell and south-easterly Trades control the climate of the tropics and subtropics, i.e. the northern two-thirds of Australia.

The midlatitude westerlies

Poleward of the STR, a strong north-south temperature gradient exists between about latitudes 30º and 60ºS (and N) - the so-called *mid-latitudes* zone. Here, strong contrasts of heat and moisture lead to the formation of low-pressure systems and frontal systems, with associated cloud and rainfall. The temperature gradient at lower middle latitudes also generates strong westerly winds in the upper atmosphere (the *subtropical jet stream*), with another jet at higher latitudes (the *polar front jet stream*): these provide an additional energy source for the growth of low pressure systems. Mid-latitude cyclones are also generated by temperature differences between land and sea, and also from the development of instability, such as when cold air passes over a warm sea. Less commonly they originate in the subtropics or tropics and then move into higher latitudes.

The mid-latitudes are predominantly a zone of westerly winds, resulting from the effects of the Coriolis Force on poleward-moving air. As a rule, cyclones move from west to east within this flow. However there is also a tendency for cyclones, as they mature and intensify, to move poleward, meaning that in general the deepest systems are found well south of Australia. The belt of lowest pressure, where intense low-pressure systems follow each other in succession, generally lies at around 60ºS (or N), and is sometimes referred to as the *circumpolar trough*.

These mid-latitude cyclones are often intense, but associated rainfall is generally lighter than in the tropics, because (a) the tropopause ‘lid’ that constrains rising motion is lower (about 10 km) at these latitudes than in the tropics; and (b) cooler mid-latitude air holds less moisture than warmer air (and in general, atmospheric moisture content determines rainfall intensity). Nevertheless, the cyclones and frontal systems of the westerlies are responsible for most of the rainfall over Australia’s southern States, and the seasonal tendency of these systems to track further north in winter/spring as the circumpolar trough expands accounts for the cool season rainfall maximum over most of the southern States.

Seasonal contrasts

The tilt of the earth's axis varies during the year, so that the sun appears to migrate north and south, giving rise to the seasons. The *thermal equator* (i.e. the area receiving the strongest heating) shifts between about 5ºS and 15ºN in July, and as it shifts, there is a tendency for the main pressure belts to follow it. Over Australia the STR shifts northward in winter, resulting in generally fine, settled weather conditions in northern regions. The southern westerlies also extend northward, and their embedded weather systems bring showery conditions to the southern States. As summer approaches, the westerlies retreat southward, resulting in drier, more settled conditions over the southern States. At the same time, warming of the continent and surrounding oceans leads to falling pressures over northern Australia, and the onset of the summer 'wet' season.

Land-sea contrasts

Land tends to heat up and cool more quickly than water, leading to heating imbalances over essentially similar latitudes. Even over the oceans, surface temperatures are by no means constant across all longitudes, especially over the Pacific where the difference has major climatic significance. Relatively cool surfaces are more conducive to high pressure; relatively warm ones favour lower pressures. This distorts the pressure distribution. The accompanying pressure map shows that in July (representing winter), high pressure prevails over Australia, with slightly lower pressures over adjacent oceans. In summer, low pressure extends over Australia from the north, with lower pressures over the continent than over the surrounding oceans. These atmospheric features vary from year to year (*inter-annual* variations), giving rise to variations in rainfall patterns.

Main Weather Patterns Affecting Australia

The summer monsoon

The low pressure area that develops over northern Australia with the approach of summer has the effect of drawing the *monsoonal trough* – i.e. the belt of lowest pressure over the summer hemisphere tropics - southward over northern Australia. This trough 'draws in' moist air from the surrounding oceans, from the northwest over western Australia and the north and east over Queensland, and this inflow of moist air is referred to as the *monsoon*. Monsoon weather is characterised by lengthy periods of rain and fresh to strong winds.

The northern Australian wet season nominally extends from October to April, but the monsoon itself typically starts in late December and ends in March. By January the mean position of the monsoonal trough normally lies between about Broome and Cairns. The period from about October to the onset of the monsoon is often called the *build-up*, a period of hot and humid, thundery conditions. In general only the far north of Australia regularly experiences significant rainfall from the Australian monsoon, and there are often frequent 'breaks' of dry weather. However, widespread heavy rainfall and flooding can occur when the monsoonal trough is well developed, as in 1973/74, 1998/99 and 1999/2000. Conversely, the monsoon of 1991/92 was relatively weak, with general failure of summer rains in the tropics.

Heavy rains are also produced by tropical depressions and tropical cyclones, while at other times, scattered thunderstorms may develop in association with shallow 'heat troughs', a common feature of summertime weather maps.

The monsoon trough frequently spawns individual low-pressure systems, sometimes called *monsoon depressions*, that move slowly across northern Australia, producing heavy rain and flooding. Occasionally - especially in late summer or early autumn - such depressions move southward, bringing flood rains to the interior, and sometimes even to the southern States.

Tropical cyclones

Tropical cyclones evolve from the strong convective complexes frequently seen in the tropics during the Wet. Provided certain conditions are met, these complexes may evolve into a *tropical depression* - a weaker cousin of the tropical cyclone, but capable of producing heavy rain and strong winds in its own right. A tropical depression becomes a tropical cyclone when it attains sufficient intensity to produce sustained winds of at least gale force (63 km/h). Such systems are referred to in cyclone advices and warnings as 'Category 1' or 'Category 2' storms, depending on their intensity. A *severe tropical cyclone* (designated Category 3-5) can produce sustained hurricane force winds (at least 118 km/h), and is the equivalent of hurricanes and typhoons in other parts of the world. Cyclone 'Tracy', which devastated Darwin in December 1974, was a Category 4 system.

Cyclones affecting Australia form over the Coral Sea and tropical Indian Ocean, the Timor Sea and the Gulf of Carpentaria - all areas of high surface water temperatures in summer and autumn. Such warm waters also fuel the torrential rains - often hundreds of millimetres within a few days – that accompany cyclones. Indeed, associated flooding is a major cause of death and losses from cyclones. On average about ten cyclones per season develop over Australian waters, of which six cross the coast, mostly between Exmouth and Broome in the northwest, and between about Mossman and Maryborough in the northeast. One or two typically develop in the Gulf of Carpentaria and affect the islands and/or neighbouring land areas. Cyclone numbers vary considerably from year to year and – especially off eastern Australia – are strongly linked to the *ENSO phenomenon* (see below).

Cyclones moving into higher latitudes or inland lose contact with the warm tropical oceans needed to sustain them and they weaken, but are still capable of producing flood rains. Such cyclonic rains can be a blessing to drought-afflicted areas. It has been estimated that in Western Australia, 30-50% of rain falling north of 25ºS between the coast and 300km inland is the result of tropical cyclones (Milton, 1978). Moreover, it is considered (Ryan, 1993) that agriculture in much of inland northern Australia is largely dependent on rain from decaying tropical cyclones.

The intra-seasonal, or Madden-Julian oscillation

Tropical rainfall shows a tendency to be organised into bursts of intense activity, lasting a few days to a week or so, interspersed with relatively quiet periods of about a month (Madden and Julian, 1972). Such bursts account for a high percentage of tropical rainfall, and most tropical cyclones form during these active phases. This behaviour is well defined over the tropical Indian and Pacific Oceans, and northern Australia. Active zones tend to migrate from west to east at about 400 km per day.

This rather irregular phenomenon has various names, among them *30-50 day Oscillation*, or *30-50 day wave* (the approximate period between active bursts), *Madden-Julian Oscillation,* or *Intra-seasonal Oscillation*. Attempts to predict tropical rainfall based on this apparent periodicity are being made, but to date predictability has been low. However, as shown later in this chapter, primary producers in northern Australia are increasingly using the information in their logistical planning (e.g. scheduling of harvest operations).

High pressure systems

The subtropical ridge (STR) was earlier defined as an area of stable conditions and fine weather. Within the STR, individual cells of high pressure – *anticyclones* - travel slowly west to east across Australia. In January the STR lies over and south of southern Australia, bringing mostly fine conditions to the southern States. In autumn the STR shifts north and intensifies, extending across inland South Australia and northern New South Wales/southern Queensland in winter.

Individual anticyclones usually control the weather for several days, producing mainly settled, dry conditions, though drizzle or light *orographic rain* can occur on their periphery in exposed coastal or hilly regions. In winter, clear skies, dry air and light winds favour cold, frosty nights, especially inland. Occasionally - particularly in the autumn/early winter - high pressure cells stagnate (so-called *'blocking highs'*), and can dominate the weather for up to three weeks, reinforced by other 'highs' moving in from the west. Typical weather patterns associated with blocking highs are long spells of clear, settled weather conditions (with winter frost and fog) under the 'high', and with fine, mild conditions on the western flank. 'Blocking' is most common over the Tasman Sea-New Zealand region, or the Bight. Occasionally a low pressure system forms north of a blocking 'high', resulting often in substantial rain over the subtropics.

Cold fronts and depressions

As the circumpolar trough of low pressure expands equatorward between March and June, the associated westerlies increasingly influence weather in the southern States. At the same time as the circumpolar vortex and westerlies expand north, pressures rise over inland Australia. Consequently a broadscale trough in the westerlies develops on either side of the continent, with its lowest values in June (van Loon, 1972). The Indian Ocean trough is climatologically the source of the truncated winter rainfall distribution in southwestern Australia (see below).

Individual fronts, and/or depressions embedded in the westerlies usually affect the southern States regularly in the cooler months, accompanied by showers or a short rain period, followed by a tendency to clear. Winds are predominantly north-westerly ahead of a cold front, and colder west to south-westerly behind it, and can reach gale force. Significant shower activity may occur about exposed coasts and hills in the post-frontal west to south-westerly stream. Occasionally, depressions develop over or near the Australian mainland itself and, if the preceding air mass has been moist, associated rainfall can be very heavy.

It sometimes happens that the influence of the westerlies is replaced for long periods by anticyclonic dominance. When this happens, the southern States, which normally receive most of their rain in the cooler months, may experience drought. For instance in 1994 and 1997 the STR was stronger and further south than usual, weakening the effects of frontal systems affecting Australia, leading to failure of winter rains over southern Australia.

There is a tendency for the latitude of the STR to affect rainfall in Victoria, Tasmania and southern South Australia in the opposite sense to that in coastal areas of New South Wales and Queensland: if the STR is further south than usual, rainfall tends to be reduced in the southern States, but increased along the east coast, and vice versa.

Occasionally, a depression becomes cut off from the westerlies, shearing off into lower latitudes. Or a depression may form within the subtropics. Such *cut-off lows* tend to move more slowly - and often quite erratically - compared with depressions within the westerlies. They can produce significant rainfall. A special sub-class of extratropical cyclones is the so-called *east coast low,* which develops near the east Australian coast between southern Queensland and Tasmania, mainly during winter or the transition seasons. Such systems can produce violent gales (at their worst approaching hurricane intensity) and flood rains – many of the major flood episodes on east coast river systems are due to these systems.

Tropical-extratropical interactions and cloud bands

Extensive bands of cloud, extending from the tropics across Australia into mid-latitudes, are quite common on satellite pictures during the cooler months. These *tropical-extratropical cloud bands* form when moist air from the tropics is forced to rise by temperature gradients in the middle and upper atmosphere. Such lifting tends to be gradual, so that associated rainfall is generally steady, prolonged and soaking, and therefore effective for agricultural and pastoral activities. Sometimes the moist air becomes caught up in the circulation of a mid-latitude depression or frontal system and lifted further, in a *tropical-extratropical interaction.* This often greatly increases rainfall from the mid-latitude system.

Tropical-extratropical cloud bands and interactions are an important rainfall source in otherwise dry areas and seasons. They account for over 50% of total rainfall between autumn and spring at most places between latitudes 15-35ºS, except in the far southern States and along the east coast (Wright, 1997). Cloud bands originating over the tropical Indian Ocean - known as *Northwest Cloud bands* – often provide significant rainfall in north-western and central Australia over the period April-June.

Tropical 'dips'

In the warmer months, weather charts frequently show a 'dip' in the isobars, extending from the tropics into subtropical and mid-latitudes. Sometimes overlain by an upper level trough or depression, these *tropical dips* frequently induce showers and thunderstorms over the eastern States, due to convergence between moist north-easterly winds on their eastern flank and drier southerly flow on their western flank

Local climate modification

The broadscale distribution of rainfall - e.g. where rain will fall, in what amounts, at what time of year, and to some extent, how variable the rainfall could be - is primarily determined by atmospheric phenomena such as the distribution of low and high pressure areas and the presence or absence of frontal systems. However the amount of rain, and other climatic features, such as temperature, at any particular location are strongly influenced by the area's topography (e.g. distribution of hills, mountains and valleys, the shape of the coast or terrain, proximity to water).

Local climate factors – 1. How orography influences local rainfall

It is well known that rainfall generally increases over hills or mountains – so-called *orographic* enhancement. This is because the orographic barrier forces air to rise, and if there is sufficient moisture in the air and the uplift is great enough, precipitation, or an increase in existing precipitation will occur. Even relatively small hills can, under the right conditions, greatly enhance precipitation – for instance studies have shown that features of only 50-60 m elevation can, in some circumstances, increase rainfall by 40% or more (e.g. Bergeron 1965, 1968; Wilson and Atwater, 1972). Orographic features may also increase precipitation by releasing instability within an air mass (this effect may cause increases in rainfall some distance upwind of the orographic feature), while preferential heating of exposed slopes may generate local showers and thunderstorms.

As a rule, rainfall increases with elevation. However, many factors can influence the simple rainfall-elevation relationship, including:

- *exposure to rain-bearing winds*. Maximum rainfall enhancement occurs when hills or mountains lie close to a moisture source, and are aligned more or less at right angles to moist winds. Enhancement is reduced if the high country is well inland, or there are intervening hills and mountains. For instance, the Monaro Plains region of south-eastern NSW is elevated but relatively dry, because it is surrounded by high ground on all sides;
- *the location of local convergence zones*: Where rain-bearing winds are forced to converge, as near the head of a valley, uplift, and therefore rainfall, increases;
- *the stability and moisture content of air masses*. In general, the moister the air, the greater the potential for significant rain. If uplift of a stable air mass is sufficient to allow precipitation to develop, it will tend to take the form of drizzle or light rain (as often occurs in hilly locations near the sea). Orographic lifting of unstable air masses will tend to trigger heavy showers or thunderstorms. On days when scattered thunderstorms develop, rainfall distribution may be less clearly tied to orographic features;
- *the height and width of mountain barriers*. Higher mountains generate more uplift, therefore more rainfall – up to a certain point, above which rainfall starts to decrease again (Australia's mountains are probably too low for the

> latter to be a consistently significant influence). Where the barrier is narrow, or consists of just isolated hills, rain may fall preferentially on the lee side (especially if low level winds are strong). This is because rain formation within a cloud takes a few minutes, during which time the clouds may be carried past the feature triggering uplift before precipitation can develop and fall.

To some degree, local variations even themselves out over time. But in areas where wind direction is relatively constant and topography marked, rainfall patterns may repeat themselves over and over, giving rise to large differences in average precipitation. For instance in western Tasmania, continuous exposure to the westerlies produces rainfall that increases from around 1500 mm on the coast to over 3000 mm on the western highlands, before decreasing to less than 500 mm in the rain-shadow areas of the Midlands. On Queensland's 'Trade Wind coast', (i.e. the coastal strip roughly between Cooktown and Ingham and the adjacent mountainous hinterland), uplift of moist south-easterly Trades causes average annual rainfall to increase to around 8,000mm at the top of Mt Bellenden Ker, inland from Innisfail.

Not only mountains influence local rainfall patterns. The distribution of land and water may favour confluence of airstreams, leading to locally increased precipitation. A common example is where a sea-breeze moving inland converges with an existing air mass, triggering showers and thunderstorms in coastal districts. This happens often along Australia's eastern seaboard and in the coastal tropics.

Local climate factors - 2. Topography and temperature modification

It is also well known that temperature falls with elevation. This effect is particularly marked with maximum temperatures, because daytime heating tends to ensure that air within the lowest 2000-3000 m is well mixed. Hence the decline of temperature with height, or *lapse rate*, tends to occur at a regular rate. Local variations are induced by aspect - windward slopes exposed to winds from the sea will be cooler than leeward slopes. Proximity to a body of water may lead to average summer maxima being several degrees cooler than even a few kilometres further inland (because of sea breezes), while winter frosts are less frequent at coastal locations than further inland.

The temperature-elevation relationship is less clear-cut with minimum temperatures. This is because, during stable night-time conditions, cold air sinks, leading to the formation of *temperature inversions*, in which cold air is overlain by a narrow layer of warmer air. In this situation - common in the cooler months - air near the ground may be several degrees colder than a few hundred metres higher. So on calm nights valleys can experience much lower temperatures and more severe frosts than on the surrounding hillsides. At higher elevations, above the inversion, temperature again decreases with height. Consequently, in hilly country even long-term average temperatures (and frost frequency) may vary in a complex way. Such topographically-induced *mesoclimate* effects have important implications for the planning of, for instance, horticultural enterprises.

Basic climate of Australia

Rainfall

The map of average annual rainfall (for the standard 1961-90 period) shows that much of Australia's interior receives under 300 mm annually - too low for most agricultural activity, apart from some low-intensity sheep and cattle grazing (Figure 2.2). In these dry areas rain falls on very few days (generally less than 60 days per year), and is erratic: much of the annual total may occur in just one or two events. The low rainfall mainly reflects the close proximity of the STR for most of the year. Distance from potential moisture sources is a second, but less critical factor: 'less critical' because in some areas arid conditions do extend to the coast, notably around the head of the Australian Bight around the border between Western and South Australia, and between Port Hedland and Shark Bay in Western Australia.

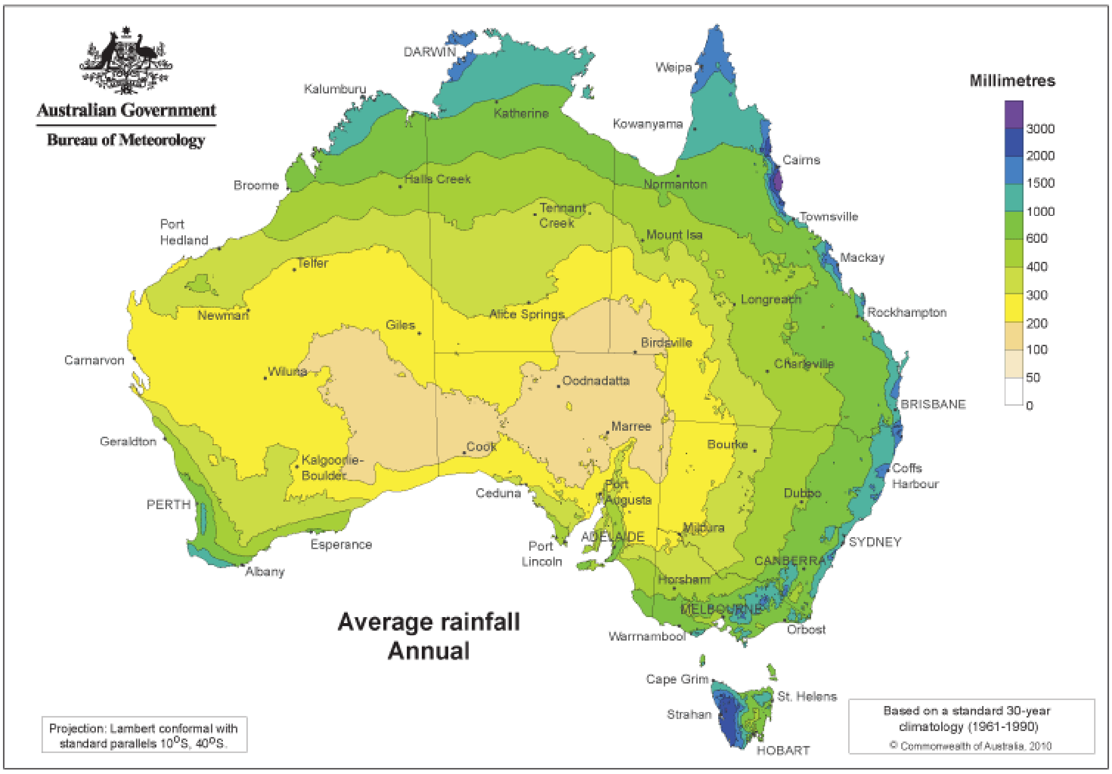


Figure 2.2 Average annual rainfall over Australia over the standard period 1961-90

Rainfall generally increases towards the coast, as proximity to both moisture sources and reliable rain-producing mechanisms improves. Totals increase northward from around 300 mm at 20ºS, near the southern limit of the area normally affected by the monsoonal trough, to over 1200 mm in far north-western Australia, the northern half of Arnhem Land, and the Cape York Peninsula. Over 1600 mm falls around Darwin and its adjacent islands, over the northern part of the Gulf of Carpentaria in Queensland, and in the Trade Wind Coast area between about Cooktown and Ingham. The area between about Cape Tribulation and Innisfail, including the adjacent highlands, is the wettest part of Australia and receives more than 3200 mm per annum. In the northern third of the continent, 50-70% of annual rainfall occurs in the summer monsoon months and less than 10% in the winter months. The maps for January and July (Figure 2.3) show this: most rain in northern Australia falls in the summer months, with little in winter when the STR holds sway.

Rainfall increases eastward from about 140ºE to between 350 and 700 mm in the major agricultural areas of New South Wales and Queensland, and to over 1000 mm along the 'eastern seaboard' over and east of the Ranges. This higher rainfall is due to proximity to the warm Coral and Tasman Seas. Along the eastern seaboard, tropical cyclones in the north and east coast lows south of the tropics can produce phenomenal short-period rainfall totals - in excess of 300 mm within 24 hours. Orography and/or coastal alignment are again important local influences, boosting rainfall to over 1600 mm in parts of northern New South Wales and southern Queensland. But year-to-year rainfall variations can still be considerable, and dry years often lead to dangerous bushfires in spring or summer (as in 1994/95 and 2001/02).

As one progresses south from northern Queensland to central New South Wales, there is a gradual transition in rainfall distribution from 'summer dominant' rainfall, to 'equi-seasonal' rainfall. Further clockwise travel around the country (into Victoria and then west into South Australia and Western Australia) coincides with a further transition to 'winter dominant' rainfall. Normally, the southern States receive most of their rain between April and October due to disturbances in the westerlies. Between 30-40% of annual rainfall occurs in the three winter months (June-August) in Victoria and South Australia. This increases to 40-60% in southwestern Western Australia which experiences the typical Mediterranean climate of wet winters and dry summers.

In southwestern Australia areas near the coast average over 800 mm a year, increasing to about 1200 mm on the near-coastal hills and in the far south. Amounts decline rather rapidly inland. Rainfall over southern South Australia and most of Victoria is mostly in the range 400-800 mm, with amounts increasing southward. Southern South Australia and western Victoria experience a clear winter maximum, with mostly dry summers. The proportion of rainfall in the summer months generally increases eastward. The higher parts of South Australia's Mt Lofty Ranges receive over 1000 mm, while higher elevations in north-eastern Victoria and around Mt Kosciusko receive over 2000 mm. In the latter areas, much of the winter precipitation falls as snow. Rain-shadow areas, with less than 600 mm, exist west of Melbourne and in the area around Cooma in southern NSW, whereas isolated exposed hilly areas in southern Victoria exceed 1600 mm.

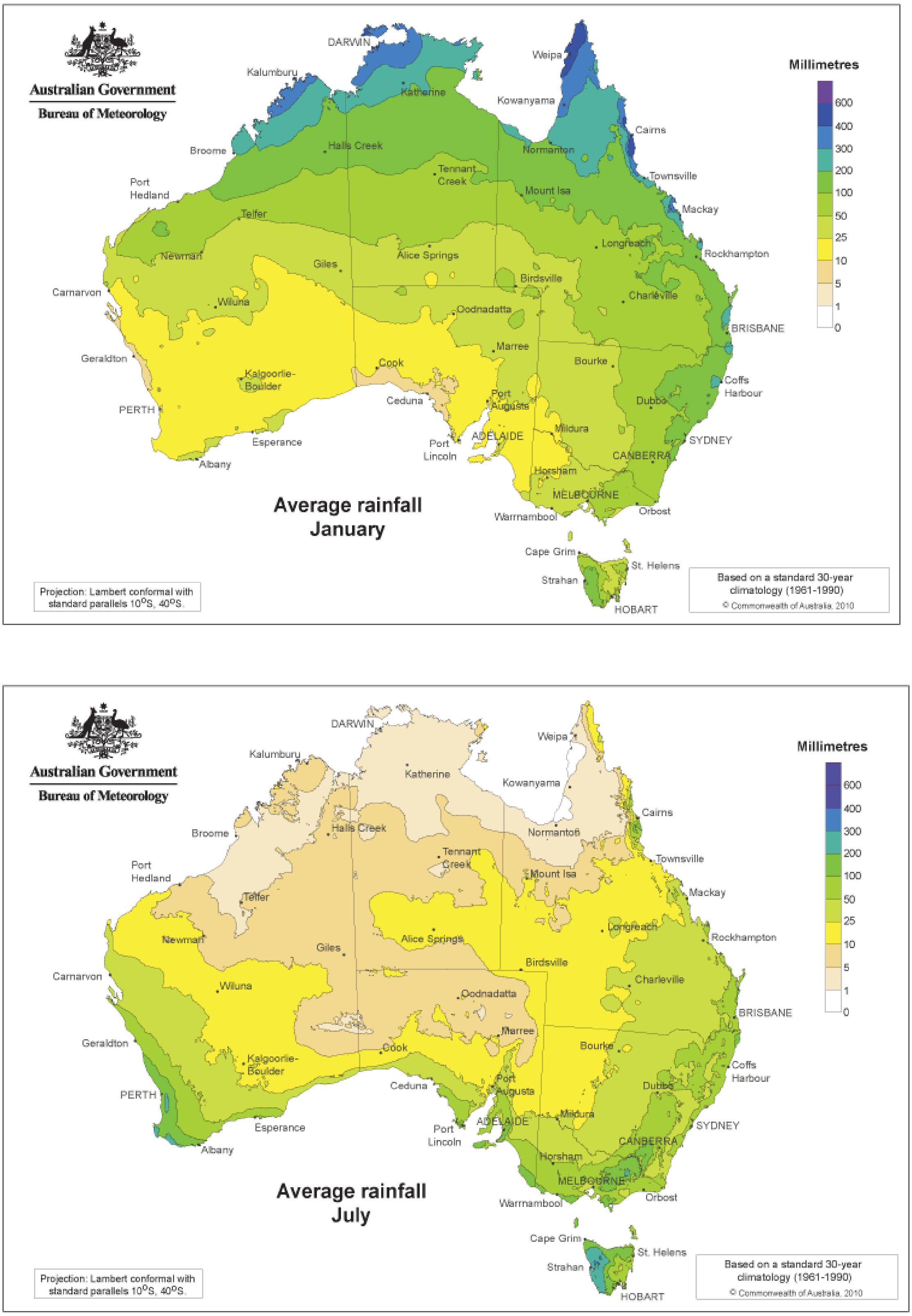


Figure 2.3 Average rainfall in January and July over Australia (1961-90).

In Tasmania, rainfall distribution is dominated by orography, increasing from less than 500 mm in parts of the sheltered Derwent Valley to more than 2400 mm over much of the west coast mountain region, with over 3200 mm in the more favourably exposed, elevated parts of the latter region. Rain falls on many days, especially in the west, where the number of rain-days reaches 220 to 250 per year. Most of Tasmania receives moderate rainfall throughout the year, with a general tendency for a winter-spring maximum.

Rainfall Variability

Rainfall variability is high on year to year time-scales over most of the country, with greatest variability over central Australia (Figure 2.4). Rainfall tends to be more regular in the wetter areas towards the coast, and in these areas, annual rainfall totals are seldom more than 40% above or below the long-term normal. Rainfall also varies considerably on other time-scales as described below.

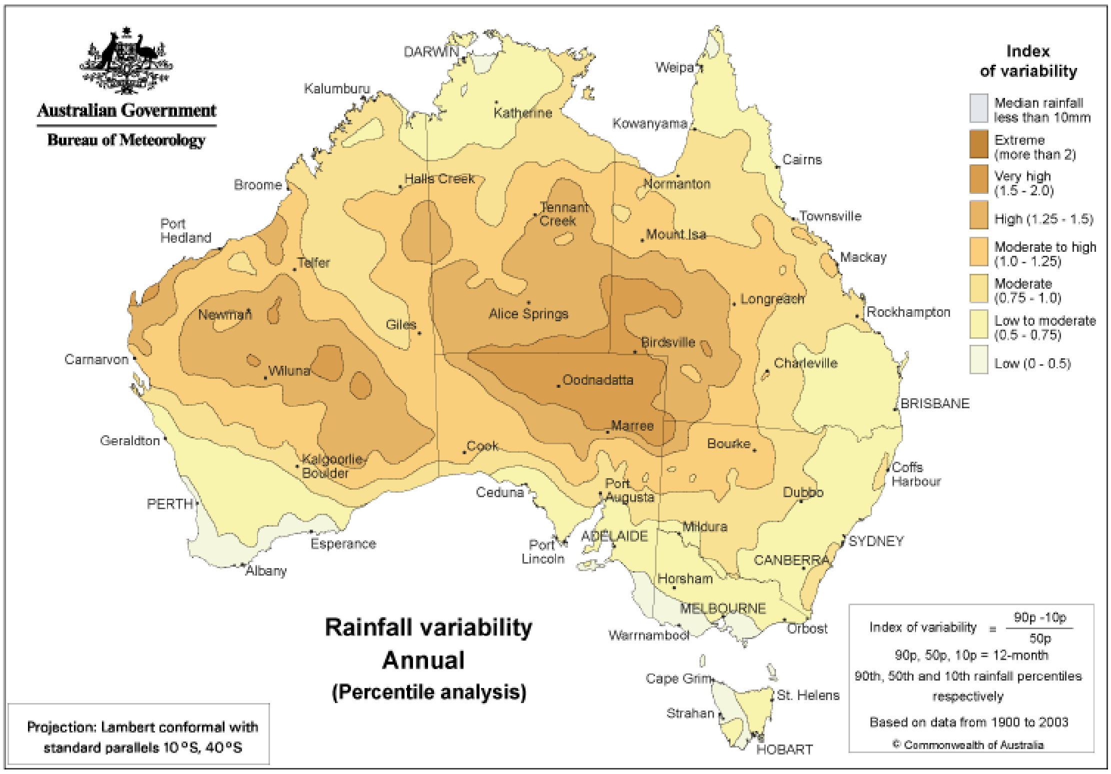
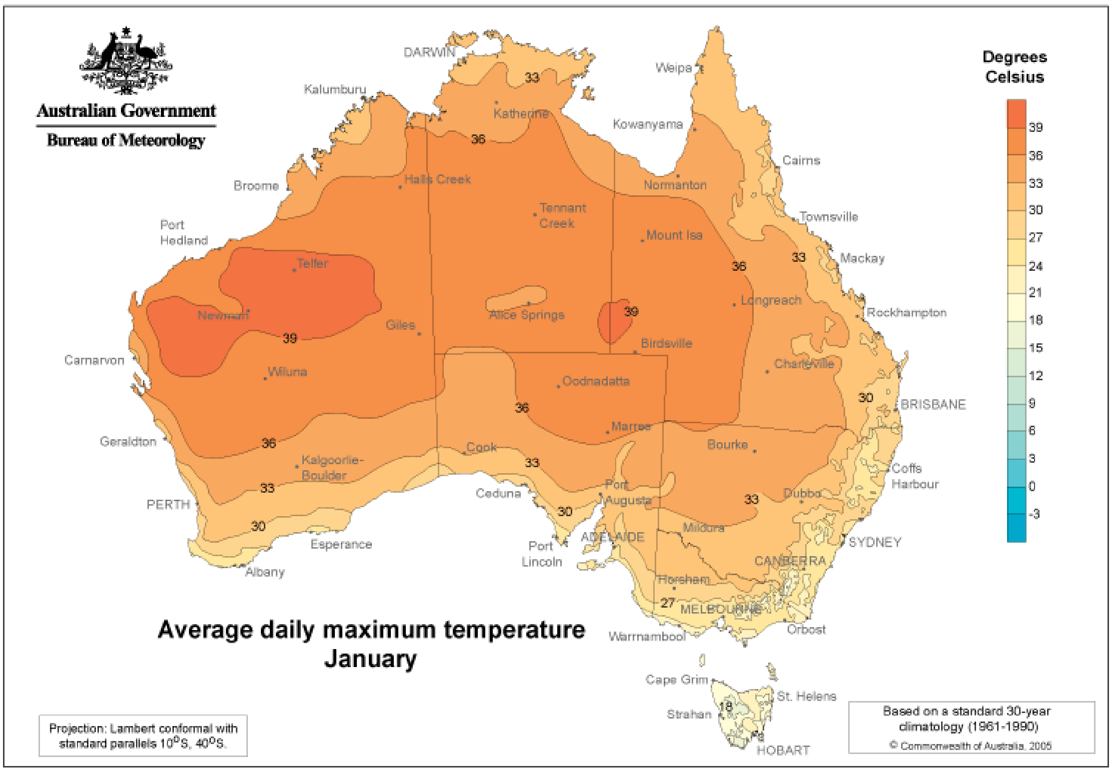


Figure 2.4 Year to year (inter-annual) rainfall variability over Australia (1961-90). Variability here is defined as the difference in annual rainfall corresponding to the 10th and 90th percentiles (i.e. the difference between the highest and the lowest 10% of recorded annual totals), divided by the 50th percentile, or mean. According to this formula, year to year variability will be largest where the range from wet years to dry years is large compared with the median. Variability is clearly highest inland, and decreases towards the coast.

Temperature

Maximum and minimum temperatures are represented (Figures 2.5 and 2.6) by the respective averages for January (representing mid-summer), and July (mid-winter). The averages are taken over the standard 1961-90 period, but as discussed below, there have been upward trends in temperatures - especially minima – since the late

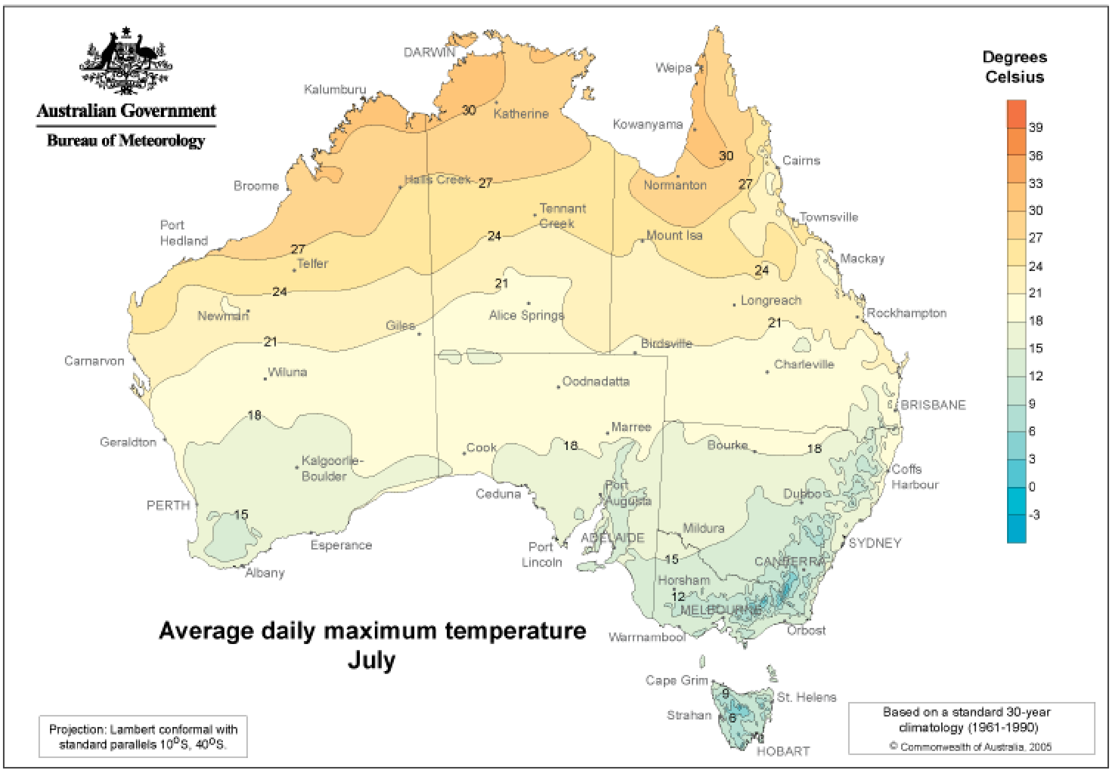
1940s in many parts of the country. So the averages presented here are in many areas somewhat higher than earlier in the century.



Average daily maximum temperature January

Projection: Lambert conformal with standard parallels 10°S, 40°S.

Based on a standard 30-year climatology (1961-1990)

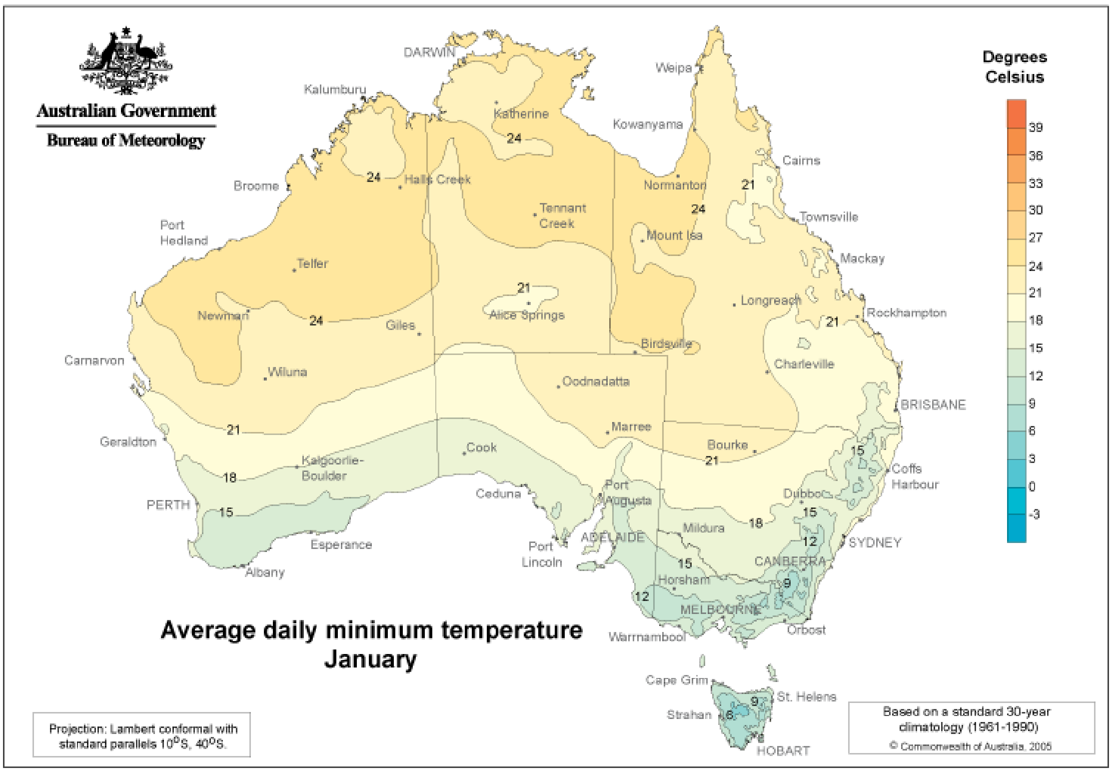


Average daily maximum temperature July

Projection: Lambert conformal with standard parallels 10°S, 40°S.

Based on a standard 30-year climatology (1961-1990)

Figure 2.5 Average maximum temperature over Australia – January and July (1961-90 averages).



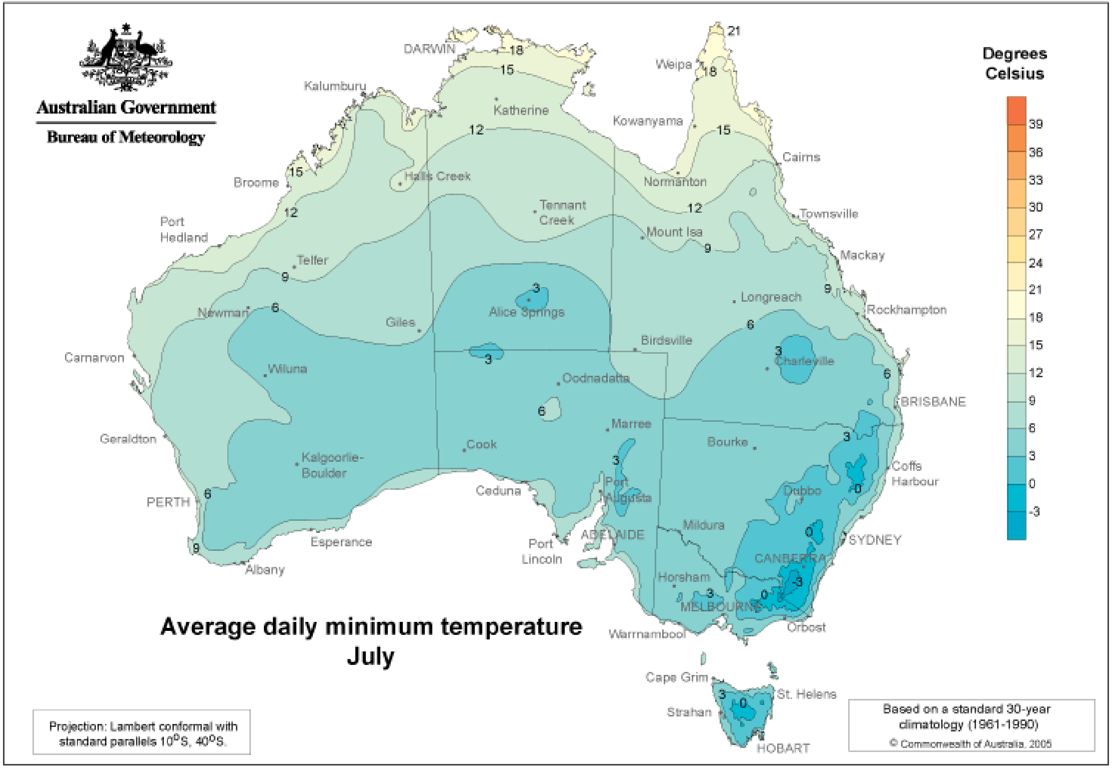


Figure 2.6 Average minimum temperature over Australia – January and July (1961-90 averages).

In January, average maxima exceed 36ºC over much of the Australian interior, and exceed 39ºC over inland north-western Australia, and part of extreme southwest

Queensland. Daily maxima in these areas frequently exceed 40ºC in the warmest months, and may approach 50ºC. Evaporation is also extremely high in these areas and over the interior: the area bounded by the 36ºC isopleth in January also experiences annual evaporation in excess of 3200 mm. The combination of extreme heat, strong solar radiation and little rain makes these inland areas inhospitable for all but specially adapted plants and animals.

Maxima decrease further north and east, as atmospheric humidity and cloud increase. January maxima are below 33ºC in coastal areas of the far north, over elevated parts of Western Australia's North Kimberley and in northern and eastern Queensland falling below 30ºC in the higher elevation areas of the Queensland tropics. Over much of the tropical north and northwest, the highest average maxima occur in November or December, before increasing humidity and cloud reduce temperatures.

Maxima decrease southward, but average below 30ºC only in far southern Western and South Australia, the southern portion of Victoria, in Tasmania, and in coastal areas of southeast Queensland and New South Wales and the adjacent ranges. They are below 24ºC in coastal regions of the southern states subject to sea-breezes, over the Great Divide in Victoria and New South Wales, and over all of Tasmania. Lower temperatures are also evident in isolated hilly areas. Mean maxima dip below 15ºC over the highest elevations of south-eastern Australia and Tasmania. However, extreme maxima can exceed 40ºC almost anywhere on the mainland below about 500 m elevation.

Minimum temperatures in January average above 21ºC over most of northern Australia, and are above 24ºC over significant areas. Minima decrease southward, being below 15ºC over Tasmania, most of Victoria, most of the Great Divide south of the NSW/Queensland border, southwestern Australia and south-eastern South Australia. They are below 9ºC over the Australian Alps and the Tasmanian Highlands. Daily summer minima in southern Australia are highly variable, occasionally exceeding 24ºC.

Minimum and maximum temperatures decrease rather rapidly during autumn, with the most rapid decline in April and May. In the southern States the first lowland frosts typically occur in April and become more frequent in May.

July is the coldest month of the year over most of the country, in terms of both maximum and minimum temperatures (though in most cases temperatures are not very different to June). Maxima average below 15ºC over south-eastern Australia including Tasmania, the Great Divide south of the Queensland-NSW border, the Mt Lofty-Flinders Ranges and in hilly parts of far southwestern Australia. They are below 6ºC over the Australian Alps and Tasmanian Highlands, and dip below zero around Mt Kosciusko.

Minimum temperatures average below 6ºC over most areas south of 25ºS, apart from the coasts and far west, where conditions are clearly milder. Mean minima vary only slowly over lowland areas of southern Australia, with extensive areas averaging between 3ºC and 6ºC. Minima average below 0ºC over the more elevated parts of the Great Divide, and below -5ºC in the coldest parts. In the tropics there is a sharp gradient of temperature near the coast. Minima in near coastal areas of the far north and northwest average over 18ºC, but fall rapidly inland to below 12ºC, and to below 3ºC over elevated areas in the southern Northern Territory, and east of Charleville.

Temperatures rise sharply in the spring months, associated with longer days, shorter nights and increased solar insolation. The rate of increase is greatest over the subtropical interior in October with temperatures some 4-5ºC higher than in September. However isolated frosts can still occur in agricultural areas well into October, and such late frosts can be devastating for crops in their flowering and grain filling stages, especially if minimum temperatures fall below –2ºC.

The El Niño-Southern Oscillation phenomenon

Of droughts and flooding rains…

Australian climate varies considerably on year-to-year, or *inter-annual*, time-scales. Over much of the country, the *El Niño-Southern Oscillation phenomenon (ENSO)* is the single most important influence on inter-annual variability. ENSO represents a coupling of the ocean and atmosphere, and dominates inter-annual climate variability in many other parts of the world besides Australia.

El Niño, and its opposite twin La Niña, refer to, respectively, anomalous warming and cooling of the equatorial central and eastern Pacific Ocean. These *sea surface temperature (SST)* changes result in changes in broadscale atmospheric circulation patterns, with associated changes in rainfall amount and distribution. Atmospheric circulation patterns are measured by an index called the *Southern Oscillation Index, or SOI*. These features are described in detail below; for now, it is sufficient to note that *El Niño* events, which generally correspond with negative values of the SOI, usually coincide with lower than average rainfall over large areas of Australia for periods of up to about a year and sometimes longer. Many of Australia's worst droughts - especially over the eastern States – coincide with such events. In contrast *La Niña* events, which generally coincide with positive SOI values, often produce above average rainfall, sometimes with widespread flooding. The generic term 'ENSO' refers to both types of climate extreme. The fact that ENSO events tend to affect rainfall for many months means that once an event is underway, it is possible to predict likely rainfall patterns in forthcoming seasons. This has significant potential benefits for on-farm decision-making.

Figure 2.7 shows the average impact on total winter-spring rainfall (expressed as *deciles*[1]) of the twelve strongest El Niño and La Niña events in the 20th Century. El Niños have their strongest effects over eastern Australia; La Niñas have a broader impact, reaching further into the tropics and westward.

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[1] Deciles are a means of specifying how unusual rainfall over a month or season is in relation to the historical record. If all recorded rainfalls are ranked in order from lowest to highest, then a decile 1 rainfall is one that falls within the lowest 10% of recorded totals, a decile 2 rainfall falls within the next 10% of recorded falls, and a decile 10 rainfall corresponds to the highest 10% of recorded totals.

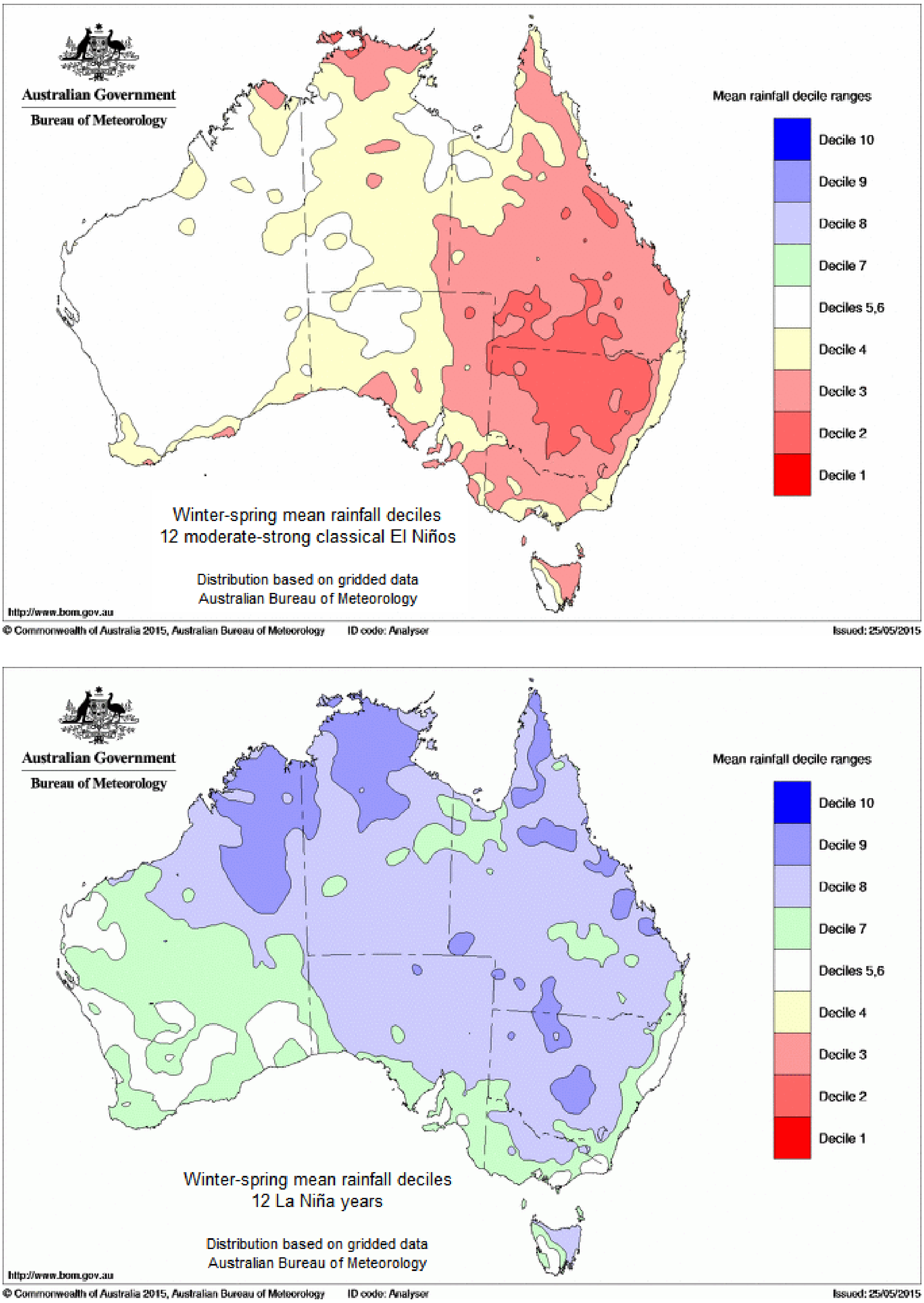

Figure 2.7 Average rainfall patterns during (a) an El Nino event; and (b) a La Nina event. These maps are formed by averaging decile patterns of rainfall for each type of event, for the years shown. Note that El Nino events have their greatest impact in eastern Australia, while La Nina events tend to affect a broader area.

As a rule, El Niño years are likely to be difficult ones for primary producers, in that not only is rainfall likely to be deficient, but frosts are often more frequent, and damaging late-season frosts more likely. By contrast, La Niña years normally favour good seasons, though there can be problems such as waterlogging, increased disease and disruption of management operations such as planting and harvesting, especially in the wetter regions.

El Niño and La Niña events represent two extremes of the world climate system, and these respective extremes tend to recur at irregular intervals of between 3 and 8 years. Years that are not classed as either El Niño or La Niña are often referred to as 'normal' – which is really a misnomer in that climate variability, even extreme variability, often occurs outside El Niño/La Niña years. For this reason the term '*neutral*' year is preferred.

A global view The effects of ENSO radiate far and wide, well beyond the Pacific Basin and Australia. El Niño-negative SOI events are usually associated with below-average rain not just over Australia, but over much of south-east Asia, the southwest Pacific, India, southern Africa, and northeast Brazil. By contrast, they are associated with above-average rainfall in many parts of South America and some southern parts of the United States. Somewhat the opposite pattern of rainfall anomalies occurs in La Niña-positive SOI phases. Some ENSO impacts have also been shown for Europe. These far-flung responses to El Niño are termed '*teleconnection* patterns', and are the global atmosphere's response to changed circulation patterns as a result of atmospheric heating over the Pacific Basin. They form a useful "first guess" for likely climate anomalies overseas during an ENSO event.

To understand ENSO, normal patterns over the Pacific Basin region - the 'cradle' of ENSO – are considered followed by how these patterns are disturbed during El Niño events.

The 'normal' situation The waters of the tropical eastern Pacific are unusually cool for a tropical ocean, because of *upwelling*. Ocean upwelling occurs when surface waters are forced to spread out, or *diverge*, causing colder, deeper waters to rise and take their place. In the Pacific, upwelling (and therefore cooling of the surface waters) is pronounced along the tropical South American coast, and along the east-west equatorial strip between the South American coast and central Pacific. Without going into the reasons for this, it is pertinent to note that the upwelling is related to the strength of the Pacific Trade winds; the stronger the Trades, the greater the upwelling.

At the same time, the steady Pacific Trades cause warm surface waters to pile up in the west, resulting in considerably higher temperatures - over 29˚C - over the near-equatorial western Pacific (*cf* low 20s over the equatorial eastern Pacific). These warm waters induce rising motion in the atmosphere and consequent convective rainfall. The result is heavy rainfall over the western tropical Pacific, northern Australia (in summer), and tropical countries to our north. On the other hand the cool eastern tropical Pacific is a region of sinking air and much lower rainfall, and, in combination with upwelling of cool sub-surface water, responsible for desert conditions in Peru and northern Chile, along the tropical/subtropical western coastal strip of South America. This combination of rising motion in the west and sinking motion over the eastern Pacific results in an east-west atmospheric circulation, constrained to the near-equatorial zone, termed the *Walker circulation*.

El Niño years

How and why this normal pattern is disrupted during El Niño is not yet fully understood. Basically, however, normal atmospheric circulation patterns over the tropical Pacific are disrupted (for whatever reason), triggering a sequence of mutually-reinforcing events in atmosphere and ocean that lead to sustained weakening of the Walker Circulation, and rising SSTs over the eastern equatorial Pacific (Figure 2.8). It is these significant warmings of the eastern Pacific that are termed '*El Niño*'. When an El Niño is triggered, the Pacific Trades weaken, which decreases upwelling along both the South American coast and the east-west equatorial strip. At the same time, equatorial easterlies (formed by the channelling of Trade wind flow in the equatorial belt) weaken, allowing warm western Pacific waters to push eastward both at and below the surface. The two effects combined - eastward warm water transport and diminished upwelling - result in substantial warming of the otherwise cool eastern and central equatorial Pacific.

This unusual warmth may induce rainfall in normally arid areas, such as over the central equatorial Pacific. Under some circumstances the atmospheric response can feed back on the underlying ocean, to further strengthen the original warming. The combination of events can push ocean temperatures in the equatorial central and eastern Pacific as much as 10˚C above normal in places (as occurred in the 1982/83 and 1997/98 El Niño events).

The 'positive feedback' between atmosphere and ocean in this growth phase of El Niño accounts for the tendency of such events to 'lock in', persist and amplify. Events do not continue indefinitely, because the eastward-spreading warm water leaves cooler than average sub-surface water in its wake in the western Pacific. This eventually spreads eastward itself, ending the event when it reaches the surface in the central and eastern Pacific – every El Niño already contains the seeds for its own destruction.

El Niño and the Southern Oscillation

The rearrangement of rainfall and SST patterns over the Pacific Basin during El Niño feeds back on atmospheric pressure patterns. As SSTs cool around northern Australia and Indonesia, air pressure tends to increase, with the effect extending across Australia. At the same time, pressures tend to fall over the central Pacific Ocean, in the form of a weakening subtropical ridge in that area. This further weakens the Trade winds, resulting in less upwelling (and hence more warming) over the eastern tropical Pacific – epitomising the feedbacks set in train by tropical Pacific SST changes. So when pressure is above normal over the Indonesian-northern Australia region, it tends to be below normal over the central Pacific, and vice versa. This 'see-saw' in atmospheric mass is termed the *Southern Oscillation*, and is monitored on a monthly basis by an index representing the pressure difference between Tahiti (representing the central Pacific) and Darwin (representing the Indonesian region) – the *Southern Oscillation Index*, or *SOI.* In the situation described, the Southern Oscillation is said to be in its *negative* phase, which generally coincides with El Niño events. The SOI is expressed as a monthly value, calculated from daily measurements of air pressure anomalies at both locations.

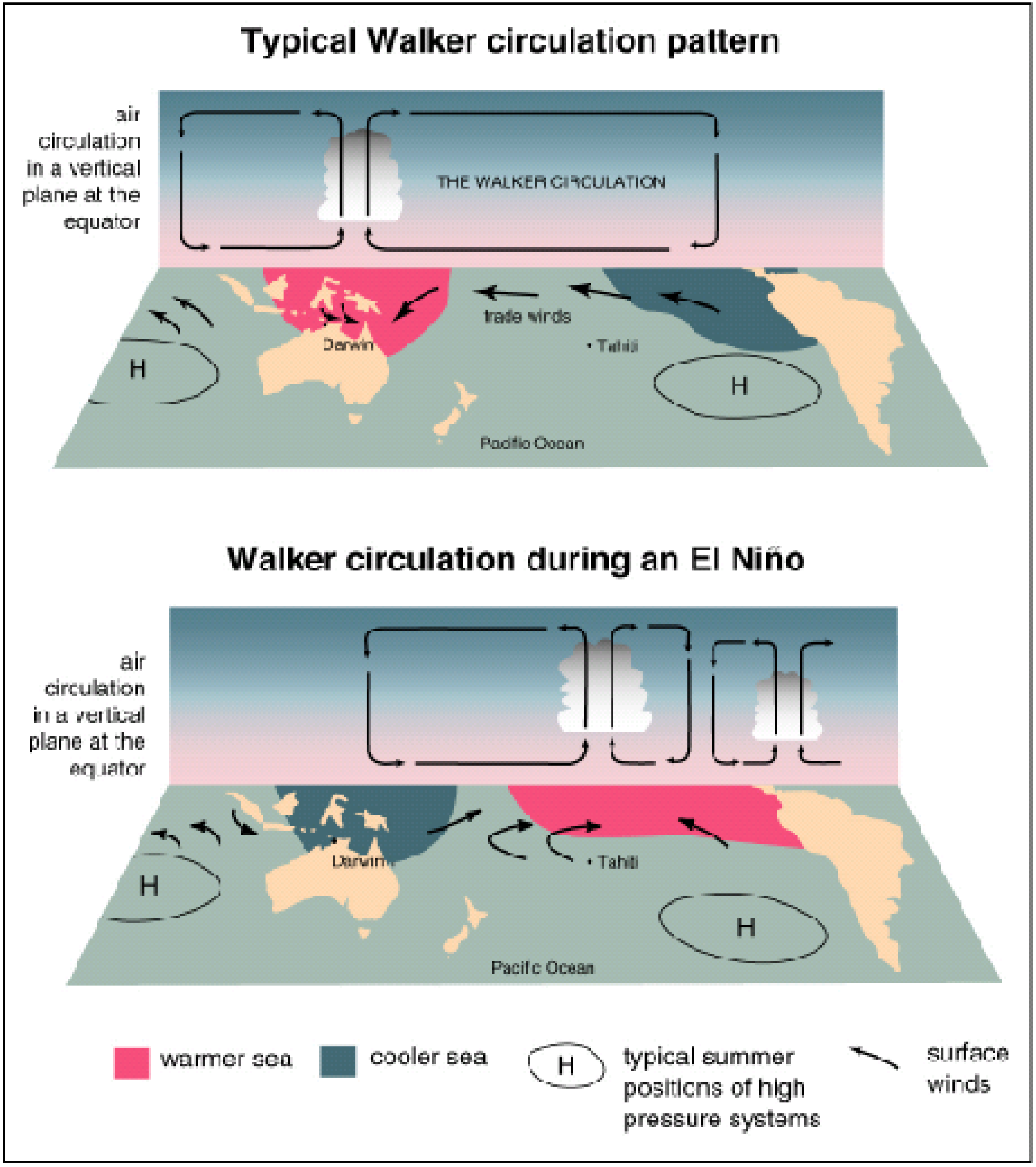

Figure 2.8 Top panel: the 'normal' situation in the Pacific Ocean, showing warm SSTs and heavy rainfall in the west, and relatively cool, dry conditions over the eastern tropical Pacific, with an east-west Walker circulation at low latitudes. In an El Nino event (bottom panel), the warmest waters and areas of heavy rainfall are displaced eastward – there is now heavy rainfall over the central and eastern tropical Pacific, but reduced rainfall over Indonesia and Australia. Trades are weaker, and the Walker circulation breaks up.

The opposite side of the coin is when eastern Pacific waters are cooler than normal - a situation known as *La Niña*. This may be thought of as an intensification of the 'normal' situation: rainfall over Indonesia and the western Pacific is heavier than normal, and atmospheric pressure lower, an effect that extends across most of Australia. At the same time, pressure is above normal over the central Pacific, the SOI is positive, and the Pacific Trades and Walker circulation are stronger than normal.

A typical El Niño year in Australia

ENSO events usually follow a somewhat predictable life cycle, tied to the seasonal cycle. Here, the evolution of an El Niño event is described, although the sequence of growth, maturity and decay proceeds with largely the same timing in La Niña events.

El Niño events usually commence between about March to May (Figure 2.9), accompanied by a falling SOI (usually to values between about –5 and –15), and a weakening of the Trades over the western Pacific (this Trade wind weakening may first happen as early as December, but is not in itself sufficient to indicate an incipient event). Parts of eastern Australia start experiencing below average rainfall in autumn-early winter. The event gains momentum during the winter and spring as high pressure builds up over Australia. Hence, frontal systems and mid-latitude depressions have less impact on southern parts of Australia, and interactions between low-pressure systems and their associated fronts and tropical-extratropical cloud bands are reduced. As a result, below average rainfall becomes more widespread and drought is common (but not universal). During this time the SOI usually persists between about –8 to –20, and the central to eastern tropical Pacific warms.

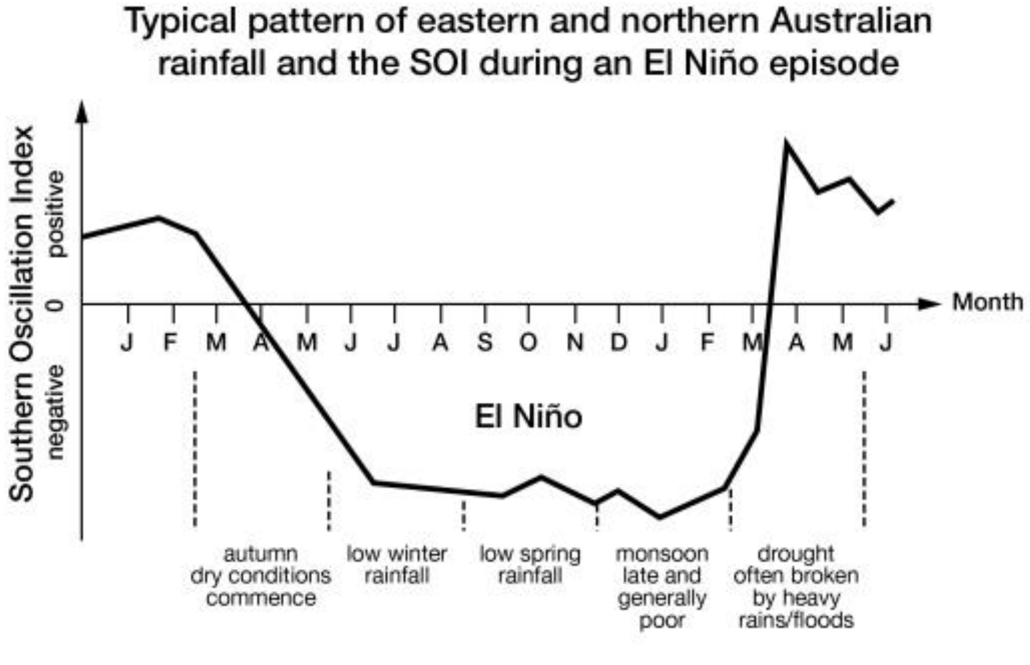

Figure 2.9 Depiction of how El Nino events normally evolve during the year, showing the tendency of events to first develop around autumn of the calendar year, intensify in the late winter-spring, and break down in late summer-autumn of the following year.

Late in the calendar year drought usually intensifies, and the onset of the northern Australian wet season is often delayed, and weaker than normal when it does come. El Niño events normally reach maturity, in terms of ocean temperatures, sometime between December and February - *after* the peak effect on Australia's rainfall patterns (i.e. in Queensland the main effect is on winter rainfall).

El Niño events usually break down around February or March the following year, often accompanied by a sharp rise in the SOI, and heavy rainfall. Sometimes floods replace drought, with considerable erosion. The end of the strong 1982/83 El Niño provided a graphic example: an intense low pressure system drifted south across central and eastern Australia, bringing drought-breaking rain, and in some cases severe flooding, to many areas in mid- to late March.

Each El Niño is different, both in terms of the way the episode develops, and its impacts. Some develop rapidly, as in 1997, whilst others develop more slowly, or take longer for events in atmosphere and ocean to become synchronised, as in 1994 and 2002. Moreover, there are considerable event-to-event variations in the regions most seriously affected. For instance, in 1997 southern NSW, Victoria and eastern Tasmania experienced the worst effects, while many producers in other parts of the country (eg. Queensland) were saved by good starting conditions and some timely rainfall events. Other El Niños affect mainly northern NSW and Queensland (as in 1991). Rainfall patterns similarly vary between La Niña events.

Other effects

Frosts Clear skies and dry air accompanying El Niño events lead to an increase in frost frequency over inland areas. There is also an increased risk of agriculturally disastrous late-season frosts.

Wind and temperatures In El Niño summers, southern parts of Australia often experience more hot days than usual. There is also evidence that winds in summer are stronger than usual over south-eastern Australia (in El Niño winters winds tend to be stronger over northern Australia). The coincidence of stronger winds, drier conditions and more extreme temperatures is reflected in more frequent high fire danger days in El Niño summers over south-eastern Australia. The infamous Ash Wednesday bushfires of February 16, 1983, which claimed over 70 lives in South Australia and Victoria, occurred near the end of an intense drought during the strong 1982/83 El Niño event.

Tropical cyclones These tend to be more frequent around northern Australia in La Niña summers, whereas during El Niño, cyclones tend to shift away from eastern Australia towards the central Pacific. Records show that the number of cyclone impacts on the Queensland coast during La Niña summers is roughly double that in El Niño summers.

Long-term behaviour

ENSO events are not periodic, but the average interval between El Niño (or La Niña) episodes is about five years. There is also something of a tendency for El Niño events to follow, or be followed by, La Niña events. The last century has featured extended periods with little ENSO activity, but also phases with frequent events. During the 1920s and 1930s, the only El Niño event of note was in 1925; three La Niña events occurred (1924, 1928, and 1938), the latter two being very atypical in their impacts.

On the other hand, El Niño dominated the years 1911-1914 and 1991-1994, and La Niña was similarly prominent between 1954-1956, 1970-1975 and 1998-2000.

Monitoring and predicting ENSO

Because ENSO events persist, and tend to 'lock into' a well-defined cycle, they have been a useful basis for climate prediction schemes in Australia and other parts of the world. Typically, anomalous seasonal rainfall and temperature patterns can be predicted some months in advance - though only for certain areas and times of the year. Unfortunately, ENSO is less well related to rainfall over Western Australia, and in the autumn months. Some prediction schemes (e.g. Stone *et al.* 1996) make use not only of current states of ENSO ('persistence'), but also of trends in indicators ('change') such as the SOI – e.g. 'consistently rising' (or falling) SOI. For instance, Stone *et al.* (1996) have shown that over large parts of eastern Australia a rapid rise in SOI over a two months period is related to a high probability of above long-term normal rainfall at certain times of the year. Conversely, a consistently negative or rapidly falling SOI pattern is related to a high probability of below average rainfall in many areas at certain times of the year. The Bureau of Meteorology bases its seasonal outlooks on *sea surface temperature (SST*) anomalies (see next section) - foremost among which is the anomaly pattern over the tropical Pacific associated with ENSO.

Skilful seasonal forecasts are potentially very valuable, because they provide an opportunity for farm managers to better tailor crop and pastoral management decisions to the season. Timing and frequency of future rainfall events strongly influences dryland crop growth and yield. Physiologically-based crop simulation models can be used as 'filters' to gauge the value of rainfall over a growing season. Often El Niño events are associated with low grain yields over South Asia and Australia and high grain yields throughout the North American prairies. It is a challenge for scientists and farm managers alike to identify decisions that can usefully be aided by climate forecasting. Such decision-making ultimately has to improve the long-term economic performance of the farming enterprise, either by increasing profits, reducing degradation (e.g. less erosion runoff or deep drainage) or reducing risk.

Predictability involves careful, ongoing monitoring of climate indicators. Recent technological advances now allow near-real time monitoring of atmospheric and oceanic conditions over critical areas of the equatorial Pacific. One important component is an array of moored buoys across the tropical Pacific Ocean. The second advance is the Internet, which allows today's climate scientists to routinely monitor the SOI and other indices such as ocean temperature over key 'slabs' of the equatorial Pacific.

Oceans and climate

The ENSO phenomenon is but one way that oceans, and their interactions with the atmosphere, affect climate. Oceans represent vast reservoirs of heat and moisture, with a considerable capacity to affect the atmosphere; and they themselves generally respond only slowly to atmospheric events. This means that oceans can exert a substantial and persistent influence on the atmosphere, and in this way, introduce some *predictability* to the climate system. Certain ocean circulation features may be implicated in longer-term climate fluctuations (see below) and in modulating, and responding to, climate change.

Climatologists are particularly interested in SST *anomalies*, i.e. differences from normal SST. The climatic effects of the large SST anomalies accompanying El Niño events have been described: more generally, if the oceans are warm (as in the tropics), differences of only 1-2ºC can be enough to induce major variations from normal climate.

The oceans influence climate in various ways including:

- *as a heat source* Warm ocean waters help drive atmospheric convection. The near-equatorial region north of Australia and adjacent tropical western Pacific are important examples of this, driving deep convection and heavy rain. Conversely, where waters are relatively cool the atmosphere tends to sink, leading to a drier climate, as over the eastern equatorial Pacific;
- *by invoking temperature contrasts in the overlying atmosphere* In areas where strong temperature gradients exist in the ocean, there may be corresponding temperature gradients in the overlying atmosphere. It seems these gradients may reinforce and help maintain each other. In the atmosphere, such gradients encourage upmotion, cloud and rain. Such a gradient, oriented northwest-southeast, exists over the east Indian Ocean, and it has been observed that in years when this gradient is stronger than normal, tropical-extratropical cloud bands and interactions tend to be more frequent over Australia (Wright, 1987);
- *as a moisture source* Evaporation from a water surface passes moisture into the air. If this air is forced upward, the moisture may be precipitated. Other things being equal, air approaching from the ocean will produce more rain than air off the land;
- *destabilising the atmosphere* Cold air moving over warm water is heated from below. The lower part of an air mass warms the most, resulting in relatively warm air being overlain by cold. This represents an unstable atmosphere, conducive to showers and thunderstorms. It is an important mechanism for intensifying cool-season showers in southern Australia;
- *through changes in surface 'roughness'* Compared with the land, the sea is smooth, and provides less friction and drag. As an airstream moves from land to sea, this change in drag can sometimes lead to convergence and divergence areas, the latter increasing vertical motion. This may be a factor in some extratropical cyclone developments off eastern Australia.

In general, when the oceans bordering Australia - particularly the tropics - are warmer than normal, rainfall over Australia tends to be above average (Streten, 1983). This is likely to be a combination of several of the above factors. As noted above, some climate prediction schemes now make use of oceanic predictors. The Bureau of Meteorology's prediction scheme makes use of SSTs over the eastern tropical Pacific (representing ENSO) and the Indian Ocean, which exerts an influence largely independent of the Southern Oscillation. The influence of Indian Ocean SSTs is, in some seasons, quite considerable in Victoria, South Australia and Western Australia - areas where ENSO normally exerts less influence.

Long-term climate fluctuations

Climate varies over a range of time-scales, ranging from seasonal through to centuries (Meinke *et al*., 2003). The inter-annual fluctuations described above are one such mode, a very important one. Another important mode, which has been a feature of Australian climate over the past century, has been variability on *decadal* or *multi-decadal* time-scales. This is manifested by a tendency for conditions to be consistently wetter or drier or cooler than what might be thought of as the long-term 'normal', for periods of a decade or longer. In such periods not every year is (for instance) dry, but most years will have below average rainfall, and droughts will be relatively frequent. Such fluctuations may influence large areas and be of considerable magnitude (*e.g*. Pittock, 1983) - large enough to significantly affect the practice, even the viability - of climate-sensitive industries such as agriculture. Historically, they have affected perceptions of what is believed to be arable land. For instance, the Federation drought between1895-1902 brought an end to optimism engendered by good climatic conditions late in the 19th Century over areas that are normally marginal or unsuitable for agriculture.

Some of these fluctuations appear to be 'natural' parts of the climate system; others might be indicative of long-term climate change. It is important that people in climate-sensitive industries such as agriculture are aware that climate fluctuations lasting for decades are natural in the climate system, have already significantly impacted upon human activities, and will no doubt continue to do so. Such historical fluctuations also provide a reference against which to judge whether future apparent climate trends are probably natural (and therefore likely to reverse) or whether they might represent human-induced climate change.

Rainfall variations

Despite the often highly localised character of rainfall, major long-period fluctuations have occurred on broad scales. The main ones during the 20th Century (Figure 2.10) have been:

- the period between the mid-1920s and mid-1940s which was unusually dry over most of the country. Serious droughts took place over eastern Australia in the mid-to-late 1920s, and between 1937-45, with the latter period noteworthy for frequent dust storms and severe bushfires;
- a very wet period over the eastern half of the country in the 1950s. This period was noteworthy for frequent and widespread flooding, especially in 1950, 1952, and 1954-56. The wet 1950s in fact marked the start of an apparent decadal periodicity in rainfall over the eastern States, with the following 1960s being generally dry in the east, though wet in the western half of the country;
- the 1970s (especially pre-1976), which were exceptionally wet over the whole country, with widespread flooding. Rainfall over eastern Australia declined again in the 1980s and early to mid-1990s, though not to the levels seen in the earlier part of the Century. In general the second half of the 20th Century was somewhat wetter than the first half over the eastern States. This does not necessarily reflect a long-term trend in rainfall, because the available evidence suggests that the second half of the 19th Century was also relatively wet;

- 1970s onward, except for a brief decline in the late 1980s. This mainly reflected trends over north--western Australia, the arid inland of Western Australia, and
- adjacent areas of central Australia (somewhat the opposite trend occurred in the southwest). The period from the mid-1990s until 2001 was exceptionally wet in the northwest and interior.

These continent-scale rainfall variations may represent natural variability in the climate system, and have been linked to the *Inter-decadal Pacific Oscillation* (see below). Multi-decadal climate variations have also been documented over New Zealand, associated with apparent changes in broadscale circulation patterns. The issue of possible underlying mechanisms that might lead to a degree of predictability at these time scales is currently the subject of a range of research projects.

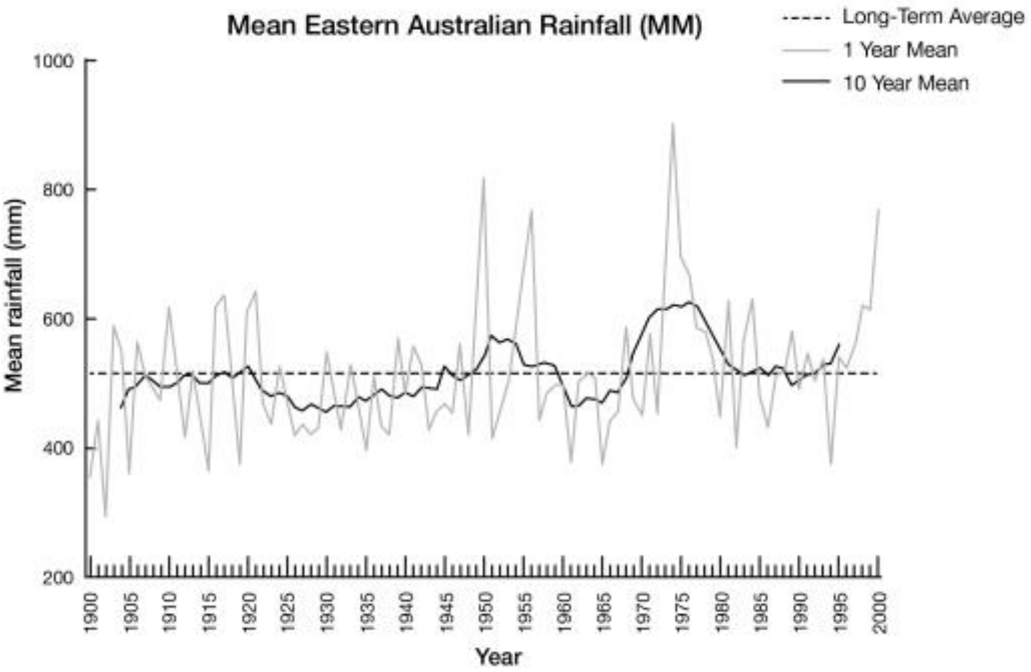

Figure 2.10 Year by year fluctuations in average rainfall over eastern Australia (i.e. that part of the continent east of 130^{0}E). The dark blue line shows year to year rainfall fluctuations; the lighter line shows rainfall 'smoothed' by averaging over successive five year periods, to smooth out somewhat the sharper year to year variations and indicate longer-term variations. The black line represents average rainfall over the period 1900-97 for eastern Australia.

Superimposed on these continental-scale variations are some notable regional variations:

- central Australia had a severe 10-year dry spell between the 1950s-late 1960s. This spread to eastern Australia in the mid-1960s with a shorter, but intense drought between 1965 and early 1968 resulted in a 40% decline in wheat harvest and the loss of 20 million sheep;
- rainfall over southwestern Australia during the winter wet season (between May and September) began to decline about 1950, a decline that intensified after the

late 1960s. The decline since the late 1960s has amounted to 15-20% of the long-term average in the higher rainfall areas of the southwest.

Known impacts of the rainfall fluctuations

Impacts of rainfall fluctuations are large and varied. Some selected examples to demonstrate this point include:

- a tendency for grasslands to become croplands in climatically marginal areas during periods of good rainfall in the 1950s and 1970s. The downturns during extended dry periods (including the early 1990s in Queensland) forced many farmers off their land;
- the long-term rainfall decline in southwest Australia being the subject of a detailed study (IOCI, 2000). Other regions in Australia, such as the area around greater Melbourne and the southeast corner of Queensland have also shown signs of sustained rainfall decline. This has sparked a debate as to whether or not this is the impact of *anthropogenically induced climate change* (see later) in these regions. However, due to the inherently larger background variability of rainfall data in Eastern Australia compared to Western Australia (known as lower *signal-to-noise ratio*), such trends are more difficult to detect statistically in the east. Climate science has not yet been able to definitively resolve this question. Careful planning is required to ensure adequate water supplies against the contingency that rainfall in the future will remain deficient in the face of an expanding population;
- the Australia-wide drought of the 1930s-40s, accompanied by many dust storms, representing serious degradation of potentially arable land. This led to a rethink of land management practices;
- myxomatosis introduction in the 1930s to control rabbit plagues. It conspicuously failed to spread among rabbits at that time, in hindsight because the dry conditions were unfavourable for the breeding of mosquitos required to spread the virus. When conditions turned wet in the 1950s, the abundant standing water favoured mosquito breeding, and the virus spread rapidly in the rabbit population, controlling numbers (at least until a degree of immunity was obtained);
- historically, wet periods such as 1916-17, the 1950s and the 1970s favouring the spread of human diseases such as encephalitis.

The inter-decadal Pacific Oscillation

It is not fully understood why such long-term fluctuations occur, but one explanation proposed (e.g. Power *et al.*, 1999) is that they are linked to long-term fluctuations in Pacific SSTs. On decadal to inter-decadal time-scales, Pacific Ocean SSTs vary in a similar manner to the inter-annual fluctuations associated with ENSO; that is, there tend to be periods of a decade and longer when the Pacific is more El Niño-like, and other periods when it is more La Niña-like. One mode of variation that encapsulates variability at time scales upward of about ten years is called the *Inter-decadal Pacific Oscillation, or IPO* (Power *et al.*, 1999), and is monitored by an IPO index. However these phases - the El Niño-like ‘warm’ Pacific phase (so-called positive IPO phase) and La Niña-like ‘cool’ phase (negative IPO) do not follow each other in a systematic way, nor do they last for a consistent period of time. Other evidence from work in progress suggests that the main mode of the IPO operates at decadal rather than inter- or multi-decadal timescales (Allan, 2000; Holger Meinke, pers. communication).

There is evidence that these long-term climate variations may also influence the impact of ENSO on Australian climate. The historically strong relationship between ENSO and Australian climate (and climate-related variables such as Murray River flow and wheat yields) has undergone periods when it is weaker than usual, and these have coincided with the warm IPO periods of the 1920s-40s and, to a lesser extent, of the 1980s-90s. In general, it appears that when the IPO index is negative (cool Pacific), SOI-climate relationships are strong; but when positive, the relationships tend to break down. This has obvious implications for the reliability of climate predictions based on ENSO.

As intriguing as these apparent links between the IPO and climate are, much is still not known about the IPO or its components, and climate scientists still have no clear physical mechanism for it. This makes it impossible to predict SST variations on decadal time-scales at this stage – but it is clear that, should the means to do so become available in the future, it would be a very useful tool indeed for long-term planning.

Temperatures - sustained warming in the second half of the Century

In contrast to the rainfall variations described above, temperature trends appear to be longer-lasting (Figure 2.11). Following a brief cooling trend around the 1940s, there has been a sustained increase in continent-wide temperatures since 1950. The rises have been greatest in minimum temperatures, amounting to an increase of 0.97ºC between 1950 and 2001. Smaller increases have occurred in maxima (0.62ºC). The 1990s were the warmest decade since records commenced in 1910, and the 1980s the second warmest. Recent cool years have stemmed the rate of temperature rise, which was highest in the 1980s.

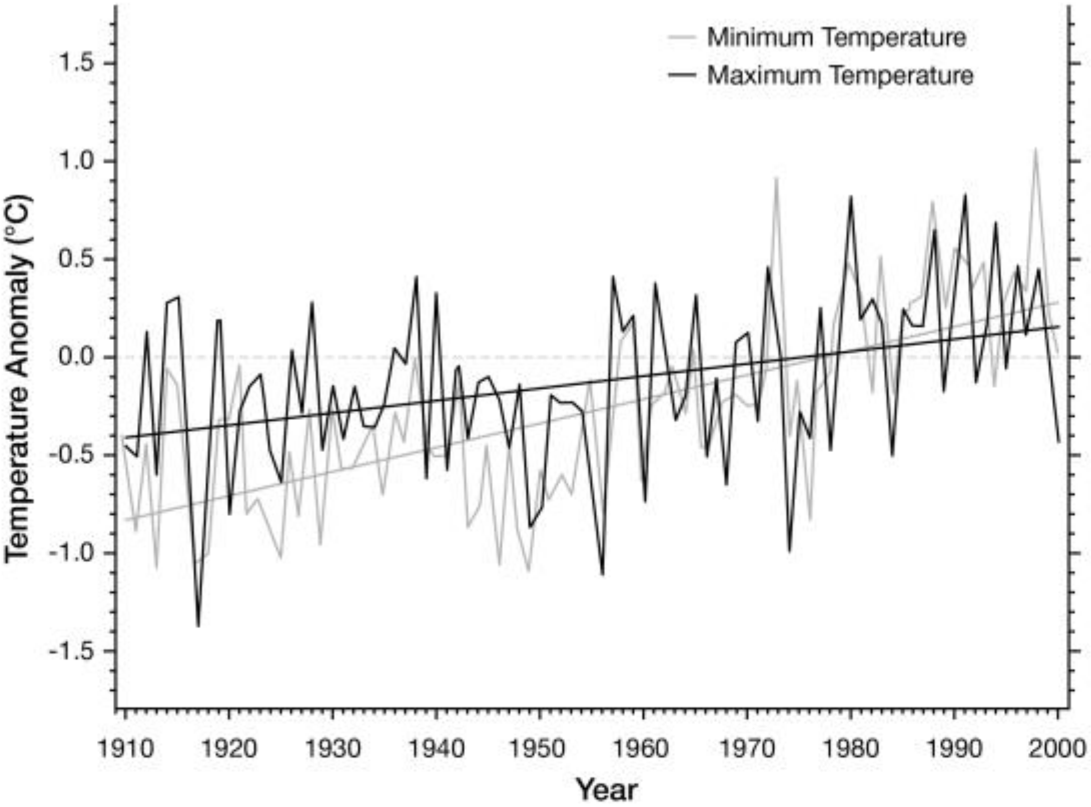

Figure 2.11 Year by year fluctuations in temperature over Australia, expressed as the departure from the long-term continental average (horizontal line). The red and blue lines show the average maximum and minimum temperatures respectively. The increasing trend since the middle of the 20th Century is clearly evident, particularly in minimum temperatures.

The rises in minimum temperatures have been greatest over the north-eastern interior, and chiefly in the period autumn through spring. They have been accompanied by a marked decrease in frost frequency, particularly over Queensland and northern NSW since the 1970s (Stone *et al*., 1996b). The average date of the last frost has also become earlier, so that a longer period of the spring growing season is now frost-free. This has coincided with a change to earlier sowing of wheat and an apparent increase in wheat yields. The frequency of extreme maximum temperatures has also increased.

Climate change

The presence of certain gases in the earth's atmosphere keeps the earth tens of degrees warmer than it otherwise would be, permitting 'life as we know it'. These so-called 'greenhouse' gases, which include carbon dioxide (CO_2), methane, oxides of nitrogen and water vapour permit incident solar radiation to reach the earth's surface, but prevent heat radiation re-emitted by the earth at a different wavelength from escaping. This effectively warms the earth and lower atmosphere.

The existence of such a natural '*greenhouse effect'* is beyond doubt. More contentious is whether, and/or to what extent, changes in atmospheric composition can further warm the earth. Since the start of the industrial revolution in the 19th Century, there has been a more or less consistent rise in atmospheric greenhouse gas concentrations (the atmospheric concentration of CO_2 has indisputably risen by approximately 30% since the mid-19th Century). The theory is that, as greenhouse gas concentrations rise due to the burning of so-called 'fossil fuels' (oil, coal) so does the warming effect – the so-called *enhanced greenhouse effect*. There is still debate as to whether, or how much, the observed increase in greenhouse gases causes the temperature increase.

Nevertheless, the evidence continues to accumulate that at least some of the global warming is *anthropogenic* (i.e. human-induced). This is the view expressed by the body of world scientific opinion, as represented in the report of the *Intergovernmental Panel of Climate Change* (IPCC, 2001). The report further estimates, albeit with considerable uncertainties, that the best estimate of future global average surface warming will be in the range of 1.4°C to 5.8°C by 2100 (cf. an estimated 0.6ºC warming in the 20th Century). Rises of this magnitude, accompanied by as yet uncertain changes in rainfall, would have major implications for agricultural activity within Australia.

The relatively sustained rise in temperature in Australia since the mid-20th Century has been cited in many quarters as evidence of such anthropogenically-induced climate change. However, it is possible that multi-decadal fluctuations may also play a role. Similarly, while it is tempting to attribute the long-term decline in rainfall over southwestern Australia - which has been accompanied by very clear changes in atmospheric circulation over western Australia and the southeast Indian Ocean - to global warming, other thinking (IOCI, 2000) is that at least some of the decline to date is due to naturally-occurring variability.

SIMULATION MODELS AS QUANTITATIVE TOOLS FOR AGRICULTURAL SYSTEMS ANALYSIS

This chapter has so far outlined the degree of climate variability and the basis of its predictability in Australia. Now demonstrated is how the impact of this variability can be objectively assessed and how information regarding this variability (including seasonal climate forecasting) can lead to better-informed policy and management decisions and hence improved outcomes in *economic*, *environmental* and *social terms*[2]. This requires quantitative tools that allow comparisons of management options and their associated risks. Simulation models are valuable tools for such quantification (Hammer *et al.*, 2001; Meinke *et al.*, 2003).

The four key environmental inputs necessary for crop growth are water, temperature, incident solar radiation (energy) and nutrients. Nutrients are largely a function of soil conditions and can generally be controlled via management factors such as fertiliser applications, choice of crops in the rotation such as legumes, fallow

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[2] This is also called the 'triple bottom line'. It means that consequences of information, advice and management interventions have to be considered in terms of their economic, environmental and social consequences. These three goals can be conflicting, but by considering all three objectives simultaneously, the emphasis is on objective information provision, consultative approaches, and conflict resolution

length and soil surface management. The other three environmental inputs are manifestations of climatic conditions at a particular location with only limited scope for control or manipulation via management options (refer to appropriate chapter). In most of Australia, solar radiation is not a significant limit to Agriculture and temperature varies on a predictable seasonal basis. It is the variability of the rainfall against a background of high evapotranspiration that makes farming in Australia a risky business.

Identifying climate risk for crop production

With European settlement of Australia about 200 years ago, farmers of the ‘new’ continent were exposed to an environment that differed fundamentally from their experience. They had no means of assessing the land’s suitability to cropping other than by trial and error. Their hard-won experiences, often featured in Australian contemporary art and folklore, were passed on and led to today’s manifestation of diverse, regional cropping systems. Analysing and improving these systems requires sound understanding of physical, chemical, physiological and climatic processes, but also tools to evaluate their interactions. Effects of management strategies need to be assessed and quantified in terms of productivity and their impact on the resource base. High rainfall variability means that often even one lifetime of cropping experience can be insufficient to sample the underlying variability adequately (Russell 1981, Meinke and Hammer, 1995).

It only took three years for the first Europeans to be introduced to the low and erratic rainfall. Nicholls (1987) noted that in 1791 the colony almost starved due to crop failure. Captain Arthur Phillip reported “…so little rain has fallen that most of the runs of water in the different parts of the harbour have been dried up for several months and the run which supplies this settlement is greatly reduced. I do not think it is probable that so dry a season often occurs”. Nicholls has established that 1791 was an El Niño-related drought.

The importance of rainfall was quickly recognised by agriculturalists. By the early 1860s three government astronomers, Charles Todd in SA, Robert Ellery in Victoria and Henry Russell in NSW had commenced a systematic increase of meteorological stations throughout south eastern Australia and established telegraphic links between their observatories. Despite the short history of European agriculture in Australia, Australia has a set of quality historical rainfall records that is the envy of many countries with far longer histories. Volunteers, many of them from farm families, collect most of the daily rainfall data.

The interest in climate by practical agriculturalists is not new; indeed the importance of climate to crop growth goes back to the first seeds sown. For this action to occur *a priori* knowledge was required that encapsulated some basic, crop physiological understanding. The farmers who had sown these seeds had already developed a mental model telling them that, if planted at a certain time and in a certain way, these seeds would develop into a mature crop. Over time, farmers developed increasingly sophisticated rules of thumb, ie. they refined their mental model based on experience and observations. Simulation models developed by scientists can be used to challenge or confirm farmers' rules of thumb or subjective judgements. Although some farm managers will use the output of simulation models in a decision analysis framework to weigh alternatives, most are likely to use it to refine their rules of thumb.

Crop-climate simulation models have their roots as early as 1914 when agricultural scientists had determined statistical relationships between regional corn production and rainfall in the USA (Decker, 1994). One of the most well known mathematical crop/climate studies was that of the statistician Fisher (1925). He developed a multiple regression of five-day rainfall data against wheat yields from the long term trial at Rothamstead in England. He concluded, "…on all plots dry weather is generally beneficial", a finding shown to be valid with 120 years of data from Rothamstead by Chmielewski and Potts (1995).

In an early Australian study, Cornish (1949) used multiple regressions to analyse South Australian district wheat yields in relation to monthly rainfall. Cornish was able to explain 50% of the variation in wheat yields for the state as a whole and up to 83% of local government areas using rainfall. Although these simple statistical approaches continue to be used and to provide some insights, Monteith (1988) criticised analyses, which "…correlated yields to sets of arbitrarily chosen weather variables using statistical techniques". Although they might describe the situation well, without understanding/simulating how plants interact with climate, the relations they produce would be site and season specific. This is illustrated by Cornish (1949) working in Australia finding the opposite relationship between rainfall and yield to those of Fisher from the humid, energy-limited environment of southern England. Regression-based approaches have their place, as long as their limitations are known and acknowledged.

Water balance

A significant step in moving from simple mathematical relationships to dynamic simulation of crop growth was the recognition that crop production is dependant on water use rather than rainfall. Although there were intermediary steps such as the notion of effective rain, the soil water budget has been foundational to crop simulation. According to Angus (1991) the water budget was built on a range of insights from soil science, plant physiology and climatology in the first half of this century. In the simplest case the profile is treated as a single layer that, once full, allows water to overflow as drainage or runoff. Modifications incorporate a number of layers with different storage capacity and flow rates and special treatment of the surface layer to allow for soil evaporation. More process-based dynamic soil moisture models have also been developed, reflecting a more detailed understanding of the infiltration and movement of water in soils. While such models allow a more realistic representation of solute movement within soils, they usually do not exhibit improved predictive abilities due to their larger number of parameters and associated parameter value uncertainty.

Simulation models

Even sophisticated water balances will not answer questions of how crops develop and grow under variable climatic, soil and management conditions. This relies on the formal concept of systems dynamics evolved over a century ago with pioneers such as Justus von Liebig, Albrecht Thaer and Carl von Wulffen. Their work led to a realisation of the interdependence of variables in agricultural systems and to an understanding of nutrient cycling depending on the three production parameters: quantity, intensity and efficiency (De Wit, 1990). The advent of crop physiological models, implemented on computers, can be traced back to some ground-breaking work in the 1950s, such as Monsi and Saeki's (1953) paper on light interception and De Wit's (1958) paper on transpiration and crop yields that also draws on some of Penman's early work (e.g. Penman, 1948). These and similar publications constructed the framework for the emerging formalism of systems analysis (Zadoks and Rabbinge, 1985). Phrasing physiological processes in mathematical terms allowed us for the first time to quantify biophysical consequences of environmental variability. According to Ritchie (1991) the minimum requirement for a crop simulation model that could be used for risk assessment was the simulation of a daily soil water balance, duration of growth, biomass growth rate and partitioning into harvestable yield. Today there is a proliferation of computer simulation models such as DSSAT, SUCROS and APSIM (IBSNAT, 1990; Goudriaan and Van Laar, 1994; McCown *et al*., 1996; Jones *et al*., 2001; Keating *et al*., 2002).

Computer models that simulate not only individual crops, but also entire cropping systems are becoming increasingly important. Analysing agricultural systems and their alternative management options experimentally and in real time is generally not feasible because of the length of time and amount of resources required. For instance, to sample the effects of climatic variability and associated management responses adequately may require many decades of experimentation, particularly in areas where such variability is high. Although simulation models cannot replace scientific experiments on crops and soil processes in the field or the lab (Phillip 1991, Passioura 1996), well-tested simulation approaches that build on insights gained from experimentation offer a time and cost-efficient means to analyse and extrapolate across sites and seasons (Nix, 1987, Keating *et al*., 2001). Today simulation analyses have become a legitimate means of evaluating policy and resource management issues (eg., Netherlands Scientific Council for Government Policy, 1992; Nelson et al., 1998a, b; Silburn and Connolly, 1998; Howden *et al*., 1999). Bouma and Jones (2001) report how many research groups around the world have now joined forces and contribute their efforts to an International Collaborative Network for Agricultural Systems Applications (ICASA).

Agroclimatic Index models

In addition to regression and dynamic simulation models, there are a many models of low to intermediate complexity that combine features of regression and dynamic simulation. These evaluate crop responses to variations in derived agrometeorolgical indices that are usually based on a simple water balance. Data requirements such as the temporal resolution of climate data and the amount of input data required are generally lower than for dynamic simulation models, and when only one or two major factors dominate the crop performance these models can have a powerful predictive capability (Nix and Fitpatrick, 1969; Nix, 1987; Stephens, 1998; Potgieter, 2002b). Operational crop yield forecasting at various scales (farm, shire, state and national) are a common use of these models (Stephens *et al*., 2000; Potgieter, 2002b). These simple models are often equal and sometimes even outperform the yield forecasting capability of more complex models (Hammer *et al.*, 1996; Truscott and Egan, 2001). While their predictive ability of a single factor (usually yield) might be at par or even higher than that of dynamic models, index models lack explanatory skill. They do not capture the dynamics of interacting factors well due to their lack of process description (ie. yield might be described as a regression based on rainfall and available soil water rather than calculated from underlying physiological processes such as resource capture by the crops to drive the photosynthetic process). This means that index models are well suited for the task for which they have been developed, but they are inappropriate when the aim is to explore more detailed management-crop- environment interactions. This tension between 'getting the job done' (predictive skill) and 'getting it right' (explanatory skill) will always exist among modellers and there is no right or wrong answer - the choice of the most appropriate approach will always depend on the task to be done. Although there is a large 'middle ground' as a general rule predictive skill in models decreases as explanatory skill increases and vice versa. As a rule of thumb we can say that as the explanatory skill of models increases (i.e. models become more 'realistic' in their representation of individual processes), their predictive skill decreases. Finding the right balance of model complexity in relation to the questions to be answered remains one of the biggest challenges in simulation modelling. Hence, in order to select the most appropriate modelling approach users must not only clearly understand its intended use, they must also have a good appreciation of the model's basis and structure.

Water Use Efficiency

The concept of water use efficiency (WUE) promoted by French and Schultz (1984) probably represents the most widely used crop climate model in Australia. Cornish and Pratley (1991) distinguished WUE calculated at the individual plant level otherwise known as transpiration efficiency (dry-weight change/transpiration), the crop level (yield/water use) and the farm level (product/rainfall). The most widespread use of WUE is a hindsight comparative analysis at the crop level to distinguish the effect of management and the climate. Some of the applications of this approach have been questioned (Cornish and Murray, 1989; Hammer *et al.*, 1993). However, as stressed by Angus (1991) and Rovira (1993), it has been a powerful tool to show growers using their own data that they use rainfall less efficiently in good seasons. Hammer (1993) cautioned that assuming a linear relationship between seasonal rainfall and yield could be quite misleading as a farmer or adviser may conclude that a low WUE was due to management (sowing time, weeds or disease) when in fact it may have just been unfortunate to get rain at the wrong time.

Quantifying Climate Risk

Climate is a major source of uncertainty in Australian agriculture. This uncertainty can be quantified as risk for management decision-making (Angus, 1991) Climate signals such as the SOI translate via rainfall variability into associated production variability. However, rainfall anomalies are not the only determinants of crop growth and factors such as starting soil moisture, planting dates, variety, management practices and other climatic conditions (eg. extreme temperatures such as heat waves, or frost, or consistently above or below normal temperatures) also impact on final yields.

Models integrate all these effects and *analog years*[3] based on, for instance, the *SOI phases*[4] (Stone *et al*., 1996) can be used to directly estimate seasonal production (Meinke and Hochman, 2000; Stephens *et al*, 2000; Potgieter *et al*., 2002b).

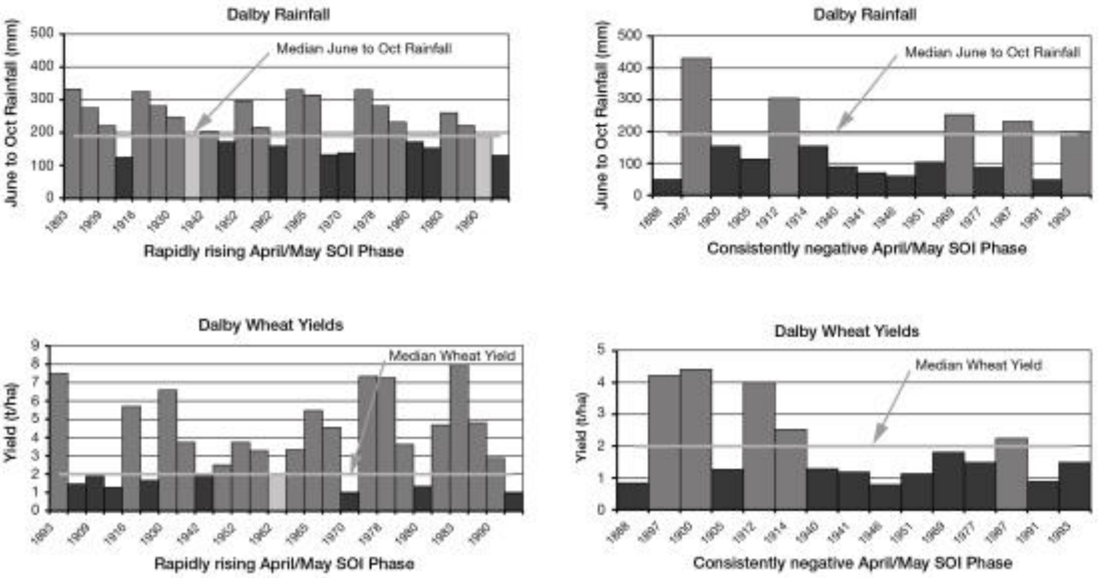

Figure 2.12: Seasonal rainfall and corresponding simulated wheat yields for Dalby (northeastern Australia) in years when the April/May SOI was either rapidly rising (left panels; 26 out of 107 years) or consistently negative (right panels; 15 out of 107 years). The median was derived from the entire 107-year rainfall (190 mm) and simulated yield record (2.0 t/ha).

Figure 2.12 clearly shows this effect: The area around Dalby in Queensland is strongly influenced by ENSO. In this environment, wheat is grown on clay soils that can store a substantial amount of water during fallow periods for use by subsequent crops. The long-term median rainfall during the wheat-growing season from June to

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[3] Analog years are years when oceanic and atmospheric conditions were the same or similar as for the current year or season. For instance, the SOI phase system allows a categorisation of past years according to their SOI phases in a particular month. Fig 2.12 shows all the 'analog years' in our existing climate record when the SOI phase at the end of May was classed as 'consistently negative'. The concept of analog years is particularly useful in conjunction with simulation models because it allows the establishment of probable outcomes in a particular class of years that can then be compared against probable outcomes under different climatic conditions. [4]SOI phases - The level and change in SOI over two months. Certain SOI phase conditions are associated with above or below average future rainfall patterns, particularly in Australia, but also in other parts of the world (Stone *et al*., 1996).

[4] Normal rainfall - An Australian myth. Australia has some of the highest rainfall variability in the world. Hence, long-term average or median rainfall rarely occurs, particularly in the eastern states. This renders the concept of 'normal' rainfall meaningless.

October is 190 mm. Although this median rainfall is often regarded as the norm, this '*normal rainfall*'[5] hardly ever eventuates (cf. top panels, Figure 2.12). In years when the April/May SOI phase rises rapidly, rainfall during the coming months is often substantially above the long-term median. The median rainfall in the analog years when the SOI rises during the April/May period is 222 mm. Often such a rise in the SOI indicates a developing La Niña (see previous section). When the April/May SOI phase is consistently negative, this winter rainfall is often drastically reduced (median = 114 mm). These years often, but not always, correspond with official El Niño years.
However, in each case there is always a distinct possibility that the rainfall in any given year could be either above or below the long-term median. Hence, responsible climate forecasting requires that we communicate our knowledge but also the associated uncertainty.

Using a dynamic wheat simulation model to simulate yields for the same analog years shows the potential impact of these changes in winter rainfall probabilities (Meinke *et al*., 1998). Long-term simulated median wheat yields were increased from 2 t/ha to 3.5 t/ha in years with raising SOI values and reduced to 1.5 t/ha in seasons with a negative SOI phase. However, 5 of these 15 years when the SOI was negative resulted in wheat yields that exceeded the 2 t/ha long-term median. Importantly, these were not always the years during which rainfall records exceeded the long-term median.

This highlights the importance of estimating the future *impact* of seasonal rainfall variability rather than just quantifying the likely *effect* in terms of rainfall. It is important to note that the model simulates the potential yield in response to environmental conditions and assumes optimal crop management. Possible yield reductions due to pests and diseases are not included in this estimate and necessary control measures need to be taken, particularly in the wetter years, if this potential is to be realised.

Communicating climate risk

The ENSO phenomenon provides a scientific explanation for the significant shifts in rainfall and yield distributions (Figure 2.12). Actual rainfall received in any given season can be anywhere on this distribution and even outside the distribution whenever an event more extreme than previously recorded occurs. Hence management decisions based on knowledge of the state of ENSO will have positive outcomes in some years and negative outcomes in others. This must not be regarded as either a 'win' or a 'failure' of the strategy employed, since each season only represents a sample of one from a not very well defined distribution of possible outcomes. To assess the true value of such information requires comparison of results in each season against outcomes that would have been achieved in the absence of such information. A sufficient number of seasons must be sampled so that statistical methods can be employed to present a probability distribution of outcomes for each management option. Hammer *et al*. (2000, 2001) provide many in-depth analyses that show how such probabilistic information can usefully contribute to decision-making.

In the early days of seasonal climate predictions and as a consequence of how weather forecasts were delivered, prediction information was issued as so-called *deterministic*[5] forecasts (often also inappropriately referred to as *categorical*[6] forecasts), where one category of rainfall (eg. much below average, below average, average, etc) was predicted to occur. Such an approach is still used by some commercial providers, who point to the perceived advantage of this approach in providing a definitive 'yes/no statement. However, the perceived difficulties in communicating probabilistic information must be balanced against the possibility of creating a misleading impression of confidence via an absolute (deterministic) statement. Murphy (1993) discusses the need for uncertainties that are inherent in judgements to be properly reflected in forecasts. He states that the widespread practice of ignoring uncertainties when formulating and communicating forecasts represents an extreme form of inconsistency and generally results in the largest possible reductions in quality and value of the forecast. All public institutions and an increasing number of private service providers now acknowledge the necessity to communicate the known level of uncertainty via probabilistic statements. In part, this trend has been accelerated by the increasing awareness of potential liability (corporate risk) that organisations expose themselves to through the provision of inadequate or misleading advice.

There are several reasons why probabilities are an integral part of risk management in Australia and overseas:

- Scientists know that chaos plays a large role in climate systems. In fact, the atmosphere frequently acts like a random number generator such that absolute statements justifiably cannot be made.
- Scientists have a responsibility to communicate their degree of ignorance as well as their knowledge.
- Scientists are not the decision makers – all they can provide is discussion support. The ultimate decision rests with the practitioner. Rather than providing a recipe, scientists should present the choices, the chances and the consequences (Hayman, 2000).
- 'Dumbing down' the message can lead to poorer risk management where farmers plan for a single most likely outcome rather than a range of possible outcomes.

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[5] **Deterministic forecasts:** Non-probabilistic forecasts of either a specific category or particular value for either a discrete or continuous variable. Deterministic forecasts of continuous variables are also known as point forecasts. Deterministic forecasts fail to provide any estimates of possible uncertainty, and this leads to less optimal decision-making than can be obtained using probabilistic forecasts. Deterministic forecasts are often interpreted as probabilistic forecasts having only probabilities of 0 and 1 (i.e. no uncertainty), yet it is more realistic to interpret them as probabilistic forecasts in which the uncertainty is not provided (i.e. unknown uncertainty). Sometimes (confusingly) referred to as categorical forecasts in the earlier literature.

[6] **Categorical forecast:** A forecast in which one of a discrete number of categories of events are forecast. Categories can be either nominal (no natural ordering – eg. clear, cloudy, rain) or ordinal (the order matters – eg. cold, normal, warm). Categorical forecasts can be either deterministic (a particular category eg. rain or no-rain tomorrow) or probabilistic (probabilities for each category eg. probability of 0.3 of rain and 0.7 for no-rain tomorrow).

- Assuming that probabilistic concepts are too difficult to understand is an insult to farmers' intelligence – they are already good risk managers and have managed effectively under uncertainty all their lives.
- Deterministic forecasts create a sharp and artificial boundary between areas where there is and is not sufficient skill to make a prediction, thus placing decision makers operating near these boundaries in a quandary.

When *probabilistic*[7] forecasts are used, the probability of, say, rainfall being in a particular category (e.g. above/below median; terciles one, two, or three) is assigned, based on the historical record or climate model outcomes. This information provides an indication of the 'shift' in odds away from normal. The median is the mid-point of all historical values – in the absence of any climate signal, the chance of being above or below this value is 50%. Should the outlook say 75% chance of above median rainfall and 25% chance of below median, then clearly the odds have shifted substantially in favour of wetter conditions. However, it is important to note that this represents only one 'slice' of the entire probability distribution. Generally, it would be desirable to present the entire population of likely outcomes (e.g. the range of wheat yields shown in Figure 2.12) to ensure that none of the information content is lost.

Clearly, probabilistic approaches are more complex than deterministically forecasting a certain value or amount, but communicating uncertainty is essential and in line with modern risk management approaches. It requires particular attention to appropriate communication. All decision-making in climate-sensitive industries is inherently risky (because of the large element of unpredictable chaos in the climate system) and probabilistic forecasts convey that level of uncertainty, whereas deterministic predictions do not. Farmers can therefore decide for themselves what level of risk is acceptable, and either convert the information into a 'yes/no' decision, or implement a strategy, somewhat akin to 'hedging' in the finance industry, designed to maximise overall returns (by e.g. trading off 'the best possible return' for a lesser gain, which will, however, reduce losses should the prediction fail to work out). A long held principle of decision-making under uncertainty is that it may not be best to manage for the most likely outcome Barnard (1938). For instance, when the issue of deciding on nitrogen rate is considered as a decision tree (Hayman, 2001) it rapidly becomes evident that because nitrogen fertiliser pays more in a good season than it costs in a bad season (unless there is a very high probability of a dry season), it is best to apply reasonable rates of nitrogen. Probabilistic forecasts empower farmers in their decision-making. This approach of indicating the uncertainty in climate prediction is largely the reason why the Bureau

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[7] **Probabilistic forecast:** A forecast that specifies the future probability of one or more events occurring. The set of events can be discrete (categorical) or continuous. Deterministic forecasts can be considered to be the special case of probability forecasts in which the forecast probabilities are always either zero or one - there is never any prediction uncertainty in the predictand. However, it is perhaps more realistic to consider deterministic forecasts to be forecasts in which the prediction uncertainty in the predictand is not supplied as part of the forecast rather than as ones in which the prediction uncertainty is exactly equal to zero. (Jollife and Stephenson, 2002).

of Meteorology, the Queensland Department of Primary Industries, and most overseas prediction agencies only endorse and employ probabilistic prediction approaches.

The notion of using probabilities to express partial understanding can be traced back to the 18th Century when the French mathematician Laplace (1749-1827) stated that probability has reference partly to our ignorance, partly to our knowledge. While science has increased understanding of the mechanisms of climate ('knowledge'), it has also pointed to theoretical and practical limits to prediction ('ignorance'). The atmosphere is a complex chaotic fluid, and although ocean temperatures 'nudge' this chaos in certain directions, there will always be a significant proportion of unexplained variation (experts refer to this as a low 'signal-to-noise ratio'). This is why probability information is essential. An increase in the odds of a good season does not eliminate the chance of a poor season. Probabilities are the language of risk management.

Most people prefer no-risk, black and white decisions whereby an 'if…then…else' statement could be employed. For example IF the season is going to be wet, THEN add extra nitrogen to the crop, ELSE continue with normal rate. Penland (1998) argued that part of the problem with climate forecasting is that people are not used to uncertainty from science. She blamed the public perception of science as 'cognoscenti', and scientists' willingness to accept that perception - and in doing so, down-playing uncertainty. This is the result of the history of science, with its roots in deterministic, reductionist approaches to physics and chemistry. Inherent indeterminacy still poses a big challenge for the 'newer' sciences such as biology, climatology and meteorology. Although the chorus of scientists advocating holistic approaches to quantify systems dynamics is steadily increasing, it is likely to take a few more generations before such thinking will become as ingrained as our traditional, deterministic approaches. The challenge for climate science is to be clear about the uncertainty, but still give a simple message. Hayman (2000) outlines one approach based on the chocolate wheel used in country fairs (which has, say, 100 nails with numbers and associated prizes). In this case, growers are presented with a pie chart divided into thirds based on the long-term record. For example in Quirindi in northern NSW, growers are led to understand that, using the historical record they have an equal chance of a poor (<220 mm), average (220 to 300 mm or good (>300 mm) season over winter. Spinning the wheel-reinforces the notion that there is an equal chance of landing in one of the three seasons (Figure 2.13a).

The SOI phases are then used to show how the pattern changes under a rising or falling SOI. The point is reinforced that the chance of a good season (>300 mm) rises from 33% to 46% when the April/May SOI is rising but that there is still a 15% chance of a poor season. The distinction is made between changing the pattern and predicting the outcome.

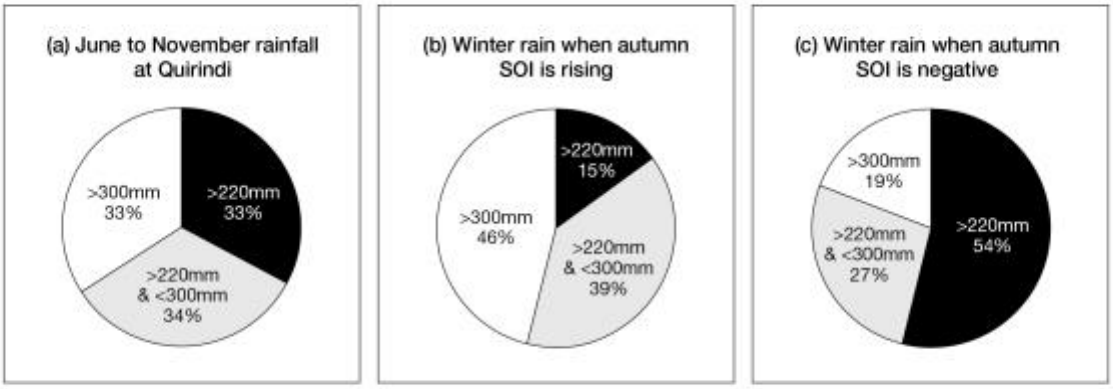

Figure 2.13 The ‘chocolate wheel’ for winter rainfall prediction at Quirindi NSW (a) in the absence of climate signal; (b) with rising autumn SOI; and (c) with negative autumn SOI.

On the other hand, when the SOI is negative in autumn, the chance of being wetter than the long term 67th percentile is 19% and the chance of a dry season is 54% (Figure 2.13c). The chocolate wheel or pie chart enables us to communicate what we do know (that the pattern on the wheel has changed), but also what we don’t know (where the pointer will end up). If the end point of seasonal climate forecasts is decision making, conveying the probabilistic nature of seasonal climate forecast is important so that decision makers incorporate the forecast into their risk management (Meinke *et al*., 2003). Recent publications (Hammer *et al*., 2000, 2001) provide many examples of such successful climate applications. Central to all of them are the use of simulation models and the probabilistic nature of the information provided to the decision makers.

It is important to emphasis that seasonal forecast systems need to be developed and statistically tested using independent data and cross-validation techniques to avoid ‘*artificial skill*’ [8].

Some of the traps leading to artificial skill in statistical forecasting systems include:

- the smaller the sample size, the greater the chance of spuriously exceeding a given skill level;
- the greater the number of potential predictors, the greater the chance of artificial skill;
- the more combinations used, the more spurious relationships found;
- that the atmosphere acts in part as a random number generator

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[8] **Artificial skill** is the apparent hindcast skill in statistical forecasting schemes arising from chance. It is the skill that does not survive when the forecasting scheme is applied in real time to new or independent data (need for cross validation, independent verification in real time). It can arise when statistical models are over-parameterised using a number of cross-correlated predictors or when a multitude of possible, statistical forecasting schemes can be employed and ‘best’ performing schemes are selected on the basis of some test statistics, rather than first principles. This issue is complex and goes beyond the realm of this chapter. However, it must be flagged as a problem that needs to be addressed as more potential forecasting schemes are promoted around Australia.

Amongst climate scientists there is increasing realisation about the need and value of probabilistic forecasting regardless of circumstances (Murphy, 1993; Moss and Schneider, 2000). This holds true even for events that are, by definition, rare (e.g. extreme events, such as a one in 60 year flood) and hence have considerable uncertainty associated with them. The likely future introduction of predictions based on output from general climate circulation models may allow more versatility in climate prediction than is currently the case, including better opportunities to predict extremes. Palmer and Rätsänen (2002) have quantified the additional value of probabilistic forecasts over a single, deterministic projection in their study of greenhouse scenarios and found that the economic value of probabilistic forecasts was significantly greater and never less than for the deterministic case.

Managing climate risk using a systems approach

Crop production in Australia is characterised by technologically advanced producers managing large areas with low intensity against the background of high climatic variability (Pratley, 1994; Meinke and Hammer, 1997). The lack of subsidies combined with low commodity prices requires producers to become increasinglyefficient. Modelling approaches are ideally suited to evaluate alternative options in terms of their resource use efficiency. Seasonal forecasting might help by increasing inputs (intensity) in years that are likely to yield well and reducing inputs when the chances for lower than usual yields are greater (Plant, 2000).

McCown (2002) details some of the advances and cautionary tales of applying simulation models to farming systems, especially in the form of decision support systems. Crop modelling, when applied to farming systems has the potential to increase profitability and reduce the on- and off farm risks of agricultural production. Building sound, physiologically based models is an important and exciting activity for scientists and software engineers. Novel model applications challenge our thinking and further our understanding of the systems under investigation. However, these scientifically rewarding activities will remain without impact as long as they stay within the comfort zone of biophysical science. It is unsatisfactory to simply claim (as it is frequently the case) that a desktop simulation analysis will have important implications for decision-making. Often researchers make statements about applications for decision-making without considering what is necessary to make it work. Pay-offs can only be expected when a truly integrated systems approach is employed that includes decision makers as partners and guarantees that they have ownership of this process. This truly participatory approach ensures that the issues addressed are relevant to the decision maker. This process will also ensure that there is sufficient scope for decision makers to alter their behaviour/management based on the information provided. This 'ability to move' might be constrained by external factors such as current policy settings or international market forces. A clear identification of these constraints can help to either collectively lobby for change (in case of the former) or to decide when taking action might be appropriate or profitable (in case of the latter).

In order to aid the decision-making process, a modelling approach must reduce complexity rather than proliferate choices. This requires precise and unambiguous problem definition and scenario analyses that quantify outcomes in terms of economic and environmental consequences. Again, this is most likely to be achieved through a true participatory approach that generates ownership of the process and confidence in the model's ability to simulate real farm outcomes (Carberry and Bange, 1998, Lynch *et al*., 2000).

Inevitably, farmers make decisions under uncertainty. By providing new information about the environment within which they operate or about the likely outcome of alternative management options, this uncertainty can be reduced (Byerlee and Anderson, 1982). Computer simulations can provide such information and are particularly useful to quantitatively compare alternative management options in areas where seasonal climatic variability is high, such as Australia, South-east Asia, Africa and South America (Keating and Meinke, 1998; O'Meagher *et al*., 1998; Stephens, 1998; White *et al*., 1998). In an analysis of the 15 year history of WHEATMAN, a decision support system for managing wheat crops in the New England region, Hayman and Easdown (2002) found that although the number of active users was relatively low (about 250 out of a possible 4500 growers) many advisers acknowledged the role of WHEATMAN in structuring their thinking and framing their advice on winter cropping in the region. Simulations not only allow assessment of the effects of management options on production, but also enable the evaluation of associated impacts on the resource base such as runoff, erosion, nutrient leaching and pesticide movement (Silburn and Connolly, 1998; Carberry *et al*., 2000). Hence, there is increasing interest in using a simulation approach also in situations where development of appropriate environmental guidelines is of comparable or greater concern than production *per se* (e.g. assessing the potential for carbon sequestration in agriculture and natural ecosystems management – an important component for climate chance scenarios and greenhouse gas studies). Ten Berge *et al*. (1997) point out the importance of such regulation and the need for growers to demonstrate compliance, often via a simulation approach.

Good farm managers have a rich appreciation of agricultural systems components and their interactions and are skilled at incorporating new information into the decision-making process. A more formal cropping *systems approach*[9] using modelling can help farmers to replace 'gut feeling' about their complex system with (i) hard

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[9] According to Hammer (2000), the systems approach to applying climate forecasts in decision-making across the range of agricultural and natural ecosystems can be generalised to:

- understand the system and its management;
- understand the impact of climate variability;
- determine opportunities for tactical management in response to seasonal forecasts;
- evaluate worth of tactical decision options;
- participative implementation and evaluation;
- feedback to climate forecasting;

A system can be defined as a network of interacting elements receiving certain inputs and producing certain outputs. The dynamics of a system is implicit in this definition, which can be applied not only to the full range of agricultural and natural ecosystems and their associated business and government systems, but also to climate systems or economic systems. It is important to consider and specify boundaries clearly when defining a system. The scale of the system and what is internal and external to the system are key issues to be clarified in the systems approach. These issues influence the perspective adopted when considering system function and management. A systems approach seeks and utilises understanding of system composition and dynamics derived from relevant research to enable prediction of the responses or behaviour of a system. In many cases, this capacity to predict utilises system models, which are a simplified representation of the system, often expressed mathematically. These concepts originated in the 1960s in industrial systems (e.g. Forrester, 1961) and were adapted to agricultural and natural systems shortly after (e.g. Duncan *et al*., 1967; Patten, 1971). Climate variability generates risks for management decision-making on both short and long time horizons because outcomes of decisions cannot be predicted with any surety, be they decisions on crop management, stocking rate, water allocation, or fish or insect population management. Risk, or the chance of making a financial or environmental loss, is a key factor pervading decision-making in management of agricultural and natural ecosystems (Hardaker *et al*., 1997).

data about the current state of their system (e.g. soil moisture stored over a fallow) and (ii) probabilistic information about the way in which the unknown (e.g. future in-season rainfall) will affect the outcome of alternative management decisions (Carberry *et al.*, 2000; Meinke and Hochman, 2000). Such a systems approach engages decision-makers in the research process and uses modelling to integrate the newly gained insights. The model is used analytically by scientists and decision-makers to gain further knowledge and insight. In other words, systems approaches in a problem solving context always require on-going connections between decision-makers, advisers, modellers and researchers for effective outcomes (Hammer, 2000; Keating and McCown, 2001).

The Agricultural Production systems SIMulator, APSIM, is such a simulation environment and provides a common communication platform for the many scientific disciplines (McCown *et al.*, 1996; Keating *et al.*, 2002). APSIM can predict and evaluate the dynamics of soil condition and crop production while allowing management intervention through tillage, irrigation, or fertilisation as well as choice, timing and sequencing of crops either in fixed or flexible rotations (Hammer *et al.*, 1999).

Simulations to aid crop management

Quantification of climatic risk to evaluate management decisions objectively is an important area for model applications. This approach aims to maximise the profitability of the whole farm operation. When combined with a seasonal climate forecast, impact of the climatic risk can be reduced considerably (Hammer *et al.*, 2001). Because water is often the most limiting resource in this environment, key management responses aim to:

- avoid erosion and run-off;
- maximise water infiltration;
- develop a surface management system that allows sowing a crop after even minor rainfall events in order to be as close as possible to the optimum sowing date; and
- avoid soil fertility decline.

Meinke and Hochman (2000) showed that farmers use, for instance, simulated ‘target yields’ based on simulations to optimise nitrogen strategies. These target yields are determined based on the amount of stored soil moisture prior to sowing, historical rainfall records and the long-term rainfall outlook. From this, they estimate the ‘10 percentile’ of achievable yield in a given season, i.e. the yield that will only be achieved or exceeded in 10% of years. Nitrogen requirements are then determined based on the available background nitrogen in the field and the appropriate amount of nitrogen is applied.

Meinke and Hochman (2000), for instance, profiled a grain/cotton grower in the north-eastern Australian wheat belt. Amongst the benefits attributable in part to simulation output were decisions relating to:

- the no-till area;
- the amount of nitrogen fertiliser applied prior to planting;

- planting dates for wheat to spread frost risk;
- double cropping barley after cotton (i.e. a winter crop sown straight after a summer crop on very little stored soil moisture; this crop yielded close to 3 t/ha, a rare yield level for a double crop and only achievable under favourable climatic conditions, which were predictable in advance);
- choice of alternative crops to wheat in order to spread risk (e.g. wheat versus chickpeas).

This grower's yield and grain quality were substantially above the district average and he partly attributes this positive result to his ability to incorporate simulation output and seasonal climate forecasting into his decision-making.

In southern Australia, where there is usually only one growing season (April-November), the main crop management decisions that are affected by climate include:

- crop area (total area of different grains, pulses and oilseeds);
- variety choice (long season, short season varieties, disease resistance etc);
- crop inputs (seeding rate, nitrogen, herbicides, pesticides, fungicides etc); and
- sowing time (adjust for soil moisture conditions and late season frost risk).

In this area, climate risk information services have been used to support crop management decisions. Using models developed within the Western Australian Department of Agriculture (TACT, SPLAT, Flowering calculator, PYCAL and STIN), farmers have been faxed information on potential yields, stored moisture, current rainfall decile, optimum nitrogen rates, potential gross margins and a forecast update (Truscott and Egan, 2001; Tennant and Stephens, 2001).

Modelling allows producers to evaluate alternative management options and quantify the likely effect on farm income and production risk. Using up to 100 years of daily weather records, producers can compare the long-term outcomes of such management decisions in terms of risk and income security. To be effective, this approach requires an understanding of the probabilistic nature of the information provided, whereby producers must not become disheartened or reckless by any perceived 'failure' or 'win' of outcomes achieved in any given season. As with any probabilistic approach, it must be used consistently over a number of seasons to accumulate a net benefit from a management strategy. Further, it must be integrated into the whole decision-making process as one of many management tools. Model output from the various management scenarios is then used to support and stimulate discussions about the possible management options. In other words, the notion of 'decision support' based on simulated data has evolved into the concept of 'discussion support' by using such tools within mixed groups of farmers, agribusiness representatives and scientists (Nelson *et al*., 2002).

This intensity of scientist/producer interactions as discussed by Meinke and Hochman (2000) in their case studies cannot be maintained beyond specific pilot projects. Methods need to be developed that allow the generalisation of the knowledge gained by scientists and producers through such intense interaction.

Regional diversity makes such generalisations difficult. One approach is the closer involvement of farmer groups and their advisers in exploring together how simulation may impact on farm decision-making (McCown *et al*., 1998). This research approach aims to explore suitable methods for agribusiness and/or consultants to access relevant simulation results and climate forecast information. In partnership with local agribusiness firms, APSRU has accessed a range of regionally diverse farmer groups for whom simulations have been provided relating to relevant management options (Keating and McCown, 2001). Evaluation of these meetings has shown that they can have significant impact on the way in which farm managers are thinking about and acting on their tactical decisions (Coutts *et al*., 1998).

Calculating the odds of growing an economically successful crop requires knowledge of the soil type, the amount of stored soil moisture reserves, nitrogen requirements, likely price movement, rainfall and frost outlook and pest and disease risks. Such information needs to be assessed within the context of tactical, crop-specific management options (sowing date, area sown, nitrogen fertilisation strategy, etc) and more strategic, rotational options (grow an alternative crop, not growing a crop at all). Depending on the issues that farmers bring up in these discussions, simulations are conducted for their specific conditions (provided that inputs such as current amount of soil moisture content, climate records, etc are available) at that point in time (Carberry and Bange, 1998; Hochman *et al*., 1998; Robertson *et al*., 2000; Hammer *et al*., 2001).

Considerable success within pilot farmer groups has led to a market now existing in northern Australia amongst a significant sector of the farming community for timely and high quality interactions based on soil monitoring and simulation (Keating and McCown, 2001). The demand for simulations has increased rapidly. In close collaboration with the Grains Industry, the intention is to transfer to agribusiness the capability to deliver simulation-based interactions via an Accredited Adviser Network for delivering simulation and related products such as soil monitoring, seasonal climate forecasts, analysis of relevant management scenarios and 'what-ifs, analysis and discussion' to farmer clients in the northern cropping region. A similar partnership between researchers and agronomists has occurred in South Australia, where consultants from government and industry have been trained in climate risk workshops. Climate risk and management information is then passed onto many farmers through workshops and fee for service.

An alternative, less intensive approach to accessing generalised simulation output is via the 'Whopper Cropper' software product, essentially consisting of a database of pre-run simulations with an easy-to-use graphical interface facilitating time series, probability and diagnostic analyses (Hammer *et al*., 2001; Nelson *et al*., 2002). It was designed for users to be able to access crop yield simulations without having to learn how to run the more flexible and comprehensive systems simulation model. It is designed as a discussion support system in response to a demand from extension professionals for easy access to cropping systems modelling and seasonal climate forecasting. The information provided aims to support, and not replace, human judgement by amplifying the cognitive elements of decision making over the emotive elements (Keen, 1993; Chang *et al*., 1994). It allows users to explore and choose solutions using context specific reasoning not easily programmed into a decision support system (Collins, 1992).

Climate risk and policy

While climate variability has significant impacts at the farm level, it is important to realise that farmers operate within a policy framework that is also a consequence of our physical and social environment. O'Meagher *et al*. (1998) reports the significant impact that droughts have in Australia and South Africa on the associated policy frameworks that deal with such climatic impacts on agricultural production. There is some evidence of simulation modelling influencing decision-making in Australia via policy analysis. For instance, the determination of appropriate drought policies and the assessment and declaration of drought exceptional circumstances are issues that require objective information regarding the impact of climate variability on agricultural production and sustainability, albeit not always at the field *scale*[10]. Simulation models allow not only an assessment of the severity and frequency of drought events, but can be used to evaluate management responses that result in a higher level of drought preparedness at the farm, regional and institutional level. A wide range of studies have shown how these concepts can be operationalised. In particular, these studies highlighted important differences between 'climatological droughts', 'production droughts' and 'economic droughts' which are rarely synchronised (e.g. Hammer *et al*., 1996; Hall *et al*., 1997; De Jager *et al*., 1998; Donnelly *et al*., 1998; Keating and Meinke, 1998; O'Meagher *et al*., 1998; Stafford Smith and McKeon, 1998; Stephens, 1998; White *et al*., 1998).

Combined with the ability for seasonal climate forecasting, this has resulted in a much higher level of drought preparedness in Australia, and hence increased the capacity to better absorb negative impacts of drought.

PRINCIPLES

- A major feature of the history of farming in Australia is the challenge of coping with the erratic and variable rainfall.
- The dry Australian climate can be explained by its position relative to the general circulation of the atmosphere.
- The season-to-season variability of climate in Australia can to a large extent be explained by changes in the sea surface temperatures in the ocean influencing atmospheric conditions and circulation patterns. Some of these changes are related to the El Niño/Southern Oscillation phenomenon (ENSO), allowing probabilistic forecasting of climate anomalies.
- Climatic parameters such as rainfall, radiation and temperature can be related to crop growth through statistical methods, simple mathematical models such as water use efficiency or simulation models.

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[10] Issues of scale also need to be considered here and it has to be ensured that the modelling approach used is compatible with the data to be predicted or tested against (eg. estimates of regional yields, rather than field or paddock yields, requires a different type of modelling approach). However, this debate goes beyond the scope of this chapter and readers are referred to some of the references cited that deal more comprehensively with this issue.

- Simulation models of cropping systems can be used to convert rainfall variability into the risk and return of different management strategies.

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