4th edition

WILL IT RAIN?

The effects of El Niño and the Southern Oscillation on Australia

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Contents

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1. An introduction to seasonal climate forecasting

Will it rain? – the words on the lips of all producers concerned with cropping or animal production, and on the lips of urban folk often more concerned with leisure activities.

The question “When will it rain?” is generally answered well by a weather forecast. But in producers’ battles with the elements “For how long and how much?” and “When will it stop?” may be as important.

While city folk may be content with the shorter-term weather forecasts available on nearly all television and radio stations, country people also need climate forecasts over a range of longer periods. They also need to know how reliable is the longer term forecast – “What is the chance of it occurring over the coming months?”

Weather decides the tactical decisions, climate decides the strategic ones.

Incorporating seasonal climate forecasts into management decisions can be improved by:

- understanding our weather systems (Chapter 2 – Our weather)
- understanding the influence of ENSO and other drivers on climate variability (Chapter 3 – Our variable climate; Chapter 4 – Our climate and the SOI)
- assessing the influence of climate variability on your production system (Chapter 5 –Plant growth and the SOI)
- decision support for reducing risk in business and the environment (Chapter 6 – Decisions)
- understanding developments in improving seasonal forecasting (Chapter 7 – Seasonal climate forecasting).

This broad understanding will help you to incorporate the probabilistic nature of seasonal forecasts when managing climate variability.

Decisions

Decisions – applying weather and climate forecasts in operational and strategic plans.

The tactical and strategic decisions that any producer has to make are almost innumerable. They will depend on the production system being undertaken, the location, the type of product, the market and price, and the level of risk that the business is prepared to take. Overlaying weather and seasonal climate forecasts can help to reduce that risk.

Daily (even hourly) forecasts may be important for planting opportunities, for spraying pesticides or for harvesting. Weekly or monthly forecasts are involved in estimates of the growth of plants, and hence crop yield, or for the growth rates of grazing animals.

Seasonal forecasts help with crop management planning. “Do I plant any crop and, if so, which?” A poor cropping season in eastern Australia may be duplicated in India but be the opposite in the USA, thus affecting local and overseas commodity markets.

The horticultural industry may be partly sheltered by being able to modify the environment. Low rainfall can be offset by irrigation – if there is sufficient water available – but crop quality may be ruined by excessive rainfall or temperature.

Beef producers have to make long-term decisions well in advance of the next wet season based on herbage in the paddock and expected grass growth. When will they need to buy, sell or agist animals to balance stock numbers against available pasture?

These are just a few quick examples of the types of decisions that producers have to make, and with which weather and seasonal forecasts can help. They are described in more detail in Chapter 6.

Forecast reliability

The reliability of weather forecasts is now generally so good that people take them as gospel and rely on their accuracy – although recalling more vividly the occasional failure.

Users of any forecast should remember that the world's climate is a chaotic system and that forecast accuracy naturally decreases as the time period extends. All forecasts are probabilistic and many sources now express their forecasts as a percentage 'Chance of event' whether the event be rain, temperature or wind.

The base source of information

The Australian Bureau of Meteorology (BoM) website (*www.bom.gov.au*) now has extremely comprehensive collections of historical data and of information with text, tables, graphics and maps for forecasts of many aspects of climate. These include rainfall, atmospheric pressure, temperatures, and wind speed and direction, together with warnings and historical records.

Short-term weather forecasts

Producers are well served with short-term weather forecasts of up to seven days on the television (Figure 1.1), the office computer and now apps on smart phones (Figure 1.2).

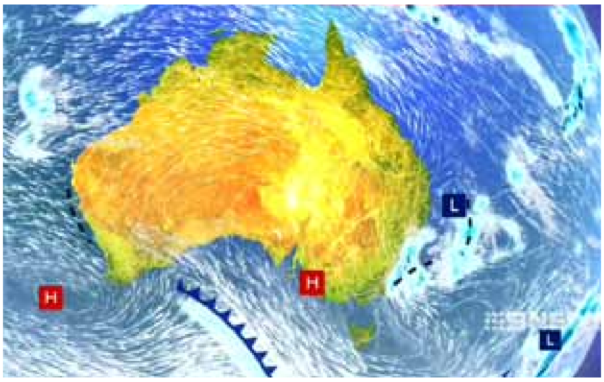


Figure 1.1. Example of synoptic map on television showing high and low pressure cells and cold fronts (Win 9)

The sources include the Bureau of Meteorology, Weatherzone and AccuWeather while many rural producers go to Eldersweather because of Elders' rural connection. Users tend to return to the product with which they are most familiar. Screen presentations may vary slightly but most forecasts rely on BoM's observations of ground, atmosphere and satellite data being incorporated into the exacting computer science.

Figure 1. 2. Example of hourly and 7-day weather forecasts on a mobile phone (AccuWeather)

Real-time forecasts

The chance of imminent rain at any location can be judged using the rain radar maps on BoM's web site; these show the location, movement and intensity of rain cells in real time (Figure 1.3).

Figure 1.3. Example of rain radar map (BoM)

Inter-seasonal forecasts

Monthly forecasting systems may incorporate the MJO (Madden Julian Oscillation). As the oscillation or wave approaches Australia from across the tropical Indian Ocean, it may bring rain; once it has passed our eastern coast, there may be a dry spell. The MJO (Figure 1.4) is explained more fully on page 8 in the next chapter.

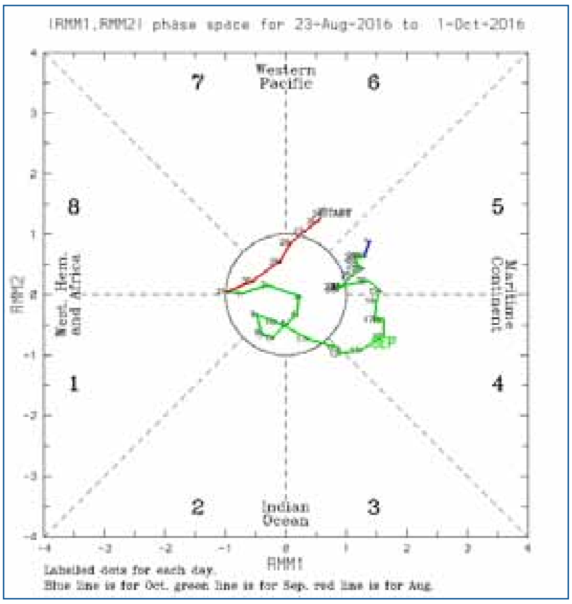


Figure 1.4. Example of an MJO phase diagram showing the movement and strength of the MJO (BoM)

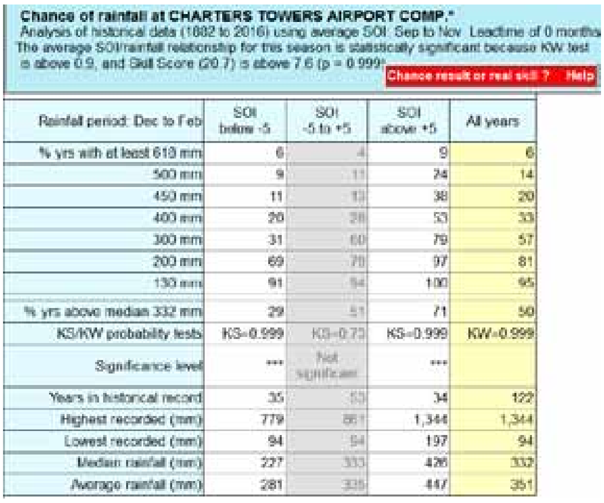
Seasonal forecasts

Longer-term seasonal forecasts for Australia are largely dependent on ENSO (El Niño–Southern Oscillation), and these may be at world-wide, national, regional, district or local levels. They can be statistical or dynamical (see Chapter 7).

Individual producers can look at the chance of local rainfall of nominated amounts by analysing their own historical rainfall records against the SOI (Southern Oscillation Index) data using a comprehensive software program such as Rainman StreamFlow on their PC (Figure 1.5) or using the interactive ClimateARM program on the Internet.

Regional and broader forecasts usually incorporate dynamical GCMs (General Circulation Models) of the interactions between the ocean and atmosphere.

In Australia, BoM developed POAMA (Predictive Ocean Atmosphere Model for Australia) (Figure 1.6), and now ACCESS with improved resolution.



Chance of rainfall at CHARTERS TOWERS AIRPORT COMP.*
Analysis of historical data (1882 to 2016) using average SOI: Sep to Nov. Leadtime of 0 months
The average SOI/rainfall relationship for this season is statistically significant because KW test is above 0.9, and Skill Score (20.7) is above 7.6 (p = 0.999)
Chance result or real skill ? Help

Rainfall period: Dec to Feb	SOI below -5	SOI -5 to +5	SOI above +5	All years
% yrs with at least 613 mm	6	4	9	6
500 mm	9	11	24	14
450 mm	11	13	38	20
400 mm	20	28	53	33
300 mm	31	60	79	57
200 mm	69	78	97	81
130 mm	91	84	100	95
% yrs above median 332 mm	29	51	71	50
KS/KW probability tests	KS=0.999	KS=0.73	KS=0.999	KW=0.999
Significance level	***	Not significant	***	
Years in historical record	35	53	34	122
Highest recorded (mm)	779	861	1,344	1,344
Lowest recorded (mm)	94	54	197	94
Median rainfall (mm)	227	333	426	332
Average rainfall (mm)	281	335	447	351

Figure 1.5. Example of local seasonal rainfall forecast from Rainman StreamFlow showing statistically significant and non-significant effects of ENSO.

ACCESS (Australian Community Climate Earth-System Simulator) has been developed under cooperation between the BoM, CSIRO and the UK Met Office (see Chapter 7 for more details).

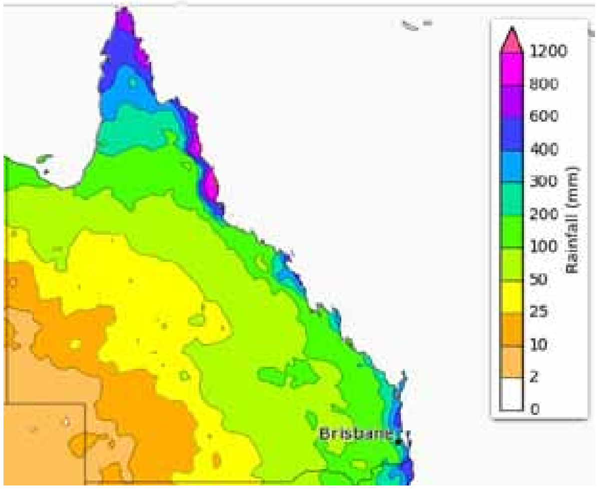


Figure 1.6. Example of broad-scale seasonal rainall forecast (BoM)

Across the world, many meteorological services, such as ECMWF (European Centre for Medium-Range Weather Forecasts), have developed their own GCMs, and their individual predictions for up to six months can be found on the BoM website.

BoM Climate Watch

The BoM website contains an encyclopedia of climate information. Climate Watch and MetEye present current forecasts of coming rainfall and many other aspects of climate at a broad scale. (www.bom.gov.au/climate/ahead/).

2. Our weather

This chapter gives a general description of weather systems over Australia as a background to understanding weather and seasonal forecasts.

Our weather is generated as the atmosphere circulates over the Australian continent and its surrounding oceans.

From day to day, the weather is controlled by the systems of high and low atmospheric pressure and the fronts that we see on synoptic weather charts on television and in the papers, and also by upper air systems. However, our systems are only a local response to the general circulation of the atmosphere around the entire Earth.

The General Circulation

The general circulation is driven by temperature differences caused as the sun heats the Earth's surface unevenly – the equator receiving most solar radiation, the polar regions the least.

The higher latitudes are effectively no extra distance from the sun, but they receive less radiation per unit of surface area because of the more oblique angle of incidence. The effect is greatest over water, which absorbs radiation when the sun is overhead, but more than 70% is reflected when the rays are oblique. Much of the radiation towards the poles is reflected off atmospheric clouds and surface ice.

The hottest area, the thermal or heat equator, shifts from about 5°S in January to 15°N in July as it follows the sun into the summer hemisphere.

In a much simplified picture, the air above the heat equator is warmed, it expands and, being less dense, rises (Figure 2.1). This creates a belt of low pressure at sea level – an equatorial trough – and corresponding high pressure in the upper atmosphere.

The air rises about 20 km to the top of the troposphere, before turning towards the poles – north or south depending on the hemisphere. After travelling some 25–30° of latitude, the air is forced to sink, 'piling up' cool dry air to form the subtropical ridge of high pressure.

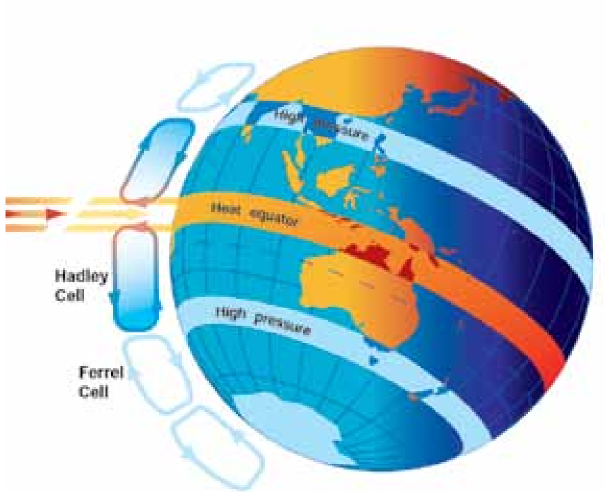


Figure 2.1. The general circulation is caused by uneven heating of the Earth's surface.

Much of this air flows back at surface level to the lower pressure trough near the equator, but some continues to the middle latitudes near the surface.

This vertical circulation of the atmosphere between the tropics and subtropics is known as the Hadley cell. The strength of this Hadley cell around the globe varies with the degree of heating of the earth's surface and overlying atmosphere.

At about 60°S or N there is another zone of rising air and low pressure – the Circumpolar trough. Air again rises to the top of the troposphere, which is at about 10 km at these latitudes, before it splits. Part moves towards the equator to descend in the zone of the subtropical ridge, thus creating a mid-latitude circulation known as the Ferrel cell; part moves towards the poles before descending over the polar regions to create zones of virtually permanent high pressure.

Belts of high and low pressure

The general circulation creates alternating belts of low and high pressure at different latitudes around the Earth. The belts of low pressure both create and are generated by zones of high rainfall, while those of high pressure create arid regions around the world. Pressures within the belts vary considerably because land and sea heat differentially.

Air flowing from higher pressure to lower pressure is deflected by the Earth's rotation – the Coriolis Effect – slightly in the tropics but increasingly so with latitude. In the southern hemisphere, air is deflected to the left and so spirals clockwise into a region of low pressure.

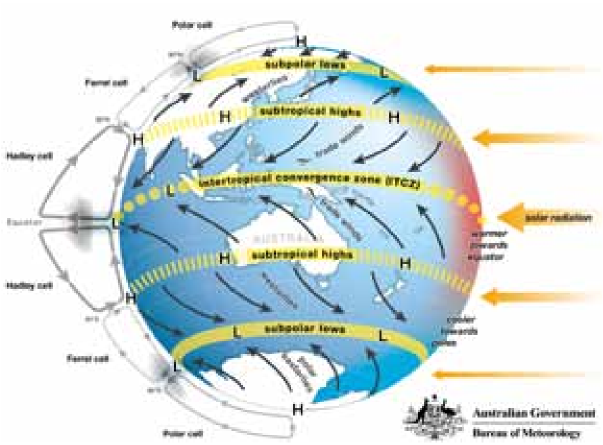


Figure 2.2. Global wind patterns

Air flowing from the southern hemisphere subtropical ridge towards the equatorial trough is deflected westward, resulting in the south-easterly trades. These meet the north-east trades from the northern hemisphere in the Intertropical Convergence Zone (ITCZ).

Within this convergence zone, these warm, moist airmasses rise and condense to form cumulo-nimbus clouds which drop heavy rain. The release of enormous quantities of latent heat energy as this water vapour condenses to water droplets is a major source of power driving the general circulation. Below about 5° of latitude, the absence of both Coriolis Effect and pressure variation gives rise to broad regions with little or no wind – the doldrums.

Air flowing poleward from the subtropical ridge towards the circumpolar trough is deflected eastward, giving rise to the mid-latitude westerlies.

Basic patterns affecting Australia

The broad scale weather patterns over Australia are strongly dictated by these belts of low and high pressure.

The ITCZ and monsoon rains

The ITCZ generally lies north of Australia but, in summer, it often merges with the equatorial trough, 'pulled' southward by the inland 'heat low' as the north and centre of the continent heat up. In January, this monsoonal trough normally lies from Broome, through Mount Isa, to Cairns.

Warm moist air drawn into this region of low pressure from over the surrounding oceans (from the north-west over the Top End and from the north-east over Queensland), generates heavy rain – the monsoon

The Australian monsoon typically starts late in December and ends in March but, compared to the Indian version, it is relatively weak and is often punctuated by breaks of dry weather. Its strength varies greatly from year to year – a strong monsoon may result in widespread flooding over northern Australia, whereas a weak and erratic monsoon may lead to a general failure of the summer rains in the tropics.

Subtropical ridge and clear skies

High pressure in the subtropical ridge presents most of Australia with its renowned dry air and cloudless skies. Within the subtropical ridge,

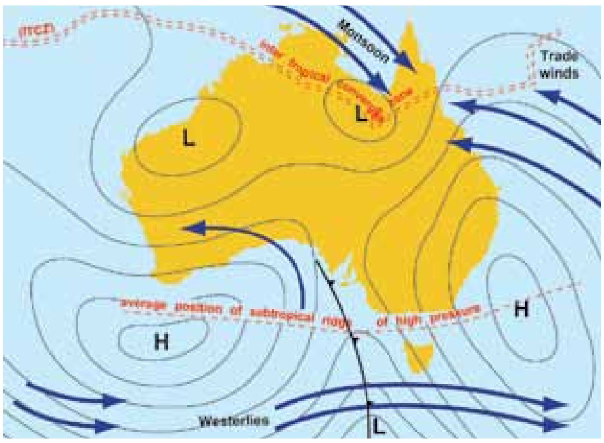


Figure 2.3. Typical synoptic pattern – summer

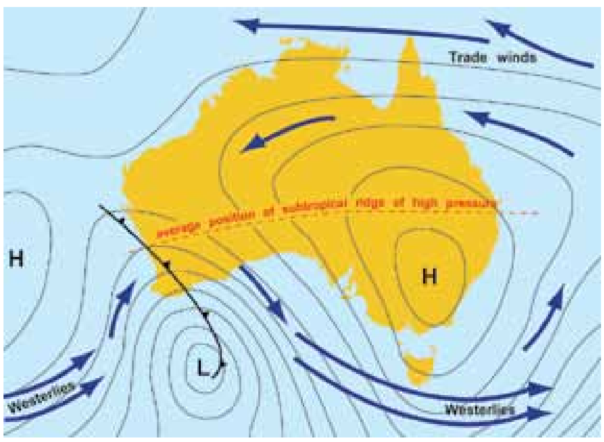


Figure 2.4. Typical synoptic pattern – winter

individual cells of high pressure – anticyclones – form, develop and decay as they travel west to east across southern Australia.

In January, the subtropical ridge lies across and south of southern Australia, and over the Bight, generating easterly winds over much of the continent. The ridge moves north in autumn and intensifies, extending across South Australia and New South Wales by July. As the latitude of the subtropical ridge may vary between years, it may affect the location of the anticyclones and hence wind direction at critical latitudes.

Individual anticyclones control the weather for several days and, over the southern states, often alternate with fronts or low pressure systems. Sometimes, especially in autumn or early winter, a high pressure cell will stagnate (a 'blocking' high), and can dominate the weather for up to three weeks, reinforced by other 'highs' moving in from the west.

Westerlies and the circumpolar trough

The mid-latitude westerlies – north-westerly to south-westerly winds – are produced as air flows between the subtropical ridge and the higher latitude circumpolar trough, and is turned eastward by the Coriolis Effect. Frequently embedded in the westerlies are fast-moving fronts and depressions; these disturb the westerly flow, giving rise to north-westerly winds ahead of a trough, and south-westerly winds in its wake.

As the subtropical ridge moves north in autumn, the westerlies also move north, and so influence the weather over southern Australia during the cooler months of the year. The embedded fronts and depressions typically produce changeable, showery and windy weather, giving southern Australia most of its rain in winter or spring.

Also an east-west circulation

There is another vertical circulation, this time east-west, in the tropical atmosphere. In this Walker Circulation, air rises over the warm seas in the Indonesian region, aided by the associated heavy rainfall. On reaching the tropopause, it flows eastward before sinking over the cooler waters of the eastern tropical Pacific.

The strength of this circulation varies from year to year. When one side has higher-than-normal pressure (which usually accompanies lower-than-normal sea surface temperatures and rainfall), the other side usually has lower-than-normal pressure, warmer seas and higher rainfall. This 'see-saw' in atmospheric pressure is called the Southern Oscillation, and is described in detail in Chapter 3.

It is changes from the normal (or anomalies) in the atmosphere and ocean that generate the major changes in our climate from year to year. Changes in sea-surface temperatures and air pressure affect the strength of the south-east trade winds, and so the amount of moisture reaching eastern Australia. The Southern Oscillation is thus strongly associated with rainfall in eastern Australia. When sea temperatures are lower than normal around Indonesia and atmospheric pressures higher than normal, northern and eastern Australia often experience droughts; when sea temperatures are higher than normal, these areas often receive above-average rainfall.

As an unusually cool sea off northern Australia usually coincides with an unusually warm sea off South America – known there as El Niño – and a weak Walker Circulation, the combined system is often referred to as the El Niño-Southern Oscillation (ENSO) phenomenon. The reverse situation, with a strong Walker circulation and colder sea surface temperatures off South America, is called La Niña or Anti-ENSO.

Other rainproducing influences

Tropical-extratropical cloudbands

Extensive bands of cloud, starting over a warm western tropical Indian Ocean and extending southeast across the continent, can often be seen on satellite pictures during the cooler months (Figure 2.5). These cloudbands form when moist air from the tropics is forced to rise by temperature gradients in the mid and upper atmosphere (sometimes called upslide). Because the lifting is general, rainfall is generally steady, prolonged, and soaking, and therefore effective for agriculture.

These northwest cloudbands can account for heavy rain in otherwise dry areas and

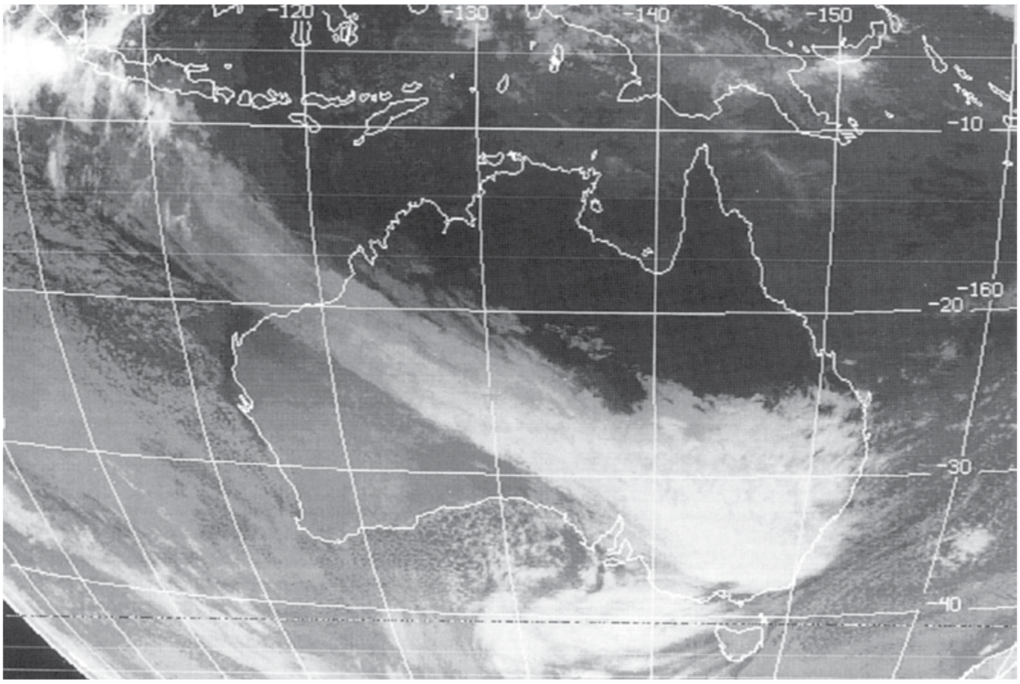


Figure 2.5. Satellite picture of a northwest cloudband (BoM)

seasons. They are associated with a significant proportion of the rainfall from autumn to spring between latitudes 20–35°S. In north-western Australia, they are virtually the only source of rainfall outside the summer months.

Northwest cloudbands are most common from late April to August, but similar bands of cloud originate over the northern Australian inland during the spring months. Climatologists prefer the generic term ‘tropical-extratropical cloudbands’ because many of the cloudbands affecting eastern Australia originate over either northern Australia or the ocean to the north.

The frequency of the bands, and especially their rainfall potency, varies considerably from year to year, and seems to be linked to sea surface temperature patterns over the eastern Indian Ocean.

Tropical-extratropical interactions

When airmasses from the tropics interact with weather systems from higher latitudes, large amounts of rain can be produced. This can happen when, for example, a tropical-extratropical cloudband gets caught up with a mid-latitude front or depression.

Interactions affect mostly the south-eastern states where they account for a high proportion of the total rainfall between autumn and spring. However they too, vary greatly from year to year. Over inland eastern Australia, they are a dominant cause of year-to-year fluctuations in rainfall, and are strongly related to the Southern Oscillation.

Tropical cyclones

The monsoon trough and the ITCZ are zones of cumulonimbus clouds and heavy rain. Enormous amounts of latent heat are released as water vapour condenses to water droplets, causing the air to rise further, and surface pressures to fall. More air flows into the updraught but is deflected in the developing clockwise swirl of the low pressure cell. If sea temperatures are high enough (above about 28°C) to keep the new air sufficiently moist, there is a chain reaction. The system intensifies, the swirl accelerates – a tropical cyclone is born (Figure 2.6).

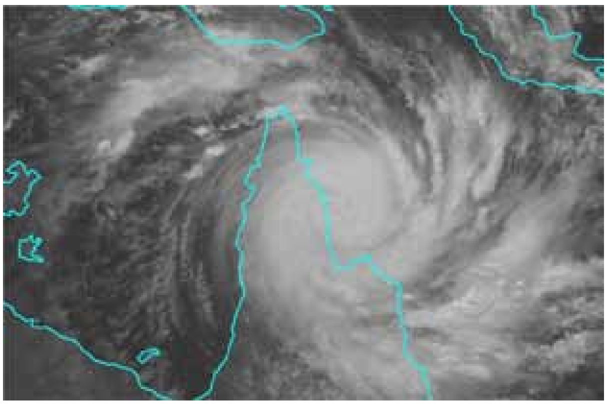


Figure 2.6. Tropical cyclones swirl clockwise in the Southern Hemisphere.

Hurricanes and typhoons

'Tropical cyclone' is the correct meteorological term in Australia for tropical systems producing sustained cyclonic winds above 64 knots (118 km/h); many other countries refer to these as tropical storms. 'Severe tropical cyclone' refers to storms above a certain intensity. Tropical depression describes organised low-pressure systems within the tropics that have not yet reached tropical cyclone intensity. Intense tropical storms are called hurricanes in the Caribbean, and typhoons in the northwestern Pacific.

(Tropical cyclones cannot form within about 7° of the equator because the Coriolis Effect there is too weak to initiate the swirling of the air).

Tropical cyclones affect the tropical regions of Western Australia, the Northern Territory and Queensland in most years. When cyclones move inland, they lose contact with the warm water needed to sustain them, and so they weaken. As they weaken, they can drop prodigious amounts of rain, causing widespread flooding.

Between 4 and 18 tropical cyclones occur over the oceans bordering Australia each year, tending to be more frequent when the Southern Oscillation Index is positive (see Chapter 3).

During an El Niño, cyclone activity tends to move away from the eastern Australian coast, following the warm water which has moved towards the central Pacific.

The MJO

At irregular intervals of between 30 and 60 days, a disturbance of atmospheric pressure may appear over the western tropical Indian Ocean and move eastward between latitudes 10°N and 10°S at 300-600 kilometres a day (Figure 2.7).

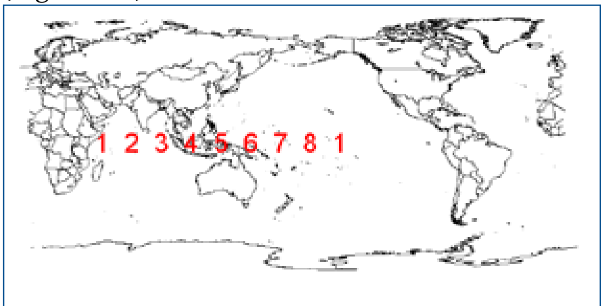


Figure 2.7. Phases of the MJO as it travels from west to east at 4–10 days per phase. Phases 4-6 tend to increase rainfall in northern Australia.

This within-season or 'intraseasonal oscillation' is the MJO (Madden-Julian Oscillation). Farming lore of old talked about rain coming every six weeks, hence an earlier name of '40-day wave'. The MJO is now recognised as a major driver of intraseasonal variability in the tropical atmosphere

The strength of the MJO varies but, during the northern Australian summer, its passage can often be seen from satellites as a 'blow up' in convection, creating large regions of enhanced cloud formation, although this may sometimes be obscured by more widespread heavy monsoonal cloud.

The strongest impact of the MJO on rainfall in Australia is in summer in the tropical north but in winter it may also influence Australia's mid-latitudes (e.g. central and southern Australia and Queensland) when it may strengthen an upper-level trough, possibly leading to the development of northwest or tropical-extratropical cloudbands or to a tropical-extratropical interaction.

Monthly forecasting systems often incorporate the MJO because of its relatively steady eastward movement that provides some predictive skill. As the MJO approaches Australia, it may bring rain; once it has passed our eastern coast, there may be a dry spell. A strong MJO results in a period of about a week of intense storm rainfall, followed by a distinct dry spell. A weak MJO during a La Nina results in continuous widespread rain.

As it moves east of Australia into the Pacific, a strong MJO may momentarily block the south-east trade winds, and so interfere with the Southern Oscillation's auto-enforcement, reversing the easterly winds and so potentially providing a start for El Niño development or generating cyclonic conditions around the Pacific islands. The MJO generally becomes less distinct as it moves over the cooler ocean waters of the eastern Pacific but occasionally reappears over the tropical Atlantic.

The frequency of this wave is too irregular to be used for routine rainfall forecasts at this stage, but its movement and strength during the 30–60 days can be seen graphically on the BoM website (see Figure 1.4 in Chapter 1.) (A current MJO phase diagram can be found at www.bom.gov.au/climate/mjo/)

What makes rain?

Dry air picks up moisture as it passes over water, with warm air able to hold more water vapour than cold air. When this moist air is uplifted, its temperature drops, and, if cooled enough, the water vapour will condense to form cloud droplets. These droplets collide and join until large enough to fall to earth as rain drops. Alternatively, ice particles generated higher in the cloud can fall, melting before they reach the ground.

For rain to be produced, an air mass must have sufficient moisture, and be cooled enough for the moisture to condense.

Frontal systems and depressions

Frontal lifting occurs when airmasses of different density and temperature are brought together. In a cold front, a relatively cold, dense, often fast-moving air mass undercuts a lighter, warmer air mass. The sudden lifting creates large cumulus clouds, resulting in showers and sometimes thunderstorms. Most fronts affecting southern Australia are cold fronts.

Rainfall may be more widespread, and often heavy, if the air mass ahead of the front is fairly moist, as in a tropical-extratropical interaction.

Very occasionally, a warm air mass overruns a cold air mass (a warm front), giving a more gradual uplift and steady rain; more often widespread steady rain is produced by uplift associated with upper atmospheric temperature gradients (see section on northwest cloudbands).

Cold fronts are frequently followed by cold winds from the west or south-west, with showers in the southern states. Much of the rain experienced in exposed or hilly areas, and most of the snow on the Southern Highlands, falls from cold fronts and post-frontal airstreams.

Low pressure areas – lows or depressions – may or may not be associated with frontal systems. Depressions may originate within the mid-latitude westerlies to affect the southern states, or within the monsoonal trough in

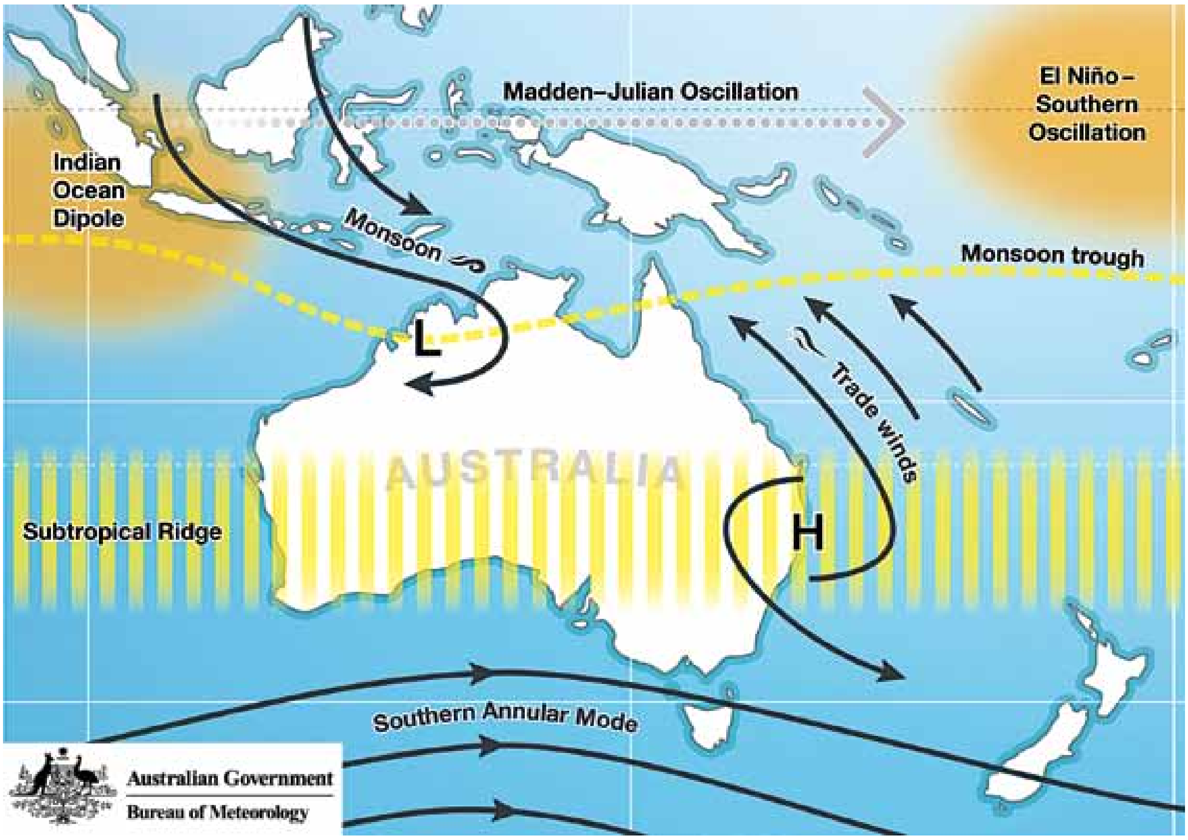


Figure 2.8. Various phenomena that influence our climate and weather over the year

summer over northern or central Australia. Depressions are generally accompanied by rain, sometimes by thunderstorms; the rain can be very heavy if the 'low' is slow-moving and associated with moist air. This often occurs off eastern Australia, where slow-moving, intense, 'east coast lows' can produce flood rains and gales, as in the record flood in Sydney in August 1986.

East Coast Lows

East Coast Lows are troughs of intense low pressure that can develop rapidly overnight in late autumn or winter. They intensify when the sea surface temperature within 50 km of the coastline is raised by warm eddies of the East Australian Current. Gales and heavy rain occur along the coast of New South Wales and Southern Queensland when the moist air is uplifted by the topography of the Great Dividing Range.

Troughs in the upper atmosphere

Troughs, associated with pools of cold air in the upper atmosphere, will destabilise the underlying air mass, and hence may cause rain. These upper-level systems, which may not show on surface-pressure charts, are most common in the cooler months. If the low-level air mass is moist and the upper-level trough is slow-moving, widespread heavy rainfall can cause flooding.

Our broad-scale patterns of climate are modified substantially by local effects such as orographic lifting over mountains or hills. These cause much of the variation in rainfall between districts or even between parts of one large property.

Blocking

Atmospheric blocking is an important climate driver for Australia, having a major impact on mid-latitude weather processes and extremes. Blocking mostly occurs near south-eastern Australia in winter, often resulting in extended dry spells over south-western Tasmania, yet its impacts can be seen over much of the continent and in all seasons.

This is largely due to a ('cut-off') low pressure system that can form on the northern flank of a blocking high and break away to produce widespread substantial rainfall. Although blocking events in the Australian region typically last about 3-4 days, they can influence rainfall across a range of timescales.

ENSO is known to influence blocking particularly in the summer months, when blocking is more likely to occur during La Niña and less likely to occur during El Niño.

Convective uplifting

Thermal currents over an area of hot land (or very warm water) can produce cumulus clouds, with showers if sufficient moisture is present. If the air mass is unstable and the thermal currents strong, the cumulus may develop into cumulonimbus – the thunderstorm cloud.

Cumulonimbus produces lightning and thunder, usually with strong wind gusts, heavy rain, and sometimes hail. However, as individual thunderstorm cells are usually small, storm rain is localised and highly variable. Occasionally in the tropics, thunderstorms amalgamate into intense clusters to produce several hours of heavy rainfall over an extensive area of northern Australia.

Convective rainfall is almost always assisted by some other source of uplift – convergence, orographic lifting, or fronts or depressions. It is best developed in the warmer months, and accounts for much of the rainfall in northern and central Australia, but for relatively little in the southern states.

Convergence

When low-level airstreams meet, or converge, they generate uplift, as in the Intertropical Convergence Zone. Convergence can occur near 'inland heat lows' or troughs over northern Australia. Easterly trade winds, shifted southward by the trough, meet dry southerly winds on the western side, often forming thunderstorms. Other examples are orographically-induced convergence, and 'sea-breeze convergence', a common source of thunderstorms in tropical coastal areas.

Orographic uplift

Moist air, lifted as it flows over a mountain range, forms showers (if unstable), or drizzle or steady rain (if stable). A drier rain shadow area often lies in the lee of a range.

Orographic rain occurs along the eastern slopes

of the northern Great Dividing Range, being most noticeable where mountains are high, steep and close to the coast, as around Cairns in Queensland. In the south, the moist westerly winds drop their rain on the western sides of the mountains, as in south-eastern NSW, north-eastern Victoria, and western Tasmania. Even relatively low hills, as occur in south-western Western Australia, can generate significant orographic rain.

The North

Rain falls mostly in summer, produced by the monsoonal trough and ITCZ, but with large, erratic falls from tropical cyclones. Rainfall is often heavy and associated with thunderstorms, but varies greatly between locations and with time.

The amount of rain in 'The Wet' depends upon:

- the amount of moisture present in the air
- the temperatures of the surrounding oceans
- when the monsoon trough arrives and departs
- the number and duration of dry 'breaks'
- how far south the monsoon trough comes
- how many tropical cyclones approach or cross the coast.

The South

Rain falls mainly in winter and spring, although it is fairly evenly distributed throughout the year on the eastern seaboard.

The amount depends mainly on the number and intensity of fronts and depressions, and on the degree of interaction with tropical airmasses. It thus depends on the latitude of the subtropical high pressure belt, which is not directly related to the Southern Oscillation, and its intensity, which is.

In-between regions

Rainfall is less seasonal between 20° and 30°S. In the west, it depends mainly on northwest cloudbands in winter (related to sea surface temperature patterns over the eastern tropical Indian Ocean), and on tropical cyclones and thundery troughs in summer.

In the east, tropical-extratropical cloudbands and interactions are important, especially over inland areas, and these are related to the Southern Oscillation.

In east coastal areas of Tasmania, Victoria, New South Wales and southern Queensland, the frequency of moist easterly flows is important (and related to the latitude of the subtropical high pressure belt), as is the frequency of 'east coast lows'.

Over central Australia, the rainfall is erratic throughout the year, and depends more on isolated events (thundery troughs or unusual southward excursions of the monsoonal trough in summer, tropical-extratropical cloudbands or depressions in winter).

The influence of the Southern Oscillation generally decreases westward across the continent.

Modifiers to weather systems

Conditions that can modify the 'normal' seasonal weather patterns may cause considerable variability between years, and account for Australia's climate reputation. These conditions often work through changes in oceanic and atmospheric circulations over the Pacific, and Indian, Oceans; some cycles last three to five years, others may be decadal. These influences will be described in Chapter 3.

3. Our variable climate

The Southern Oscillation

The summer-winter shift of the seasons as the equatorial trough and subtropical ridge move south and north has the strongest control over our weather. The Southern Oscillation is the most important influence on the year-to-year variability, and explains as much as 40% of the variance in eastern Australian rainfall; indeed, high rainfall variability is often a sign that a region is under the influence of the Southern Oscillation.

The Southern Oscillation is a see-saw of air pressure between the eastern equatorial Pacific and the Australian-Indonesian region; when the surface atmospheric pressure is abnormally high over one region, it is usually abnormally low over the other.

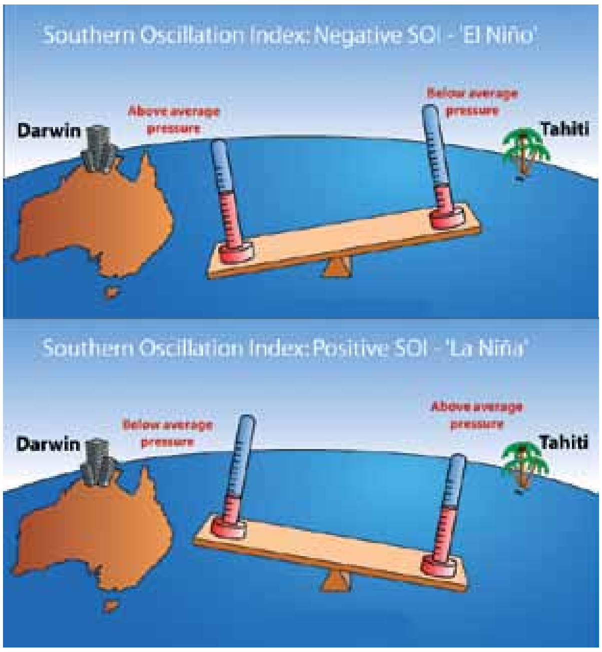
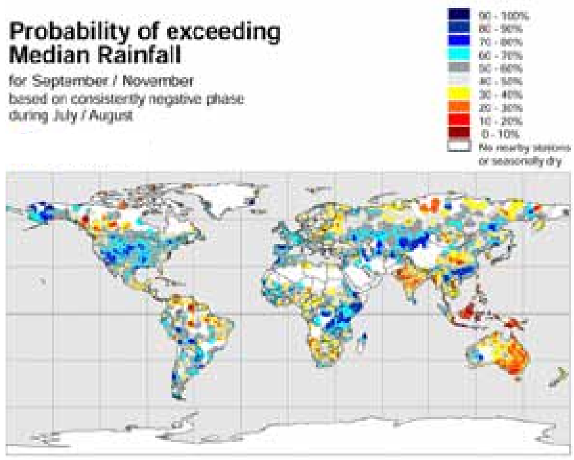


Figure 3.1. The Southern Oscillation is a see-saw of atmospheric pressure between the Indonesian region and the east equatorial Pacific.

This slow-moving, large-scale oscillation of air pressure affects the weather in many parts of the world (see Figure 3.2.) The Southern Oscillation may cause droughts in Australia, India and parts of Africa at the same time as floods in North and Central America. It influences much of Australia, but its effects vary between regions and at different times of the year.



Probability of exceeding median rainfall in the next three months when July–August SOI is consistently negative (above) or positive (below)

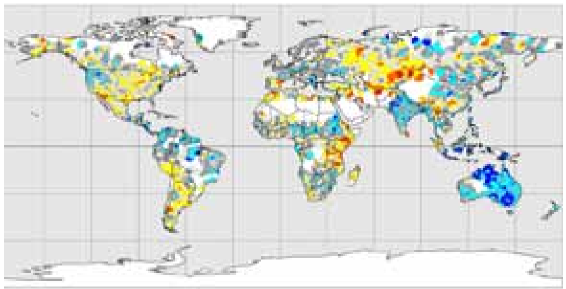


Figure 3.2. Examples of regions of the world affected by ENSO

The Southern Oscillation Index (SOI)

The strength and phase of the Southern Oscillation is measured by the difference in anomalies – the monthly means *minus* the long-term means – in air pressure between Darwin and Tahiti, records for which started in 1869 and 1876 respectively. The BoM Troup SO Index usually ranges within the extremes of –30 to +30. It includes a times ten factor, thus a Troup SOI of –10, for example, is equivalent to an SOI of –1 from the USA.

ENSO

The terms El Niño and Southern Oscillation are encapsulated as ENSO – the term commonly used to describe the whole phenomena of climate variability affected by atmosphere and ocean interactions in the Pacific.

When the Southern Oscillation Index is strongly positive, the trade winds blow strongly across the warm Pacific picking up plenty of moisture; much of eastern Australia is then likely to receive above-average rainfall.

When the SOI is strongly negative, trade winds are weak, or even reversed, and rainfall in the Indonesian and Australian region can be much below average – a possible drought in an El Niño.

Various values of the SOI have been used to define El Niño and La Niña, commonly used have been ±5 or ±7, but there are no strong correlations between the strength of the SOI and severity of drought for example.

As satellites have been able to measure sea surface temperatures (SSTs) since 1981, actual SST changes in the central tropical Pacific are now used as a major component in declaring an El Niño.

The Equatorial Pacific Ocean has been divided into four regions for monitoring El Niño (Figure 3.3), but the region between Niño–3 and Niño–4, namely Niño–3.4 (5°N-5°S, 170°W-120°W) is that most used to define an El Niño .

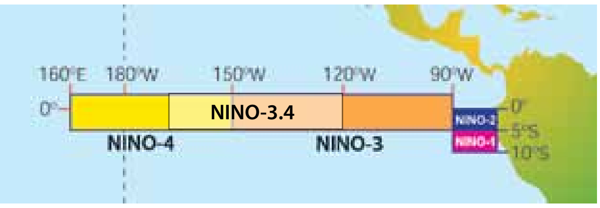


Figure 3.3. An El Niño may be declared when the sea surface temperatures in the Niño 3.4 region are 0.8°C warmer than average.

The critical SST anomaly in Nino-3.4 for BoM to declare an ENSO event is 0.8°C – although other institutions use different critical values. BoM predictions are given as an 'El Niño or La Niña WATCH' (Figure 3.4).

Figure 3.4. Example of El Niño or La Niña WATCH or alert from the Bureau of Meteorology

When is it an EL Niño?

BoM requirements for an El Niño:

- Sea surface temperatures in Nino-3 or Nino-3.4 are 0.8°C warmer than average.
- The trade winds have been weaker than average in the western or central equatorial Pacific Ocean during any three of the last four months.
- The 3-month average SOI is –7 or lower.
- Most of the surveyed climate models show sustained warming to at least 0.8°C above average in Nino-3 or Nino-3.4 until the end of the year.

Ocean and air in the Pacific

In the Hadley Cell, the atmosphere circulates between the hot tropics and the cooler latitudes, creating the equatorial zone of low pressure and the subtropical ridge of high pressure (see Chapter 2).

Both atmosphere and ocean circulate in three dimensions, with each acting upon the other. The atmosphere moves faster than the ocean, but the ocean stores large amounts of heat and releases it slowly over a long period. Thus the ocean acts as a 'memory' in the general circulation.

Ocean currents

The prevailing south-easterly trade winds force the waters of the South Pacific Ocean basin around in a great anti-clockwise swirl, called a gyre.

The south-easterly trade winds and westward currents together pile up warm water in the western Pacific – creating a slope of some 30-40 cm between the western and eastern sides (Figure 3.5).

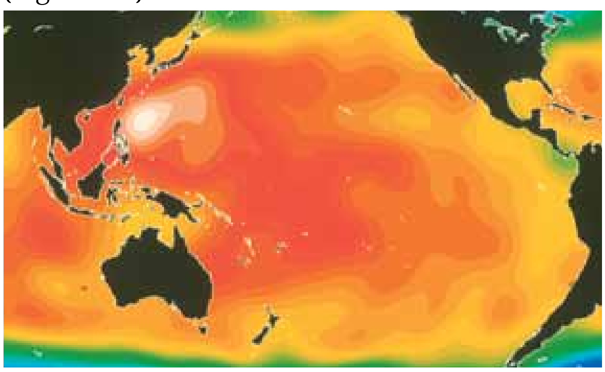


Figure 3.5. Long-term average topography of the Pacific Ocean – the highest sea level (white and red) is normally in the western Pacific.

The thermocline comes closer to the surface in the east Pacific; cold upwelling water there can cool the surface more effectively (Figure 3.6).

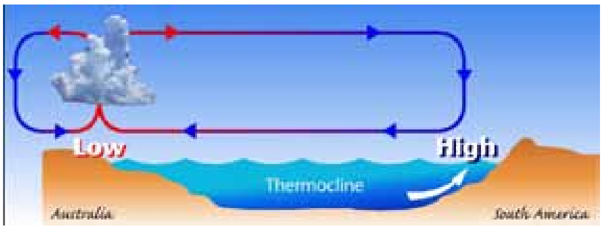


Figure 3.6. Easterly winds push warm water westward toward the Indonesian region. Upwelling of cold water cools the eastern equatorial Pacific.

A significant weakening of the trade winds will allow a wave in the ocean to move slowly eastward along the equator. This equatorial Kelvin wave takes about three months to cross the ocean, warming the sea surface as it goes, pushing the thermocline in the east deeper, thus reducing upwelling of cold water.

When the Kelvin wave reaches the South American coastline, much of its mass and energy are reflected as a series of slower-travelling Rossby waves heading back west. Over the next few years, the equatorial 'reservoir' of warm water in the west refills; when full, another Kelvin wave is ready to start moving warm water eastwards again.

These waves flowing back and forth help to create the perpetual oscillations of the ENSO cycle; some persist on a longer scale for decades to become an Interdecadal Pacific Oscillation.

Warm ENSO-related water piled up in the western Pacific may pass through the Indonesian throughflow (Figure 3.7), and so may influence the Indian Ocean Dipole.

Figure 3.7. Piled-up warm water in the western Pacific can pass into the Indian Ocean through the Indonesian throughflow.

Sea surface temperatures

The temperature of the sea surface of the West Pacific Warm Pool is fairly constant, averaging around 29°C.

The cold Peru Current and upwelling of cold, deep water keep sea surface temperatures in the tropical eastern Pacific as much as 6°C cooler than those in the west (Figure 3.8). When upwelling of the cold water declines, 'normal' temperatures of 22–24°C of the eastern Pacific may rise to 26–29° during an El Niño phase.

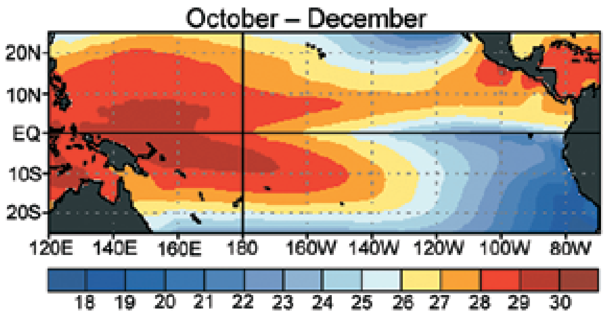


Figure 3.8. Average ocean temperatures

Upwelling of cold water

Vertical circulation of the ocean can keep waters unusually cool in some areas in the tropics.

The south-east trade wind typically flowing parallel to the Peruvian coast tries to drive the ocean current along with it but the Coriolis Effect deflects water westward. Cold water from the ocean depths rises to the surface to replace it – this coastal upwelling results from a phenomenon known as Ekman transport (Figure 3.9).

Figure 3.9. Upwelling of cold water off the South American coast through the Ekman transport phenomenon

This cold water area can be extended along the equator past the International Date Line by upwelling between the anti-clockwise gyre of the south Pacific and the clockwise gyre in the north.

If upwelling in the central and western Pacific stops because the easterly winds decline or are checked momentarily by a westerly windburst, the sea surface will warm quickly – an El Niño may be born.

Figure 3.10 shows the difference in water temperature in the Pacific during a La Niña and during an El Niño.

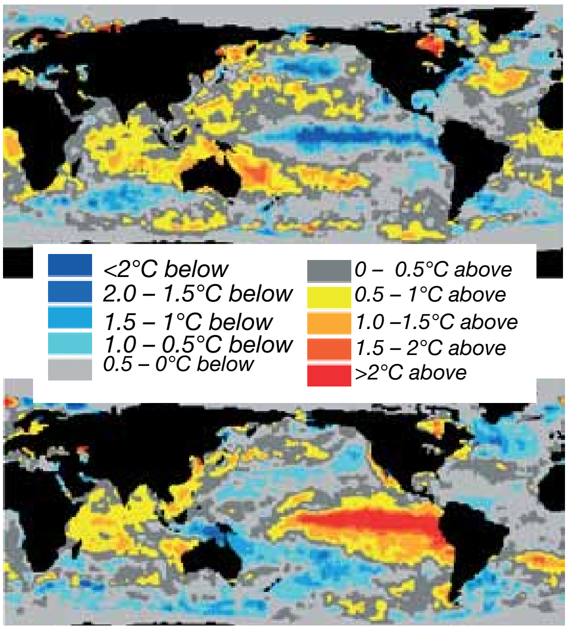


Figure 3.10. Sea surface temperature anomalies during La Niña (top) and El Niño (bottom).

An east-west circulation

Besides the north-south circulation of the Hadley Cell, the differences in sea surface temperature between the east and west of the equatorial Pacific cause another great circulation of air – the Walker Circulation. Walker, Director-General of the British Observatory in India in the 1920s, was the first to correlate droughts in one part of the southern hemisphere and floods in another, especially as failed monsoons effected massive famine in that sub-continent.

The Walker Circulation has three main elements:

- air flows west across the tropics of the Pacific (south-east trade winds), being warmed and gathering moisture from the warmer waters of the western ocean
- it is uplifted over the Indonesian region, dropping the moisture as rain
- the dry air then flows east, at an altitude of about 12,000 metres, to sink again over the normally cold waters of the eastern Pacific.

This ‘normal’ Walker Circulation is greatly changed during extreme phases of the Southern Oscillation. It is strengthened when the sea surface temperature in the eastern Pacific is abnormally low (Figure 3.11).

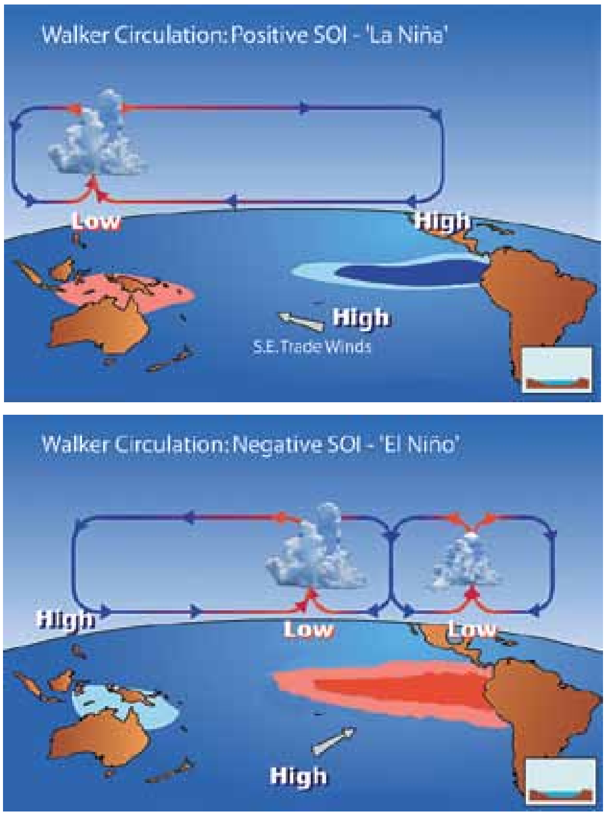


Figure 3.11. The Walker Circulation is strengthened during a La Niña with the eastern tropical Pacific kept cold by upwelling (top). It is weakened or reversed during an El Niño (bottom) with the eastern ocean warming as the Kelvin wave deepens the thermocline.

Auto-enforcement

A strong circulation under a positive SOI reinforces the differences in east-west temperatures. Strong trade winds help push warm equatorial water towards northern Australia-Indonesia, promoting more rainfall, while ocean upwelling keeps the sea surface cool off the South American coast.

When the SOI becomes negative, the chain reaction accelerates in the opposite direction. Weak trade winds reduce the strength of the equatorial current flowing westward towards Australia and Indonesia, the Kelvin wave moves eastward, the sea surface off the Australian

coast cools, the equatorial current may reverse to become an 'El Niño current', upwelling weakens and the sea surface warms in the eastern Pacific.

How quickly does the SOI change?

Major changes in the SOI persist when associated with major changes in ocean temperatures although it may fluctuate monthly with local troughs or high pressure cells over Darwin or Tahiti. If the South Oscillation behaved in a regular cycle, it would allow climate predictions one or two years into the future. Unfortunately, although the average cycle is about four years, strong negative or positive phases occur irregularly at intervals of three to six years, as seen in Figure 3.12.

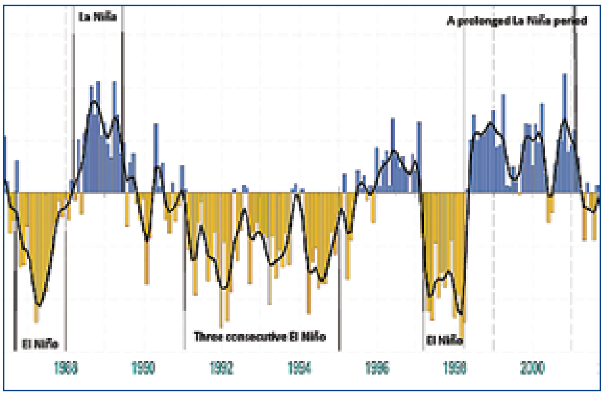


Figure 3.12. A Southern Oscillation phase usually persists for about nine months once firmly set (BoM).

Extreme phases of the Southern Oscillation usually last for about nine months once they have become established; they set in winter and do not break until the following autumn when triggered by the northward movement of the heat equator and subtropical ridge. Thus the SOI is often variable in autumn, and can change rapidly when the auto-enforcement collapses, sometimes triggered by the passing of an MJO. The SOI in autumn is rarely a reliable indicator of the future winter weather.

While the Southern Oscillation modifies the climate pattern, the weather continues its natural variability under the other influences described in Chapter 2. These are sometimes so dominant that the Southern Oscillation cannot be a totally reliable indicator of future weather.

An ENSO event may be strong or weak, or of short or long duration and, while most last for about a year, those of 1939–42 and of 1991–1994 for example, persisted for three (see Figure 3.12), possibly under the influence of the Interdecadal Pacific Oscillation. Not every drought is caused by an El Niño, nor does every El Niño cause a major drought in Australia, nor do all La Niñas cause floods. However, we can estimate the chances, or probabilities, of their influence.

A typical El Niño episode

In a typical El Niño episode (Figure 3.13), the SOI becomes strongly negative from late autumn. In Queensland, the normal dry winter conditions become more severe as spring rain is low. Drought conditions may begin as the main summer rains start late and are weak. In autumn, the SOI becomes positive and the drought breaks.

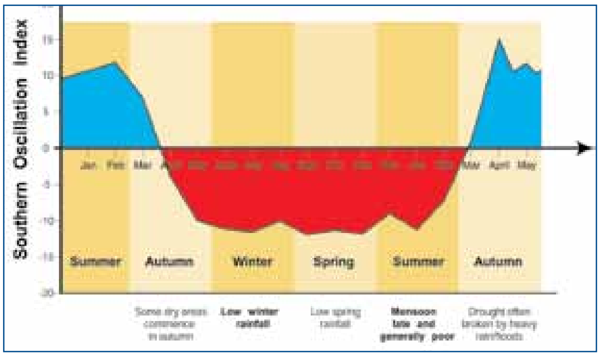


Figure 3.13. Rainfall pattern in northern Australia during a typical El Niño episode

Droughts may break dramatically with floods when the SOI rises rapidly from extremely low values even if it does not become positive, for example, when it changes from –15 to 0. These trends, up or down, are used as indicators (see Chapter 4) in the SOI phase system.

Variations in ENSO relationship

The Australian climate is not constant – there have been significant variations in both average temperature and rainfall over large areas of the continent even during our short period of recorded history, and larger variations over a longer time-scale.

The effect of ENSO on summer rainfall in eastern Australia has not been consistent throughout the last century. The relationship was strongest in the periods 1891 to 1920 and 1940 to the present, but it declined slightly between 1921 and 1940.

Climate in eras before scientific records were kept can be estimated from 'proxy' sources. These include measurement of Java teak and north Mexican–south Texan tree rings, and of annual florescence in cores of corals in the Great Barrier Reef and Pacific. Florescent bands in coral cores from the Great Barrier Reef suggest that, over a 245 year long period, the five wettest years were 1887, 1974, 1755, 1768 and 1890 (in that order), while the five driest were 1902, 1867, 1812, 1823 and 1865.

These proxy sources suggest that there have been longer term or interdecadal variations in the strength of ENSO; these include the Inter-decadal Pacific Oscillation (IPO) and the Pacific Decadal Oscillation (PDO).

Interdecadal Pacific Oscillation and Pacific Decadal Oscillation

Whereas the PDO reflects ocean surface temperatures mainly in the northern Pacific Ocean, the IPO reflects more of the whole ocean and so may have more influence on ENSO.

During positive phases of the IPO, ocean temperatures are warmer in the tropical Pacific and ENSO's influence on Australian rainfall is weak (Figure 3.14); When the IPO was in a positive phase between 1978 and 1998, there were more El Nino events.

When the IPO is negative, ENSO's correlation is strongest – but with more influence on La Niña than El Niño.

'Negative or 'cool' IPO regimes prevailed from 1890 to1924, and from 1947 to1976, with positive (warm) IPO regimes dominating from 1925 to1946 and from 1977 through (at least) the mid-1990s.

As the IPO oscillates on a 15-30 year cycle with just two full cycles in the past century, its causes and its potential predictability are not currently understood nor is its exact relationship to global climate change.

Despite the lack of understanding about whether the sea temperatures are driving the IPO or vice versa, IPO climate information improves longer term climate forecasts because it does persist for a long period.

What's normal?

Long-term oscillations in sea surface temperatures enforce the observation that climate perceived as 'normal' to one generation may really depend on when they were born, in the same way that farmers often perceive 'normal' rainfall to be that which was occurring when they started farming.

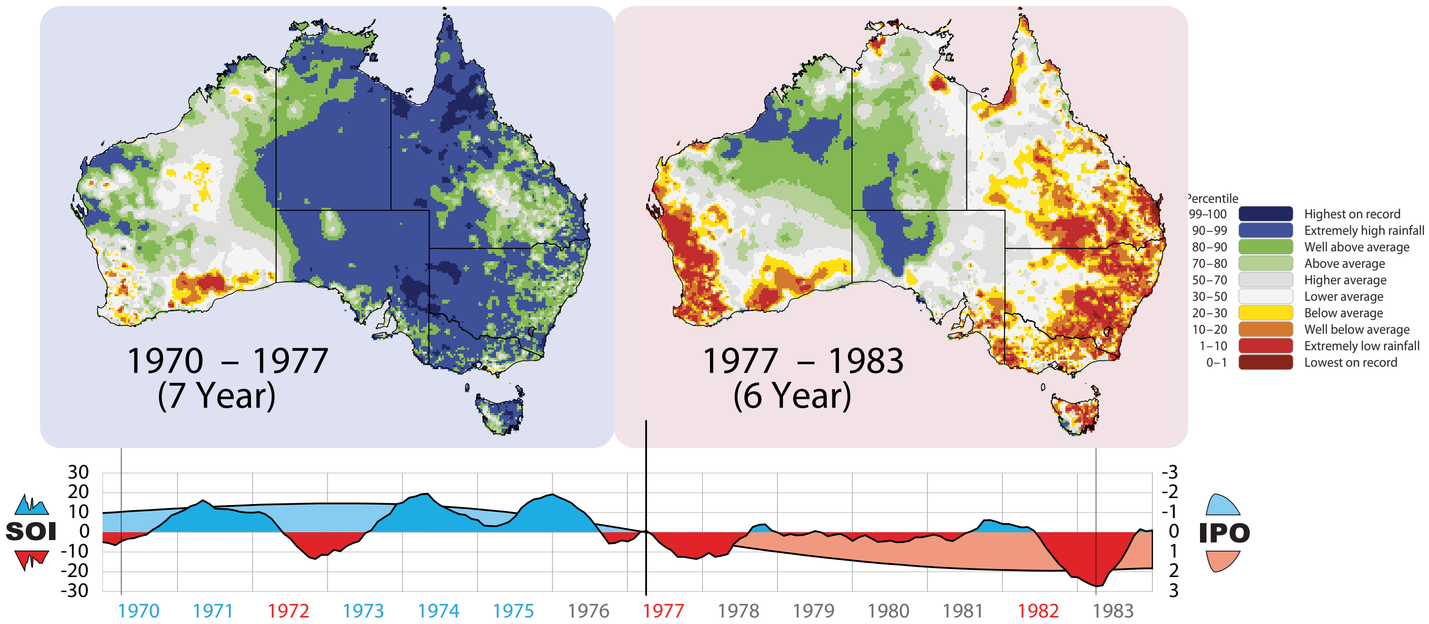


Figure 3.14. Examples of possible modulation between the IPO and SOI. Between1970 and1977, the SOI was generally positive under a cool IPO (smooth line); between 1977 and 1983, the IPO was warm with more frequent negative SOI.

Indian Ocean influences

The relationship between the SOI and rainfall is strongest in winter, spring and summer in eastern Australia. Across the centre and south of the continent, winter rainfall is more influenced by sea surface temperatures in the Indian Ocean.

Sea surface temperatures in Indian Ocean

Sea surface temperatures (SSTs) in the equatorial Indian Ocean in summer and autumn may be useful in predicting the probability of rainfall in early winter over parts of southern and eastern Australia. The strongest relationships have been found between Indian Ocean SSTs in February-March and rainfall in May-June and June-July, with the strength varying between different regions.

Formation of northwest cloudbands

Many of the tropical-extratropical cloudbands (described in Chapter 2) that can bring winter rain to parts of southern, eastern and northern Australia are generated over the eastern Indian Ocean when the temperature difference (SST gradient) between Indonesia–northern Australia and the central-southern Indian Ocean is greater than normal.

The Southern Indian Ocean also circulates anticlockwise in a gyre that brings a cold southern current north to the coast of Western Australia producing a band of cold water, and associated high atmospheric pressure, extending from the south-west coast diagonally across the Indian Ocean.

If a low develops over southern Australia in early autumn, cold southerly winds become stronger than normal off the west coast of Australia. These winds cool the sea surface of the eastern Indian Ocean more rapidly than is normal with the seasonal change.

At the same time, the south-east trades will be weaker than normal (with more north-west winds around northern Australia), and the sea surface in that region will not cool as much or as quickly as normal.

These unusual south-easterly and north-westerly airflows reinforce the anomalies (changes from normal) in sea surface temperature in their respective regions; the steep temperature gradient between the adjacent cold and warm waters enhances the formation of northwest cloudbands.

As the low over southern Australia may itself develop more strongly when the sea surface off the west coast is cooler than normal during autumn, SSTs off the west Australian coast during summer and autumn (December to April) allow prediction of the chances of rainfall in early winter (May to July) over parts of southern and eastern Australia.

Indian Ocean Dipole (IOD)

Differences between sea surface temperatures in the western and eastern tropical Indian Ocean create a similar oscillation to that seen in the equatorial Pacific. This Indian Ocean Dipole influences the northwest cloudbands that affect the winter crop growing season, especially in south-west and southern Australia; it can also bring heavy rain to the dry centre.

Since 1960, when reliable records of the IOD began, to 2013 there have been nine negative IOD and nine positive IOD events making a cycle averaging 2.5 to 3 years.

Phases of the IOD usually start around May or June, peak between August and October and then rapidly decay when the monsoon arrives in the southern hemisphere around the end of spring.

The IOD may be linked with the Pacific’s ENSO as warm water passes through the Indonesian throughflow. Hence positive IOD events are often associated with El Niño and negative events with La Niña. When the IOD and ENSO are in phase the impacts of El Niño and La Niña events are often more extreme; when out of phase the impacts of El Niño and La Niña events can be diminished.

Positive IOD phase

The warm water moves towards the African coast while the easterly wind encourages upwelling of cool water in the east. The cooler seas to the north-west of Australia generate a drier atmosphere, and this often results in less rainfall and higher than normal temperatures over parts of Australia during winter and spring.

Negative IOD phase

More westerly winds along the equator concentrate warmer surface waters near Australia. This warm water increases atmospheric humidity so a negative IOD typically results in above-average winter–spring rainfall in the weather systems crossing over parts of southern Australia. Frontal systems and lows crossing Australia – the 'north west cloudbands' – are described in Chapter 2.

A negative IOD typically brings above average rainfall to eastern Australia during spring, cooler than normal daytime temperatures to southern Australia, and warmer daytime and night-time temperatures to northern Australia

IOD and SOI interactions

A negative (moist) IOD aligning with a positive (moist) SOI can result in wet years, such as during mid-2016. The July 2016 monthly IOD index value was the strongest negative value in at least 50 years of record, and could be associated with the exceptionally high winter rainfall over central Australia. Growth of winter crops and some pastures is vigorous but major flooding can occur.

A positive (dry) IOD aligning with a negative (dry) SOI can result in extended droughts with failed winter and summer crops and loss of pastures and ground cover. Fires in the south can be devastating when this combination follows good grass growth in the previous season. The mean winter-spring rainfall is below average across nearly all of eastern and central Australia as with an El Niño. However, there is also lower rainfall across central Australia, which is not usually seen when El Niño occurs on its own.

SAM

The Southern Annual Mode (SAM) reflects atmospheric variability in the mid and high latitudes of the southern hemisphere. A positive SAM can result in reduced winter rainfall on the southern extremities of the mainland and in western Tasmania as the westerly windbelt contracts towards the Pole (see Chapter 7 for more information).

Summary

Climatologists know that the SOI (and IOD) can be used to improve the estimates of the probability of rainfall – in parts of Australia and during certain months.

The SOI can be used to generate better probabilities of:

- when the wet season will arrive in northern Australia
- the amount of summer rain to be expected in northern Australia
- the intensity of cyclone activity
- the amount of winter and spring rain to be expected in eastern Australia.

An ENSO may be strong or weak, with most lasting about a year. Not every El Niño causes a major drought in Australia, nor do all La Niñas cause floods. Longer, multi-year droughts may be under the influence of the Interdecadal Pacific Oscillation.

The longer cycles of the IPO may modulate the influence of the SOI and may account for the wetter years of the early 1970s and the subsequent drier six years.

Sea surface temperatures in the Indian Ocean may also give better estimates of winter rainfall in southern, eastern and northern parts of the continent.

As 'living memory' is generally of less than sixty years, long-term historical records are essential for a full understanding of relationships between climate drivers and climate.

Seasonal forecasts generated using General Circulation Models (GCMs) that include many of these aspects of the atmosphere and ocean are increasingly being used for seasonal forecasts, and are described in Chapter 7.

Predictions or probabilities?

All seasonal forecasts are probabilistic, showing the chances of a climate threshold (e.g. an amount of rain or higher than normal temperatures) occurring.

The Earth's climate system is too chaotic for definitive predictions of climate or the degree of climate change.

4. Our climate and the SOI

After the seasonal cycle, the Southern Oscillation is the second most important influence on the climate in many parts of eastern Australia. What is its effect on rainfall, and what else is affected? Where and when does it have most influence? Does the SOI influence the climate only during the same season or can it be used to predict the climate in the next season?

In this chapter, the relationships between the SOI and the climate over the past hundred years are examined, and examples are given of both concurrent and predictive relationships.

Floods, droughts and the SOI

The years of drought and flood in eastern Australia have been strongly associated with the SOI; rainfall from El Niño years can be compared with that from La Niña years

In Table 4.1, rainfall over eastern Australia during ENSO years (May to March) when the SOI was below –5 is compared with rainfall in the ENSO years when it was above +5.

Table 4.1. Effect of SOI on rainfall in Queensland. (703 long-term stations using concurrent SOI and rainfall seasons from May to March)

Year type	SOI May–March	Median rainfall (mm)	Chance of exceeding all-yrs median rainfall
El Niño	below –5	592	27%
La Niña	above +5	887	75%

Climate records

In 1881 and 1882, most of Queensland was gripped by a severe drought – now known to be associated with an El Niño. This stimulated many rural areas to keep better records of rainfall. Some towns had already been recording the weather for many years – Paramatta was first in 1832, Brisbane's records go back to 1840. Besides recording rainfall, many stations have also noted cloud cover, temperatures and relative humidity. Most records of barometric pressure started around 1940 but those from major cities may go back much further. The records of barometric pressure at Darwin and Tahiti used to calculate the SOI date back to 1869 and 1876 respectively.

Computers make it possible to analyse these masses of historical meteorological data, written down by thousands of conscientious recorders over the years. To supplement the work of the current observers, the Bureau of Meteorology has introduced automatic weather stations and electronic data collection systems.

Not a certainty but a better estimate

We can look at the records of the past hundred or more years – local rainfall, air pressure in Darwin and Tahiti – and see how many times abnormal rainfall coincided with abnormal values of the Southern Oscillation Index.

We can then see if the SOI has given us a better estimate of different-from-average rainfall and in what percentage of years, and so help to improve our predictions of rainfall.

SOI-based forecasts could be more accurately described as 'conditional probability hindcasts.

The values in the monthly SOI over the 1990s are shown in Figure 4.1. The more extreme phases usually persisted for about nine months, and have been associated with droughts or wet periods in parts of Australia. There have been more El Niños than La Niñas during this time.

SOI phases and classes

Five SOI Phases are often used in seasonal forecasts. The phase for each month is mathematically derived from the last two monthly SOI values. The five phases and their approximate definitions are:

- consistently negative (mean below –7)
- consistently positive (mean above +5)
- rapidly falling (by 7 to below +3)
- rapidly rising (by 7 to above –3)
- near zero

Seasonal SOI averages (usually over 3 months) – negative (below –5), positive (above +5) and neutral – are often used to explain simply how SOI forecasting works and for concurrent analyses.

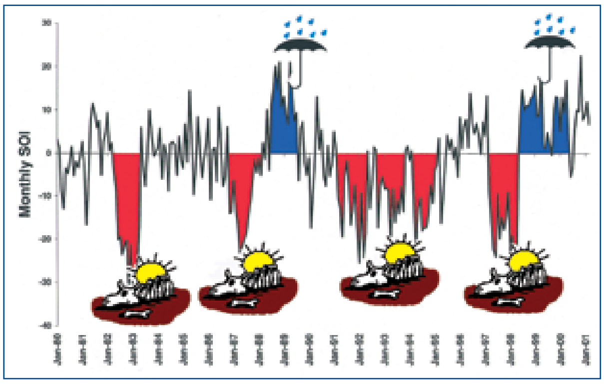


Figure 4.1. Prolonged anomalies in the monthly SOI are frequently associated with droughts and wet years.

Check for yourself

Rainman Streamflow, a PC program developed by the Queensland Government and the Bureau of Meteorology, provides and analyses climate information from more than 3700 locations over the continent. It allows you to compare historical monthly or daily rainfall records from your location against phases or classes of the SOI. You can check whether the SOI provides a significantly better estimate of the probability of rainfall in your district for any coming season.

Rainman can be downloaded free-of-charge from the Queensland Government DAF website.

'Same season' influence of SOI

This section looks at influences of the SOI on the concurrent (same season) climate during the past century. Rainfall may be the most important aspect of the weather but it is associated with everything from cloud cover to the amount of water flowing down our rivers.

Cloud cover

There is more cloud cover when the SOI is positive. Average cloud cover calculated from 20 000 morning and afternoon observations at each station in Queensland shows that cloud cover is 20% higher when the SOI is positive than when it is negative. The effect has been greater in winter and spring (30%) than summer and autumn (10%); it has also been greater in southern Queensland (35% in winter) than in the north (25%). Cloud cover reduces the level of solar radiation reaching the ground.

Temperatures

Clouds slow the rate at which the earth warms during the day and cools at night. When the SOI is negative, average monthly maximum temperatures have been 1–2°C hotter in summer and minimums 2–3°C colder in winter, and with more frosts, than when the SOI has been positive. This can be seen in the following averages from Dalby in southern Queensland (Table 4.2).

Table 4.2. SOI and temperature in southern Queensland

SOI class	Max temp in Dec (°C)	Min temp in July (°C)	Frosts in July
Below –5	32.5	2.7	18
Above +5	30.8	5.3	9

Humidity and evaporation

The air is likely to be more humid and evaporation lower with a positive SOI when there is more cloud and a greater chance of rain. For example, the average relative humidity during summer at Emerald in central Queensland has been 51% when the SOI was above +5 and 46% when below –5. Similarly, the average daily evaporation has been altered by about 10% in winter and spring and by more than 15% in summer and autumn.

Rainfall

Less cloud in the sky when the SOI is negative probably means less rain, especially in northern Australia. There, average summer rainfall has increased by 25% in summers with a strongly positive SOI and decreased by the same amount with a negative SOI; in the south, these differences are 10–15%. The effect is expressed as more wet days rather than from heavier rain on each wet day.

Droughts

Much of eastern Australia has often been in drought when the average annual SOI has been strongly negative; on the other hand, there has never been more than 5% of Queensland in drought when it has been strongly positive.

The SOI has been associated with about half of the widespread droughts in Australia. The other half have occurred when the SOI has been in the middle range of –5 to +5 – but never when the SOI has been strongly positive. El Niño is the main cause of droughts but their severity may well be modified by other factors.

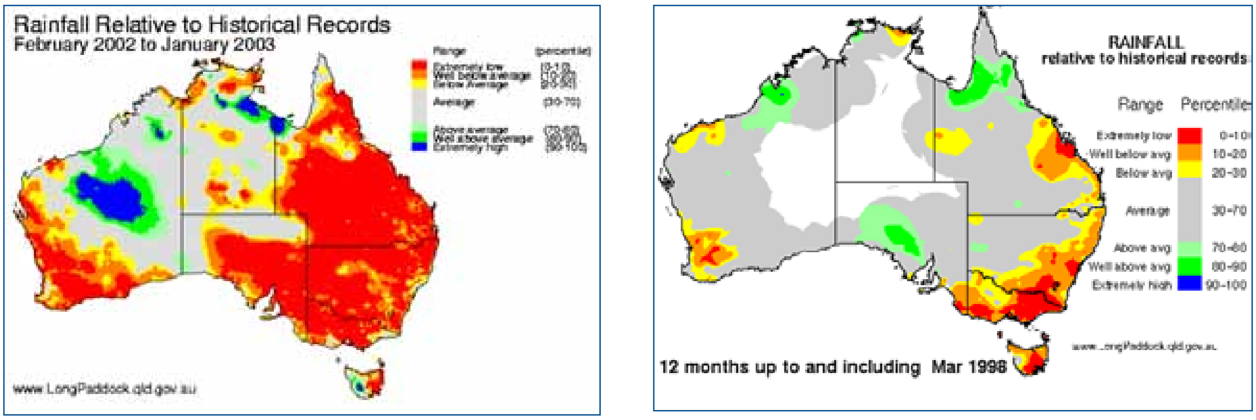


Figure 4.2. Examples of El Niño droughts with each affecting different regions and with different severity

No two El Niños are similar in their intensity and regions affected. Some produce severe widespread droughts, others are more localised. Figure 4.2 compares regions affected in the 2002–2003 El Niño with those in, for example, that of 1997–98. Interactions between ENSO and the Interdecadal Pacific Oscillation (IPO) may account for some of these differences. These relationships were described and illustrated more fully in Chapter 3.

Tropical cyclones

Most tropical cyclones start over the ocean in the Intertropical Convergence Zone and usually broaden into rain depressions that bring flooding rains if they cross the coast. In Chapter 2, we saw how convergence needs a warm ocean to intensify into a cyclone. As a strongly negative SOI occurs when the waters around the north of Australia are unusually cool, there are then fewer tropical cyclones affecting north-east Australia; instead they tend to follow the warm water in the central Pacific (Figure 4.3). In general, more tropical cyclones cross the Australian coast during La Niña years, and fewer during El Niño years.

'Future season' influence of SOI

Strong movements of the SOI usually persist for almost a year. Thus once the SOI has set into a consistent pattern by winter, it will tend to stay in that class until the following autumn. We can use either the average SOI or its trend in one season to predict the weather in the next, or even further into the future. These 'timelag' relationships are the subject of much current research; some of the latest results are presented here but anyone with a PC can do their own research into relationships using Rainman StreamFlow.

Rainfall

The SOI during winter and spring has, in the past, had an effect on rainfall during the following season. For example, the difference in average spring rainfall between opposing phases of the winter SOI is 33% at Katherine (NT), Port Lincoln (SA), and Tamworth (NSW). Similarly, the difference in average summer rainfall after the spring SOI is 22% at Tamworth and 45% (250 mm) at Charters Towers.

Large differences in wet season rainfall over much of eastern Australia result in seasonal isohyets moving east or west under different SOI classes.

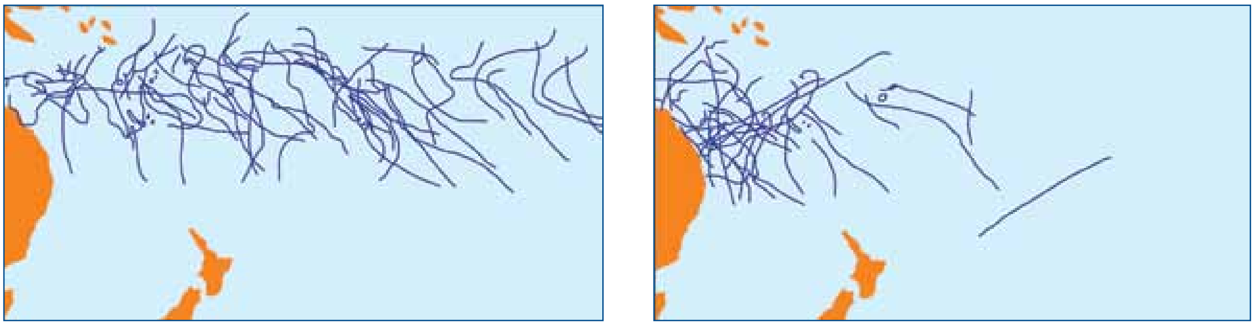


Figure 4.3. Tropical cyclones generate over warm water. Cyclone paths in El Niño years (left) and La Niña years (right)

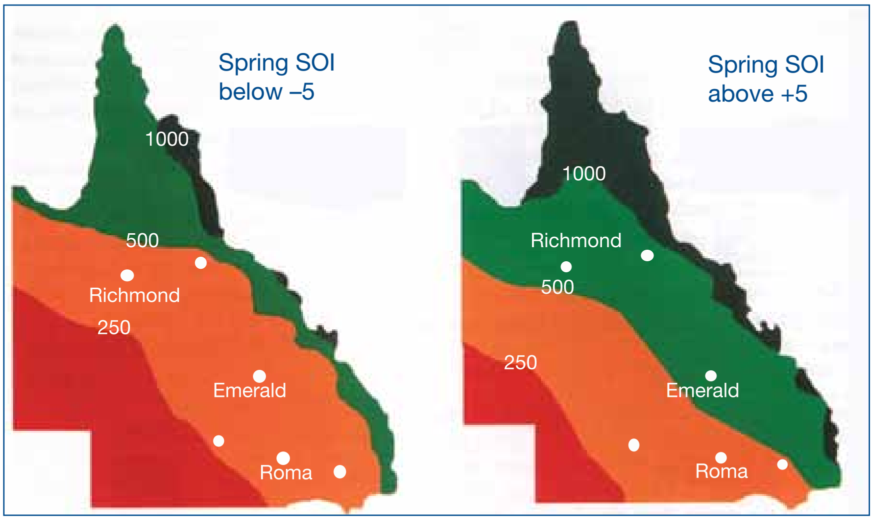


Figure 4.4. Isohyets of wet season rainfall across Queensland move east or west depending on the SOI.

Although the SOI in autumn is changeable and unreliable, once it has become deeply entrenched and consistent by late autumn to early winter (May–June) it is likely to stay that way ('phase-locked') for the next nine to ten months.

The reliability of the SOI in Queensland can be judged by the relationship between the SOI from August to October and the rainfall during the next six months of summer over a period of more than one hundred and twenty years for the Emerald district in the Central Highlands of Queensland (Table 4.3).

Table 4.3. Spring SOI and summer rainfall at Emerald from 1883 to 2016

Summer rainfall (mm)	SOI in spring	
	below –5	above +5
Lowest	147	197
Highest	904	1129
% with <350 mm	51	9
% with >550 mm	13	42
Average	378	516
All years average 448 mm		

Because of the SOI predictability barrier in autumn, SOI phases may be more useful than 3-month averages for winter crops such as wheat in eastern Australia. However, in the wheat belt of New South Wales, the median winter (June–Sept) rainfall following a rising SOI over April–May may be only about 25 mm more than that following a rapidly falling SOI.

Break of the wet season

ENSO influences when the monsoon arrives in the north. It is earlier when the SOI is positive than when the SOI is negative (Table 4.4).

Table 4.4. Start of wet season (defined here as 2nd event of receiving at least 50 mm in a week).

% chance of rainfall at Georgetown, N. Queensland based on average SOI during May to June	SOI below –5	SOI above +5
by 1st Nov	0	6
by 1st Dec	18	44
by 1st Jan	64	78
by 1st Feb	89	97

Runoff and streamflow

Once the soil has become saturated under prolonged rainfall, water will run off the soil surface. Runoff accumulates in streams, creeks and finally into the major river systems. Conversely there is little runoff in periods with below-average rainfall as small falls are used by plants or evaporate (Table 4.5). The effect of the SOI on streamflow is much more pronounced than its effect on rainfall.

Table 4.5. Run-off under grassland at Richmond, Qld

Average spring SOI (Aug to Oct)	Summer run-off (Nov to April)
Above +5	49 mm
Below –5	15 mm

Table 4.6 illustrates how the SO alters the summer flow of the Fitzroy River in Queensland, with Figure 4.5 showing the effect on river flow into the Wyangala Dam in NSW.

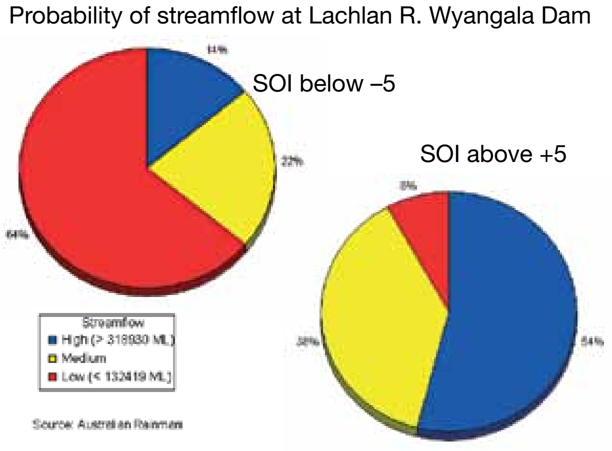


Figure 4.5. Late autumn SOI and streamflow into the Wyangula Dam

Table 4.6. Median streamflow of the Fitzroy River (at Riverslea); concurrent flow and SOI for October to December

SOI (Oct to Dec)	SOI <–5	SOI >+5
Median flow (ML)	42,500	52,250

Evaporation

The effect of the SOI on evaporation in the following season has been similar in most parts of Queensland but not throughout the year. Winter and spring SOI values have been useful, but not those of summer and autumn.

Temperature

Cloudless skies during an El Niño increase the chances of early and late frosts, and the number of frosts. As a strong SOI trend in early autumn will set the SOI pattern for the next nine months, the trend as early as February may predict the dates of the last frost in seven months' time (Figure 4.6).

Similarly a consistently negative SOI value during late autumn signals that the pattern has set, and that the probability of receiving a late frost is much higher than if the SOI had been positive.

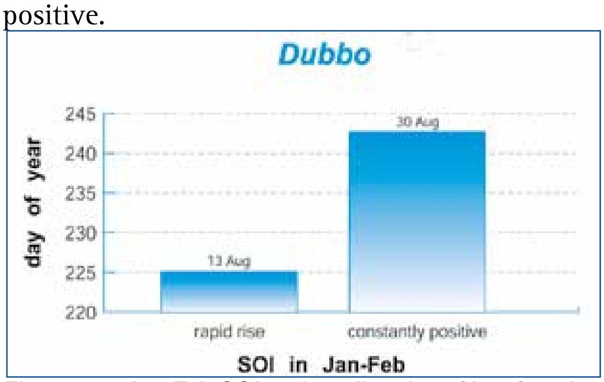


Figure 4.6. Jan-Feb SOI and median day of last frost in August at Dubbo

Water for plant growth

A consistently negative SOI in spring is linked with lower rainfall and higher evaporation in summer. Together, these have a synergistic effect on how much water is available for plants.

To illustrate this in a simple way, we can estimate how many days rain-water would be available for plant growth at Emerald by dividing the average seasonal rainfall by the average daily rate of evaporation (Table 4.7).

Table 4.7. Water for plant growth at Emerald

Spring SOI	Summer rainfall (mm)	Evap. (mm/day)	Days water will last
Above +5	540	7.5	72
Below –5	385	8.5	45

Using the SOI improves the estimate of probability of receiving rain, but cannot predict future rainfall with total reliability – there are too many other factors involved. Sometimes heavy rain may fall because of a single event such as a rain depression following a tropical cyclone, or from a heavy localised thunderstorm – two of the unpredictable causes of local rain described in Chapter 2. Climatologists are currently refining the relationships between climate, the SOI and SSTs, and other drivers (see Chapter 7); in the meantime, the SOI has enough reliability to influence many decisions based on the climate.

Summary

Over the last hundred years, the Southern Oscillation has had a strong influence on: rainfall, number of wet days, arrival of the wet season, runoff, streamflow, cloud cover, temperatures, humidity, evaporation, frosts and frequency of cyclones.

No climate forecasts can ever be one hundred percent accurate; there are too many other factors involved.

Meanwhile SOI forecasts represent as probabilities more than a century of experience – 'this is what has happened in the past whenever the SOI has been in this state'.

SOI-based forecasts could be more accurately described as 'conditional probability hindcasts.

5. Plant growth and ENSO

ENSO has a strong influence on weather in eastern Australia – not only on rainfall, but also on evaporation rates, humidity, radiation and the incidence of frosts. As these aspects of climate affect plant growth, we can model how the growth of crops and pastures can be related to the SOI.

The lack of green vegetation and ground cover over east Australia in an El Niño year (Figure 5.1) illustrates the effect of failure of the wet season.

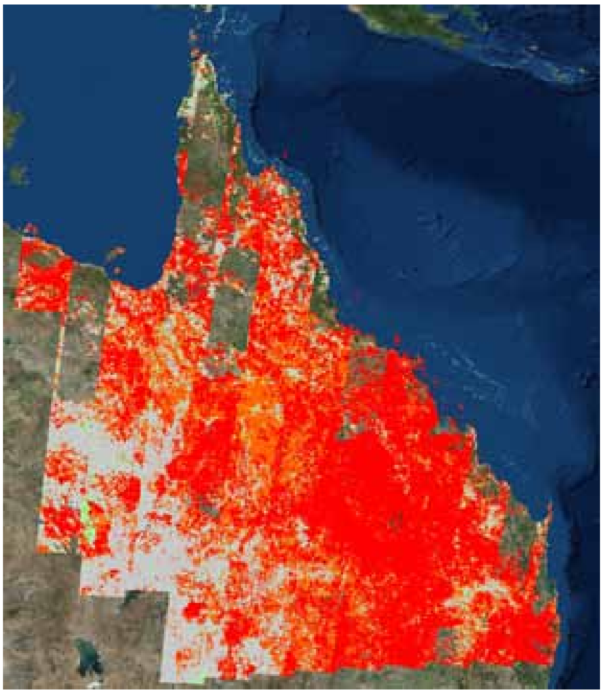


Figure 5.1. Lack of green vegetation over eastern Australia during the 2002–2003 El Nino is indicated by bare ground (red pixels) in this Landsat imagery.

SOI and crop yields on the farm

We can calculate potential yields of summer and winter crops using crop growth models. If the SOI can be used to predict changes in climate in the crop's growing season at that location, it can be used to predict likely changes in yield.

Modelling, such as with the APSIM crop model, can show the probability and magnitude of the effect, and hence whether it is reasonable to consider the SOI when making management decisions (e.g. using CropARM decision support). This chapter gives examples of the influence of the Southern Oscillation Index on yields of crops and pastures. The growth of winter crops uses SOI phases in autumn since the Southern Oscillation frequently changes at that time of year; growth of summer crops can be estimated using SOI averages in spring and this is often used here to simplify figures.

Crop and pasture modelling

Modelling plant growth allows us to calculate yields at any location and in any year with the model results being validated in the field.

A simple plant growth model might look at the effects of soil moisture, temperature and solar radiation on growth of an individual plant; more complex crop models may calculate how plant spacing, soil nutrients, leaf area, rainfall use efficiency (including losses through run-off and evaporation) affect yields of grain.

To check the effect of the SOI on plant growth, we need to see which aspects of climate relevant to plant growth are influenced by the SOI (for example, rainfall, radiation and humidity), and by how much. We can then test the likely changes while keeping other factors constant.

The likely differences in summer rainfall in eastern Australia between years with strongly negative or with strongly positive spring SOI have been shown in Figure 4.4 in the last chapter. From this, we can calculate the overall regions (Figure 5.2) that could grow a crop of sorghum yielding more than 1 tonne per hectare under these different SOI classes. Since 1 t/ha is a marginal yield, much land classified as 'suitable for cropping' may not grow a profitable crop when the SOI is negative.

Such broad correlations of the SOI with rainfall, and rainfall with agricultural production over whole regions do not allow for the variability in local rainfall. A different approach is needed for most on-farm decisions.

Models of growth of crops and pastures are described in more detail in Chapter 6.

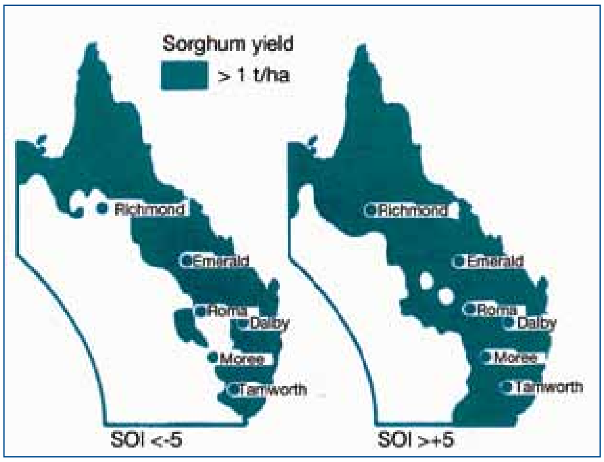


Figure 5.2. Potential area receiving enough rainfall for growing sorghum is influenced by the spring SOI.

Sorghum in southern Queensland

Growth of a summer grain crop (sorghum) was simulated, and yields estimated from the rainfall and climate recorded at Dalby over a hundred and forty-five years. The yields for each year were ranked from lowest to highest and chances of getting above the middle (median) value were calculated for each SOI class.

The median yield of sorghum over all years was 5.3 t/ha (Figure 5.3). When the average SOI value over the preceding season (spring) was above +5, the average yield was 0.9 tonnes higher; when the SOI was below −5, it was 0.5 tonnes lower.

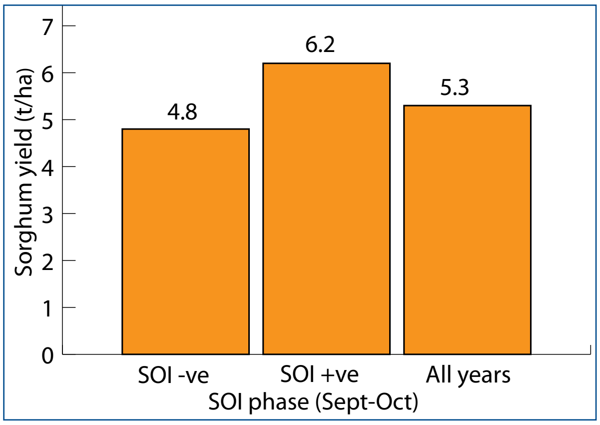


Figure 5.3 Yield of summer sorghum after spring SOI

Wheat on the NSW-Queensland border

Yields of a winter crop (wheat) have also been simulated from data from over a hundred years at Goondiwindi. Wheat yields (with a two-thirds profile of soil moisture) in all years averaged 2.9 t/ha. When the SOI was negative in autumn, the yield averaged only 2.4 t/ha; when it was positive, the average was 3.4 t/ha (Figure 5.4).

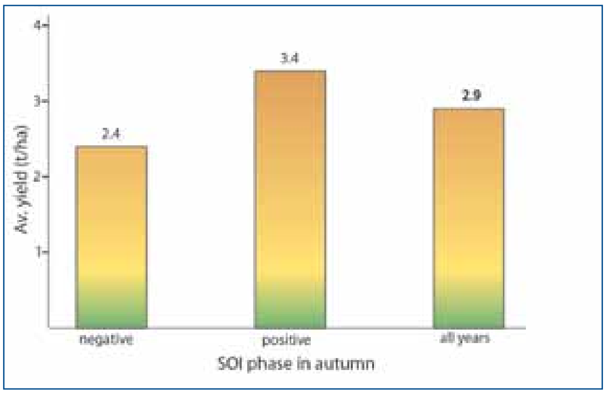


Figure 5.4 Yield of winter wheat after autumn SOI

As the Southern Oscillation usually flips during autumn, the average value of the SOI over that season may be less reliable than whether the SOI is rising or falling. Soil moisture after a fallow may over-ride the effect of the SOI (Chapter 6).

SOI and pasture growth

Pastures in southern Queensland

SOI-based seasonal forecasting can be applied to summer pasture growth with lead times of up to three months. Spring-summer pasture growth was 20% below the long-term median following a negative SOI in winter or spring, but 26% above following a positive SOI.

Modelling has been used to study how the SOI can affect the length of the growing season of native pastures. Table 5.1 illustrates the effect of the SOI on rainfall and evaporation over the growing season of native pastures in the upper Murray-Darling Basin in southern Queensland.

Some possible opportunities for using seasonal forecast information to target specific pasture management decisions include: adjusting the seeding rates and pasture species; choosing the months for establishing pastures; choosing the time of year and extent of operations when burning for pasture renovation and woody weed control, and adjusting stock numbers and therefore grazing pressure on pastures.

Spring pasture growth in S.E. Queensland

The chances of getting various yields of spring pasture are presented in Figure 5.5. The vertical line in this figure shows the probability of pasture growth exceeding 600 kg/ha during spring for different classes of the SOI. In years when the winter SOI was above +5, the probability rose to 81 per cent, but it dropped to 36 per cent in years when the SOI was below −5.

Table 5.1. Effect of ENSO on duration of pasture growing season (as assessed by simple water balance)

Average SOI in winter (Jun–Aug)	Early summer rainfall (Oct–Jan) (mm)	Evaporation – Class A pan (mm/day)	Duration of pasture growth (days)
Above +5	316	7.1	90
Below –5	250	7.8	64

Thus avoiding burning when the winter SOI is below –5 would reduce the risks of over-grazing and of running out of feed.

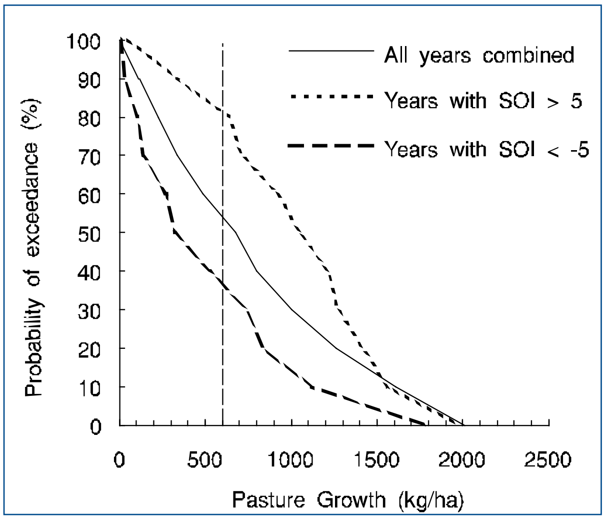


Figure 5.5. Spring pasture growth after winter SOI

Summer pasture in north Queensland

In the Charters Towers district, a conservative stocking rate for cleared land is one steer on 5 hectares. Even at this stocking rate, at least 1.2 t/ ha of pasture growth are needed during summer to maximise beef production without damaging the pasture through overgrazing.

Figure 5.6 shows how the spring SOI can alter the percentage of years in which the growth of grass during summer is less than 1.5 t/ha or more than 4.2 t/ha.

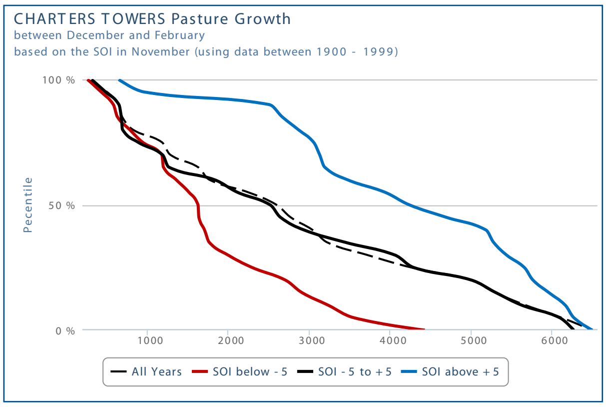


Figure 5.6. Probabilities of summer grass growth after spring SOI

SOI and animal production

The effects of the Southern Oscillation on native pasture production can be carried further to sown pastures and forage crops, and to animal production. In the brigalow region, for example, twice the number of cattle can be carried on forage sorghum in years when the SOI is strongly positive than when it is negative.

Graziers should try to keep their stock numbers at levels that allow them enough feed in 80% of years. Although this conservative stocking rate dampens the impact of rainfall variability, cattle growth rates are still altered between the opposing classes of the SOI.

The differences in pasture growth at Charters Towers shown in Figure 5.6 result in a difference of almost 40 per cent in the weight gains of steers, despite the conservative stocking rate. This difference is shown in Figure 5.7. Differences would be much greater at current commercial stocking rates.

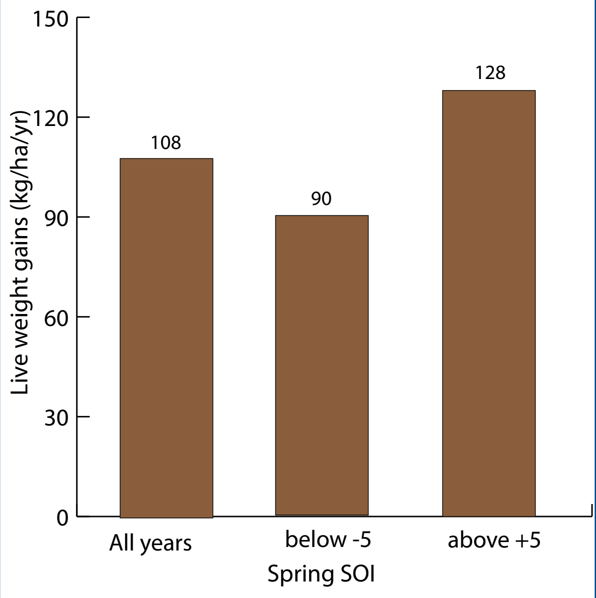


Figure 5.7 Liveweight gains of cattle over summer after spring SOI

6. Decisions – application of seasonal forecasts

From data to decisions

While the Bureau of Meteorology has been responsible for the collection and storage of climate data over Australia, changing that data into information for agricultural and pastoral management and planning has been led by state and university departments of agriculture, often with federal or industry funding. Much of the research into developing information for the application of seasonal forecasting was started by the Queensland Government Industries.

Modelling growth of native pastures for the management of pastoral lands was developed by the Queensland Department of Natural Resources while models for crop growth were developed with the APSIM Initiative Joint Venture in Toowoomba.

Other products from these organisations included the Rainman StreamFlow climate analysis program allowing individuals to look at their historical rainfall data and to assess the value of SOI-based seasonal forecasting at their location; the development of the pasture model GRASP to study the effect of our variable climate on the growth of native pastures; AussieGRASS to provide vegetation mapping available on the internet; and the development of the APSIM crop growth model for incorporation into the crop management decision support program CropARM

Decisions and risk

Any method of reducing the risk involved in a management decision affected by climate is useful, and farmers, graziers and businesses can make more efficient decisions if they have a better assessment of the forthcoming season. Risk should be looked at from the whole-farm perspective rather than as a single crop decision.

Everyone has a different attitude to risk – some are cautious, others are happy to gamble – and how any manager reacts to the use of seasonal forecasting will be an individual decision based on numerous other factors often including personal experience.

Farmers tend to be conservative and are generally more averse to the risk of losing money than to the chance of making a fortune.

While some managers may wish for an earlier – but less reliable and less skilful – forecast, this brings a proportionally greater level of risk, and is likely to eventually result in a loss of faith in the value of seasonal forecasting.

Forecasts that do not present a statistical measure of their level of skill should be ignored.

This chapter gives some examples of the application of seasonal forecasting. It is based mainly on the use of the SOI because this has a strong relationship with the weather in eastern Australia, and it enables historical comparisons between weather records and agricultural production.

Living memory versus history

Many producers prefer using their personal experience – 'living memory' – rather than the full historical records of more than a hundred years. They then regard any conditions outside of this 'memory' as abnormal and, in times of hardship, sometimes may request government assistance. 'Living memory' tends to represent a period of about 60 years.

Programs such as Rainman, which can present local full historical records with ranking of extreme periods, help to overcome such selective memory.

Decision support programs

Plant growth models are used for decision support to help reduce the risk associated with our variable climate. They are especially useful for encouraging discussion of the options available when allied to a system of seasonal forecasting.

Cropping modelling

CropARM (Crop Agricultural Risk Management)

Farmers working under a widely variable rainfall have to make critical management decisions before each cropping season.

CropARM is a decision support tool based on crop modelling to help growers consider and discuss their exposure to risk under different management options. The crop simulations use more than 115 years of climate records to predict potential year-to-year variability in yield and allow the effect of different levels of inputs to be compared under a current seasonal climate forecast.

The management factors that can be examined include:

- crop type – wheat, chickpeas, sorghum, mungbean, sunflower, cotton, and maize
- effect of stored soil water at planting fallow
- sowing date
- maturity length
- plant population
- row configuration
- effect of soil nitrogen
- nitrogen fertiliser rate (sowing and in-crop)

CropARM can provide some twenty output options, including crop yield, water use, days to harvest as well as temperature stress indices (e.g. frost/low temperatures around flowering). It allows a producer to study the effects of the SOI phase and includes a simple gross margin calculator.

Associated risk management tools for crops on the internet include the interactive programs FallowARM and NitrogenARM.

Pasture modelling

Plant growth models can be used to calculate grass growth with all the interactions between grass, trees and grazing cattle.

GRASP

The most sophisticated model for the growth of tropical native pastures is GRASP.

GRASP uses five key components:

- daily weather (rainfall, temperature, radiation, vapour pressure and pan evaporation)
- soil characteristics (such as water-holding capacity and soil fertility)
- vegetation characteristics (such as grass basal area, pasture condition, species composition, tree density, decay of green biomass to litter, and losses in biomass through litter decomposition, animal intake, land clearing and fire)
- animal impacts (through effects on intake, pasture condition and trampling losses)
- management influences (land clearing, pasture establishment, fire and grazing management).

GRASP predicts the effects of these components on:

- the water balance (runoff, infiltration, soil evaporation, transpiration and drainage)
- pasture growth (green growth, death and detachment)
- animal intake (diet selection, utilisation and live weight gain)

GRASP modelling is used in the AussieGRASS model which looks at the condition of native pastures across the continent.

AussieGRASS

AussieGRASS provides a 3-month forecast of grass production across Australia down to a 5-kilometre grid scale, and has been used by land managers, fire management agencies and policy makers for more than 15 years.

AussieGRASS uses the following data:

- climate data from the SILO database
- livestock numbers from Australian Bureau of Statistics
- macropod (kangaroo and wallaby) and feral animal numbers from state government agencies

- soil data based on the Atlas of Australian Soils (with some calibration from the Australian Soil Resource Information System)
- tree density (remotely sensed)
- fire scars from Landgate, WA
- calibration data from the field such as rapid mobile data collection along with NOAA, MODIS, LANDSAT, radar and gravity satellites and miscellaneous sources such as inflows to dams.

Maps include current total standing dry matter, areas of grass ground cover and fire risk. AussieGrass maps are updated monthly, but can also provide experimental forecasts up to six months ahead based on the International Research Institute's consensus forecasts of ENSO state. Rainfall, pasture growth and many other maps are freely available on The Long Paddock web site.

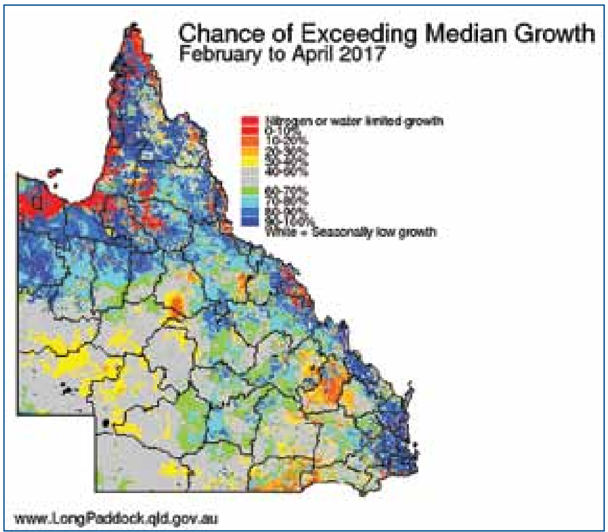


Figure 6.1. 3-month forecast of pasture growth (as moderated by SOI phase) from LongPaddock

Better decisions for cropping

Summer grains

Which crop? – The chances of crop failure are much higher with a strongly negative SOI than with a positive one in double cropping areas, especially if there is less than 60 cm of stored soil moisture. **Is there a less risky crop?** Dry-land cotton may be too risky when the SOI is negative, it needs more water and costs much more to grow than sorghum. Sorghum is always preferred over maize as the summer crop for lower rainfall areas and is less risky during an El Niño year.

With some crops, the farmer can allow for expected lower or higher rainfall by choosing a more suitable plant population – using a higher seed rate with a positive SOI and skip row configuration or a lower seed rate with a negative SOI.

Yield and profit – Crop modelling (Chapter 5) has calculated the average yield of sorghum at Dalby in southern Queensland as 5.3 tonnes/ha. Yield increases to 6.2 tonnes when the spring SOI is positive but decreases to 4.8 t/ha when the SOI is negative.

The effects on profit are more pronounced than effects on yield. If it costs $150 a hectare to grow and harvest a crop of sorghum, a small change in yield can have a large effect on the gross margin. For example, if sorghum sells for $225/tonne an average crop of 5.3 t/ha provides a gross margin of $715/ha, a 6.2 tonne crop a margin of $880/ha and a 4.8 tonne crop only $625/ha. The difference in yield between the positive and negative classes of the spring SOI may be about 30% but the difference in gross margin is 40%. This can become even more serious in crops that have higher costs of production.

Winter grains

In wheat-producing regions of eastern Queensland, likely yields of crops are estimated on winter rainfall which is strongly influenced by ENSO (see Chapter 4).

In the Maranoa district of southern Queensland, three-quarters of total profit from wheat over a 10-year period came from only three good years while farmers made either no profit or a loss in three other years (Figure 6.2). The profit years were associated with rising or positive SOI values in autumn, the loss years with falling or negative SOI values.

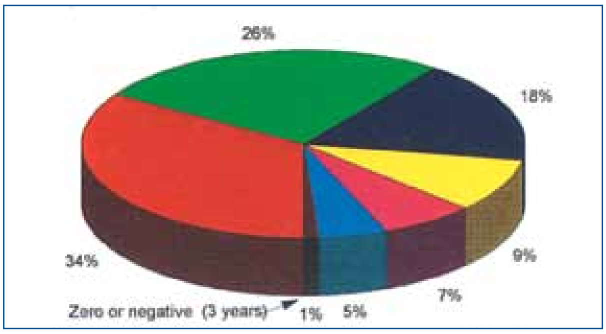


Figure 6.2. Profits from wheat at Roma – with sections for each profitable year; 75% of profit in 3 good years

Which crop? – Choice of crop may depend on commodity prices, but also on available soil moisture and likely in-crop rainfall. Chick peas are a profitable rotation crop with winter cereals but are susceptible to disease under wet conditions in a La Niña year.

Which wheat variety? – Wheat growing in Queensland is complicated by the fact that early planted crops produce higher yields but may be knocked by frosts during flowering, while late crops are harvested into the beginning of the summer rainfall period. Early-, mid- or late-maturing varieties should be selected depending on likelihood of a late frost.

Yield – Winter crops grown in regions with heavy clay soils having high water-holding capacity rely greatly on summer rainfall stored during the fallow. The influence of the SOI on winter rainfall may be less important here than the amount of water stored; it is small with a full profile of moisture but larger when yield has to rely on in-crop rainfall (Figure 6.3).

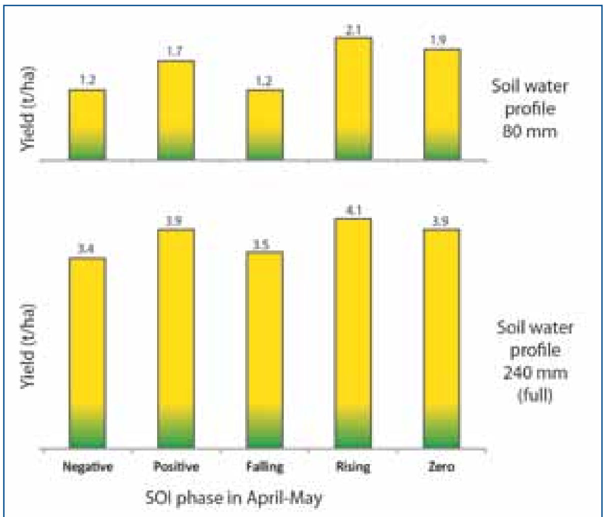


Figure 6.3. Median wheat yields, based on the SOI April–May with soil profile one third full of water (top) and full (bottom).

While the median yield used in Figure 6.3 for illustrative purposes shows a reasonably defined response to the SOI, CropARM output presents the full ranges of yields over the hundred years of climate data and provides a better overview of risk (Figure 6.4).

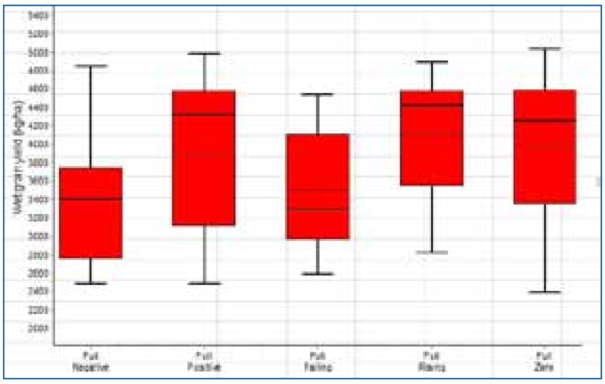


Figure 6.4. Wheat yields based on a hundred years of rainfall data. The red block shows yields between the 25% and 75% probabilities, the solid line the median yield, and the extremes as outliers.

Fertilising – Higher rates of nitrogen fertiliser may give higher gross margins – but with a greater risk.

The best amount of fertiliser to apply to a growing crop can be calculated for a given level of risk. An example has been calculated for a wheat crop planted on a soil at two-thirds moisture capacity at Goondiwindi. Instead of applying a standard dressing of 50 kg of nitrogen per hectare every year, applying tactical dressings based on the SOI in the two months before planting is worth an extra $20 per hectare per year overall (Table 6.1).

When gross margins from tactical dressings are compared with fixed dressings each year, there is a small chance of making less money but a good chance of making much more (Figure 6.5).

Planting opportunities and weeds – Baked dry soil cannot be tilled before planting while wet soil will not stand traffic while the crop is growing. Weed control can be a problem in a wet season although this is reduced with zero-till and tram line farming systems. Under wet conditions, the higher incidence of insects and

Table 6.1. Example of overall benefit from basing fertiliser on the SOI phase in autumn at Dalby

	Every year	Tactical fertilising						
	Av. GM ($/ha) from 50 kg N every year	N (kg/ha) applied according to SOI phase in April-May					Av. GM ($/ha) from tactical application	Benefit to tactical N application $/ha/yr
		SOI –ve	SOI +ve	SOI falling	SOI rising	SOI zero		
N (kg/ha)	50	25	75	25	100	50		
Gross Margin	$424	$281	$523	$289	$465	$462	$444	$20

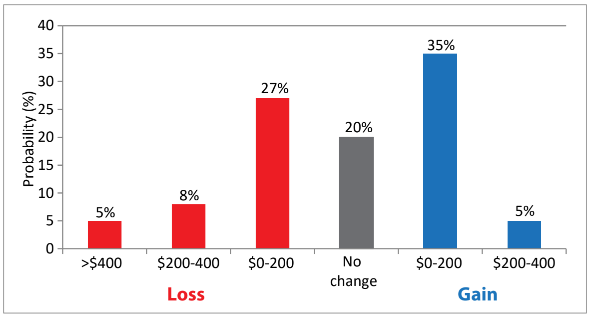


Figure 6.5. Probability of benefit ($/ha) from applying nitrogen fertiliser according to the SOI instead of applying 50 kg N every year.

plant disease may need extra insecticide or fungicide.

Bushels or bales? – If a cereal crop is faltering in dry weather and the chances of dry weather becoming a drought are high, it may be more profitable to graze or bale the foliage than to try to harvest shrivelled grain. The demand for forage will increase as the drought deepens.

Irrigating – Does the dam or the irrigation equipment have the capacity to irrigate the sown area without help from rainfall and during increased evaporation associated with a low SOI? Will the dam surface water evaporate more quickly, will the local creek flood sufficiently to allow water harvest or will there be enough run-off to fill the dam during the wet season?

When a low SOI in spring suggested that the drought would continue, many farmers in southern Queensland, who normally use irrigation to top up rainfall over a large area of cotton, restricted their planting to an area that they could irrigate fully for the whole season.

Would a more water-efficient irrigation system be worthwhile? Capacities for irrigation should be checked using probabilities of rainfall based on the SOI rather than average figures.

Sugar industry

Sugarcane is grown along the east coast in regions strongly affected by ENSO. As it needs about 1.5 metres of rain each year, over 40% of Queensland sugar receives full or supplementary irrigation depending on the region's average or actual rainfall.

Sugarcane has a typical cropping cycle of one plant crop and 3-4 ratoon crops so that crop management decisions may be limited to times of planting, spraying and harvest (as affected by mediium term forecasts and the passage of the MJO), and to amount of irrigation required and to levels of fertiliser applied (as affected by seasonal forecasting based on ENSO or GCMs.) Insufficent water will reduce sugar yield while high fertiliser levels with excessive water from rain or irrigation can lead to nutrient run-off and associated damage to the Great Barrier Reef.

Seasonal climate forecasts can help in machinery investment planning to determine the appropriate mix of wet and dry weather harvesting equipment, and also to support millers and growers in planning the start of the harvest to optimise the harvest season.

Better decisions for livestock

Beef production is a long-term operation that is not easy to change rapidly. A beef production cycle may be three to four years from mating to the sale of marketable stock. Over this time period, ENSO may well have gone through much of its oscillation cycle between El Niño and La Niña.

As an El Niño may follow an average or better year, there may be sufficient feed in the paddock to keep all stock until the end of the dry season after which the break and subsequent wet season are critical for animal and grassland condition. By August-September, an ENSO state should have established and seasonal forecasting can be used to predict the probabilities of the amount of wet season rainfall and the timing of the 'green break of the season' which can vary by up to 6 weeks.

Most of northern Australia shows a reasonable forecast for November–March rainfall as early as September, thus management decisions covering the coming wet can be applied at the time of the second muster.

Stocking rates

How should the number of stock (the stocking rate) be altered to cope with the forthcoming season? Too many stock on too little grass may result in mortalities and will cause damage to the pasture base that could take years to recover. Having too few animals wastes feed and loses potential income, but may allow native grasses to set good seed and recover, and later carry a fire to control woody weeds.

Decision support programs such as Stocktake Plus help graziers choose suitable stocking rates

for their type of country by integrating animals, grass and trees. (http://www.stocktakeplus.com.au/)

Buy or sell? – Should a grazier buy more cattle or sell more, and which class of stock should be sold first while other districts still have grazing? Should stock be sent on agistment for a few months – which may stretch out to a year – or sold to the meat works? Sell the steers as stores or start an opportunity feedlot? Order or forward buy the feed for the lot in case the price rises too much in the drought? Early wean and yard-feed the young calves so the cows will not lose too much condition and fail to get back into calf, or even die? Generally supplements should be fed for survival, not for production.

There can be no generalisation about which class of animal to sell. It will be that which will do least damage to future income, whether from the cost of feeding supplements to keep stock alive, the loss of income for two to three years after selling young stock or the cost of replenishing the breeding herd when the drought finishes.

BBSAFe (Breed, Buy, Sell, Ajist, Feed evaluator) is a program that helps evaluate the benefits or costs of these listed options. The effects of management decisions on cash flow over coming years can also be calculated using modules such as 'Bullocks' and 'CowTrade' in Breedcow/Dynama.

On extensive northern beef properties where mustering is time-consuming and costly, one of the problems with using seasonal forecasting in management planning each year is that most herd decisions have to be made during the main or first muster around April-May. However, autumn is the most unstable period for ENSO – when the SOI year could change from or to a negative, positive or neutral phase, As forecasting becomes less and less reliable as the lead time lengthens, April-May is generally too early to predict reliably the break of the next wet season six months away or its subsequent strength.

Thus a management programme needs to monitor the grass feed available in the paddock at the time of muster, and do a feed budget to estimate how long it will last at the current level of stocking. The breeding herd should be segregated on foetal aging at pregnancy diagnosis so that stock potentially for sale can be moved quickly if conditions do not improve.

Harder decisions on herd management on these extensive beef operations can be made at the time of the second muster around September when the seasonal forecast is more reliable.

On more intensive beef properties, herd management decisions can be made more quickly, and appropriate action can be taken as soon as an ENSO alert is given – as early as June or July.

A broad-scale map (Figure 6.6) showing the likely onset of useful rain over tropical far north Australia is available on the BoM web site (www.bom.gov.au/climate/rainfall-onset/).

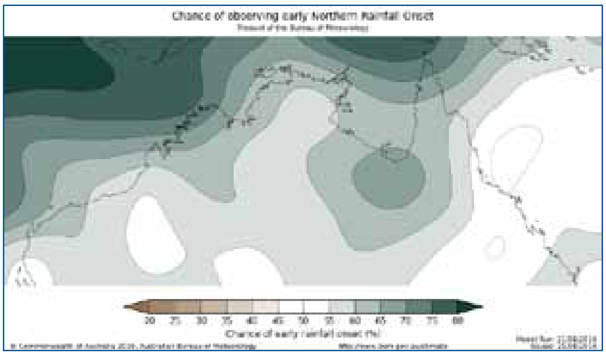


Figure 6.6. Example of BoM map showing the probability of 'break of season' rainfall being earlier than normal.

Planting pastures – Planting improved pastures, or oversowing legume seed into native pasture, is a major expense. Many graziers on extensive properties do not sow seed because of the high risk of failure through subsequent poor rainfall. In marginal rainfall districts, seed should be sown only in years with positive or rising SOI. Figure 6.7 shows how the SOI in December affects the mean number of planting opportunities in the main planting season of

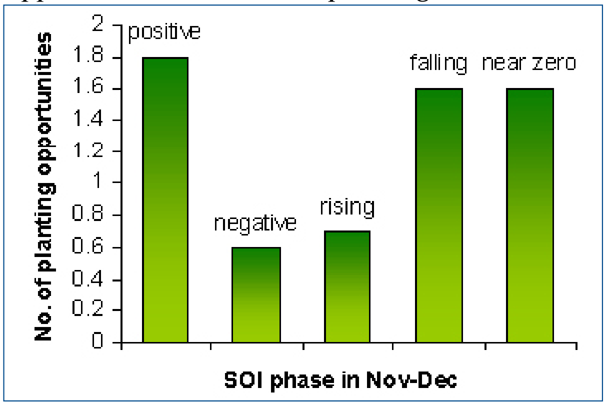


Figure 6.7. Pasture planting opportunities at Roma in January-February, based on December SOI

January-February in the Maranoa district of southern Queensland.

Burning – Native pastures in higher rainfall districts are frequently burnt in spring to remove old, dead leaf and to control regrowth of woody plants. If there is insufficient follow-up rain or a poor wet season, there may not be even poor quality roughage to sustain cattle.

For example, the risks of running short of feed during summer in the Gayndah area of south-eastern Queensland as influenced by the SOI in winter (June-August) are illustrated in Table 6.2.

Table 6.2. Risk of feed shortage after burning in spring

Jun-Aug forecast	Risk of feed shortage over next summer if pasture is burned in spring	
SOI falling	50%	1 yr in 2
SOI rising	10%	1 yr in 10
All years	25%	1 yr in 4

Diseases – If the season is likely to be especially wet, the producer needs to budget for vaccination against 3-day sickness; ticks can spread into tick-free regions and fly strike in sheep will increase.

Better decisions for agribusiness

A forewarning of the coming season allows managers of other businesses to buy equipment or stock that may be needed.

Merchandise – Agricultural agents, manufacturers and importers have to carry enough stock to meet demand without having it sitting on the shelf for too long. The demand for all agricultural chemicals – herbicides, fungicides and insecticides – will depend greatly on the season, as will the demand for fertilisers, animal health products, feed supplies, irrigation equipment and seeds of pastures and crops.

Graziers may look at buying in fodder or supplements while they are locally available if they do not want to sell animals with a drought expected.

Machinery – Machinery plant operators can estimate the likely demand for crop or sugarcane harvesting, clearing regrowth timber, blade ploughing or bore drilling, while spraying contractors can judge whether they can service the likely area with their existing plant.

Machinery suppliers can expect greater demand for new equipment in a year with a positive SOI.

Construction companies may need to increase downtime due to wet weather or flooding. Mining companies in central Queensland have stockpiled resources in case of the mines flooding.

Better decisions for planners

Water resources – BoM puts out 'Seasonal Streamflow Forecasts' while the Rainman StreamFlow analysis program can be used to study the effects of the SOI on seasonal stream flow. This would help water-usage planners to decide how much water to release from storage for irrigation, power generation, recreation or the environment (see Chapter 3).

Marketing – Merchants and commodity traders need estimates of crop yields and storage requirements while understanding how the SOI affects crop production in other parts of the world and hence world prices.

Extension – State departments of agriculture can plan timely extension or drought management programs to deal with the problems of unusually long dry or wet conditions.

Treasury – Climate forecasting should be used to inform state and federal government planners for forecasting the rural outlook and hence for Treasury budgets, for drought declarations and revocations, and for planning government assistance and services.

Drought monitoring

Governments like to be able to define droughts so that appropriate assistance can be provided.

Various indices can be based on rainfall and evaporation, for example a Standardised Precipitation Evapotranspiration Index (SPEI). This is based on local climate recordings and can be compared to satellite maps of modelled regional pasture growth and modelled growth relative to historical records (Figure 6.8).

The Queensland Government drought monitoring system for the grazing industry issues 'Pasture alerts' based on a number of inputs (Figure 6.9).

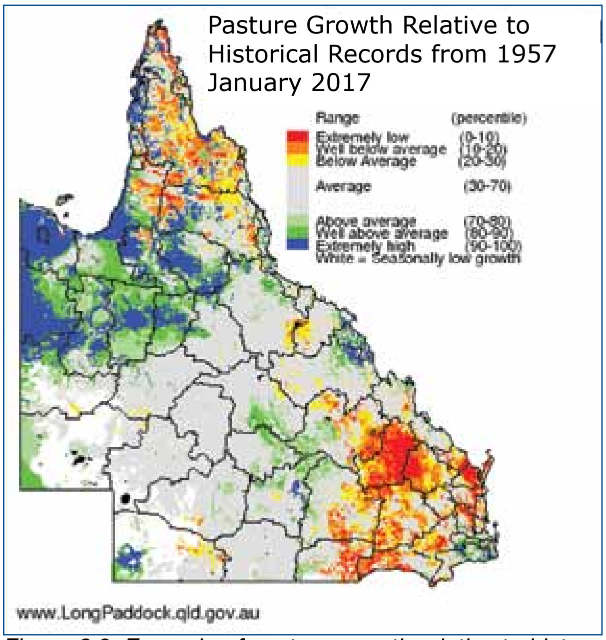


Figure 6.8. Example of pasture growth relative to history

These include: satellite data and images of current vegetation which show the current state of pastures; GRASP growth models using the SOI, the expected pasture growth, and the likely grazing pressure from the livestock population and its effect on ground cover.

Risk management – SOI and ISO

The Australian Standard for principles and guidelines on risk management has been accepted as the International Standard ISO 31000.

The five basic steps, which include risk from climate variability and change, (Figure 6.10) encourage informed choices by identifying priorities and selecting the most appropriate action.

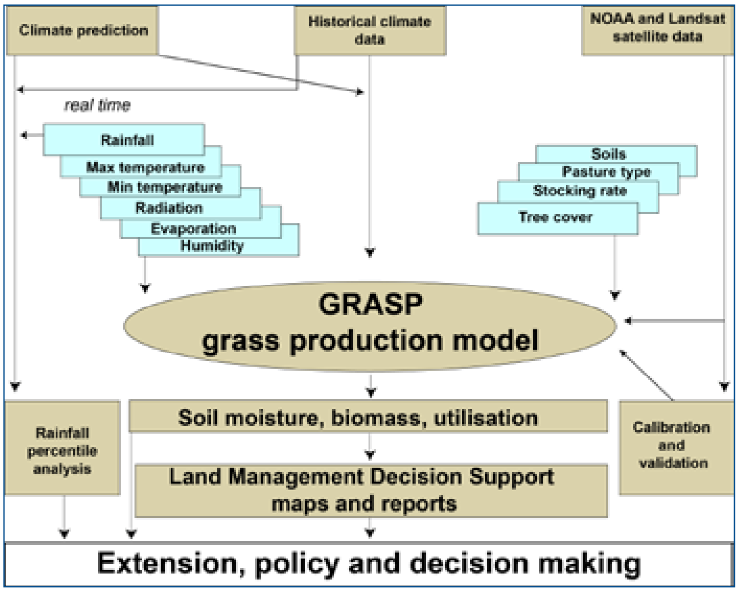


Figure 6.9. Schematic diagram of the inputs into the drought monitoring system

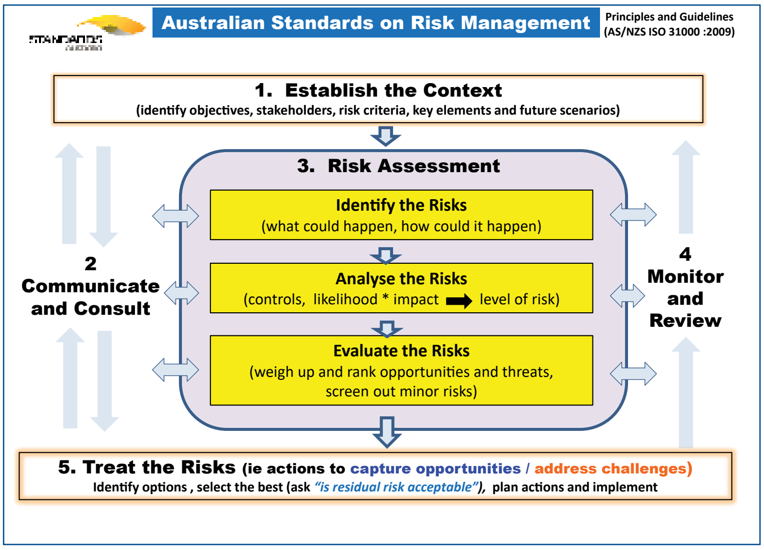


Figure 6.10. Integrating climate information into risk management. Standards Australia, AS/NZS ISO 31000

Hydro cycles on human stress

The cycles of good and bad years are part of crop and animal production in much of Australia, and most producers incorporate them into normal management. They can plan to manage drought lasting for one year but their system can become highly stressed by extended droughts.

In the hydro-psychological cycles (Figure 6.11), rainfall drives the cycle of plant growth and hence crop or animal production. This drives cycles of financial strain and ultimately of psychological stress on individuals and their families. Some producers are forced from their land by indebtedness, other families suffer more permanent damage before some sort of recovery.

Summary

Many management options in the agricultural and livestock industries are greatly affected by our variable climate. Seasonal climate forecasting can help to reduce risk with a better informed decision, and these decisions can be aided with the use of computer-based decision support programs.

Decision support programs are often as valuable for encouraging discussion between groups of producers as for providing any definitive answers.

Seasonal climate forecasting will always be probabilistic, and the ultimate management decision is a personal one.

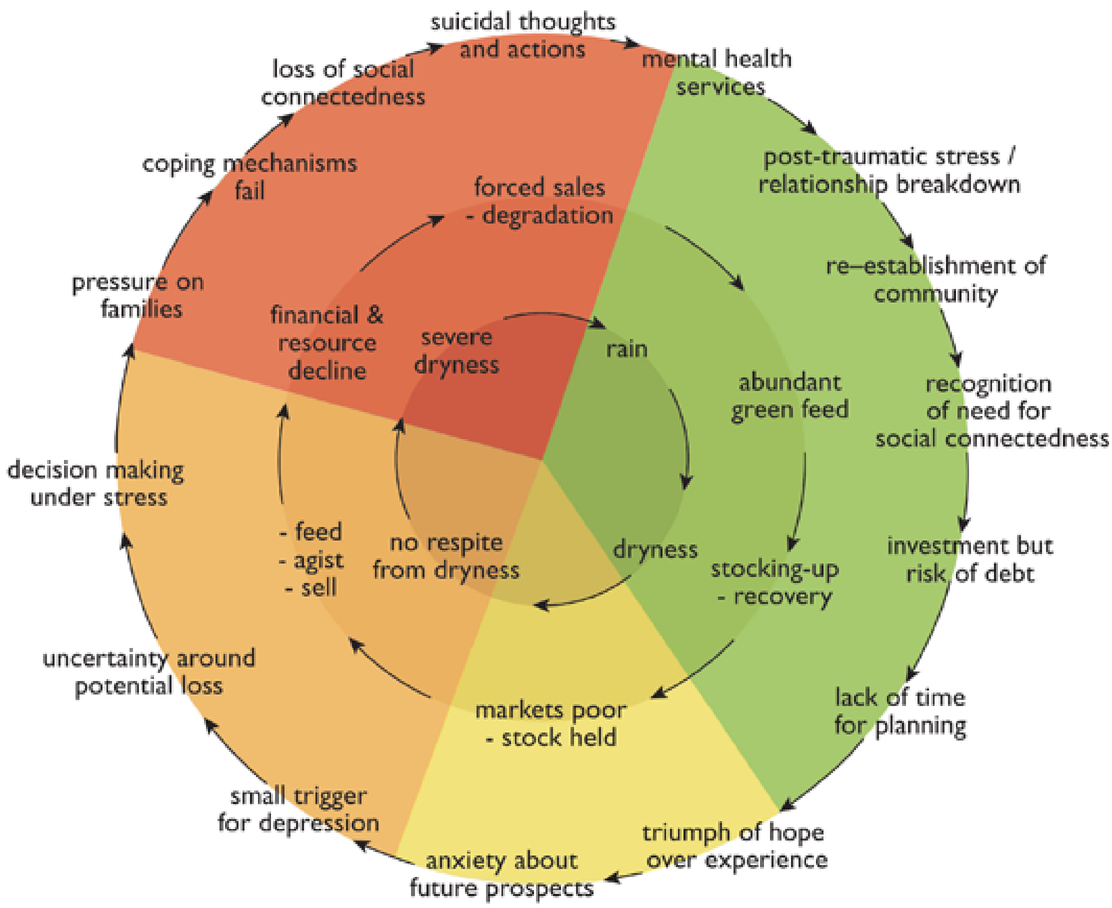


Figure 6.11. The Hydro-Cycles of rainfall (inner), production and income (middle) and psychological stress on families (outer) as conditions cycle from wet (green) to drying (yellow-red) and back to wet.

7. Seasonal climate forecasting

The science of seasonal forecasting is developing rapidly as the many interactions of atmosphere and ocean are better understood, and as more powerful computers allow complex calculations to be made quickly. However, the most important component for forecasting seasonal conditions is still ENSO – and its basic determinants; these include the pattern and strength of winds over the equatorial and southern Pacific and the temperatures of the ocean water. New indicators or drivers for seasonal conditions are being incorporated into forecasting techniques.

Many countries are involved in seasonal forecasting: in Australia, the Bureau of Meteorology, CSIRO, universities and state agencies; in the USA, by a number of centres including the International Research Institute for Climate Prediction (IRI), the National Oceanic and Atmospheric Administration (NOAA), the National Weather Center, and the National Center for Atmospheric Research; in Europe, by the European Centre for Medium-Range Weather Forecasts (ECMWF) and the UK Met Office; in Japan, the Japan Meteorological Agency. Many countries, such as India and Indonesia, issue more regionally-focused forecasts. The Queensland Government and more recently the International Centre for Applied Climate Sciences at the University of Southern Queensland have led the way in the application of seasonal forecasting to agricultural and grazing industries.

Types of forecasts

There are basically two main types of seasonal forecasts – statistical and dynamical.

Statistical forecasts

Statistical forecasts look at long-term historical records of the SOI and of rainfall (or any other climate data). Records of the SOI go back to 1876 while some rainfall data in Australia go back even further. The records are then correlated to see whether nominated values of the monthly SOI (say +5 or –5) are related to heavier or lighter monthly rainfall.

Statistical tests show values of the relationship may be real or just due to chance; 90%, 95% or 99% statistical confidence in a relationship can be accepted as real or skillful – values below this should be ignored.

The best examples of local detailed statistical forecasts with statistical validation can be found in programs such as Rainman StreamFlow available for your PC or the interactive ClimateARM on the web.

> Statistical forecasts might be better referred to as conditional hindcasts.

Forecast probabilities are always below absolute certainty because there is always a chance that a single weather event may ruin the climate relationship in a single year.

Value of SOI forecasts

ENSO is the most powerful driver of the Australian climate but does not have a universal influence on all regions and in all seasons; thus it cannot always provide skill in seasonal forecasting. Its strongest influence is on the eastern side of the continent, but many other regions may be affected at certain times of the year. An example of a map showing the regions of Australia where the Southern Oscillation influences rainfall in a season, and hence where the SOI has value, is shown in Figure 7.1. However, there may still be large regional and local influences, and the usefulness of the SOI to forecast local rainfall can be determined by using statistical forecasts with local data.

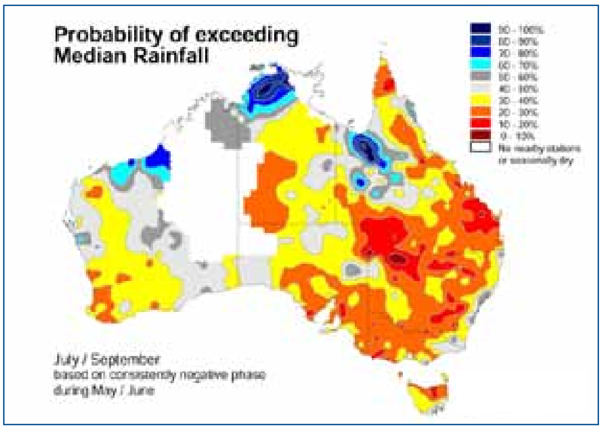


Figure 7.1 Example of a statistical seasonal forecast for Australia based on phases of the SOI

World-wide SOI forecasts

The Pacific Ocean covers such a large proportion of the Earth's surface – almost one third – that ENSO influences, through teleconnections, the climate and rainfall in many parts of the world.

World-wide rainfall data can be analysed to provide detailed maps of the probabilities of exceeding median rainfall based on the SOI phases (Figure 7.2).

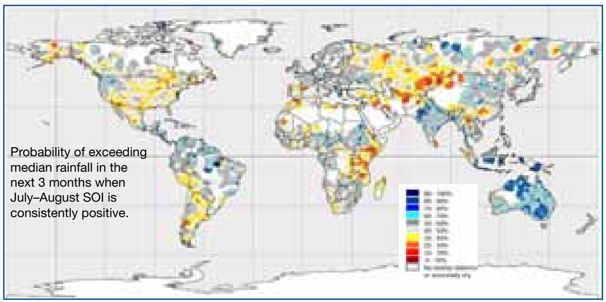


Figure 7.2. Example of a statistical seasonal forecast for the world based on phases of the SOI

Climate monitoring and ENSO

Climatologists keep a close watch on the key indicators of the climate system. Each month, the sea temperature of the equatorial Pacific Ocean is measured by ships using Argo floats, from the Tropical Atmosphere Ocean (TAO-TRITON) array of buoys, from satellites and with bathythermographs; sea levels are measured with tide gauges and from satellites, the atmosphere is monitored by satellites, aircraft, radiosonde balloons, and from the ground; winds are measured from Pacific islands, ships and aircraft; cloud positions and heights by satellites, cloud location by radar. Atmospheric pressures from Darwin and Tahiti are used to calculate the SOI daily.

Meteorological information is transmitted throughout the world by satellite through the Global Telecommunication System.

For Australia, the National Operations Centre in Melbourne processes this information, which becomes available to the climatologist within hours to a few days.

Dynamical forecasts

Dynamical model forecasts are, or will be, the way of the future. They are being improved each year as more of the influences affecting climate through the atmosphere and oceans are better defined, and as supercomputers become more and more powerful. General Circulation Models (GCMs) are described in more detail later in the chapter.

General Circulation Models can provide world or regional forecasts (Figure 7.3) based on systems beyond the SOI.

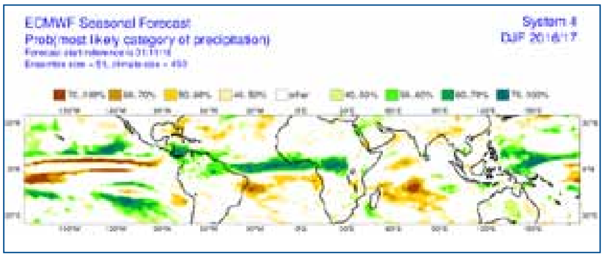


Figure 7.3. Example of a global GCM seasonal forecast

Phenomena that may modify ENSO

Climatologists are looking for new drivers that can be used to improve or extend climate prediction. The strong influence of the Southern Oscillation on seasonal patterns of rainfall in many parts of Australia may be modified (or modulated) by interactions with other phenomena or by other periodic oscillations. Longer-term patterns can be found statistically – some might be statistical artifacts only; others may have physical drivers.

Cycles

Spectral analysis of global historical SST and mean sea level pressure anomalies reveals significant climatic signals at intervals of 2–2.5 (TBO/QBO); 2.5–7 (ENSO); 11–13, 15–20 (Interdecadal oscillations); 20–30 and 60–80 years and by long-term secular trends (Figure 7.4). While some influences may be less than that of ENSO, they could allow improved seasonal climate forecasts in some years. How all these cycles interact is only partially understood.

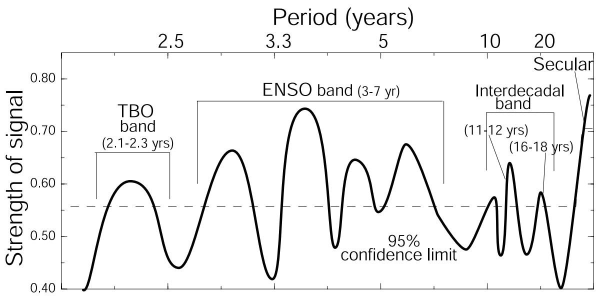


Figure 7.4. While ENSO is the strongest climatic signal, analyses of global SST and atmospheric pressure reveal other cycles. (Signals below the 95% confidence limit may be statistical artifacts.)

Long-term cycles

Other cycles that influence the Earth's climate may be generated by external sources such as the sun and the planetary system. Such 'secular' frequencies are too long to be used for seasonal forecasting but are likely to be involved in climate change.

The sun contributes to an 11-year cycle and the moon to a lunar cycle of 18.6 years.

The Gleissberg cycle (80–90 years) is one of the sun's total activity and sunspot structure. It has been detected by proxy indicators including tree rings and the history of flooding of the Nile.

Interglacial ages occur at frequencies of 10,000 years while Milankovitch cycles occur at 19,000, 24,000 and even longer intervals. Milankovitch cycles affect incoming solar radiation as the orbit and tilt of the Earth alter.

Madden-Julian Oscillation (MJO)

At irregular intervals of between 30 and 60 days, a disturbance of atmospheric pressure circling the Earth may reappear over the western tropical Indian Ocean and move eastward, between latitudes 10°N and 10°S, at 300-600 kilometres a day. This wave – the MJO – has been described in Chapter 2.

TBO and QBO

The period of the TBO (Tropospheric Biennial Oscillation) averages 2.4 years; it is more related to ENSO than the QBO (Quasi-biennial oscillation - with quasi indicating that is not truly biennial). The definition of the TBO is based on the tendency that a relatively strong monsoon year is followed by a relatively weak monsoon year and vice versa; however other views are that the TBO is indistinguishable from 'white noise' or normal variability.

The QBO is a stratospheric tropical zonal wind continuously circuiting the Earth - above the troposphere - but changing direction (east-west-east) about every 28 months. As an easterly wind descends towards the troposphere it weakens but is replaced by a westerly wind at a higher level, and so on.

Although the basic physics of the QBO are well known, some quantitative details are still unclear. The ENSO influence on the QBO is such that the QBO has larger amplitude and longer period during La Niña conditions than during El Niño. Currently, many of the models used for numerical weather prediction (NWP) or climate modelling are unable to accurately produce a QBO, or they produce a QBO which looks very different from observations. However, models with finer vertical grid spacing in the stratosphere are better at the QBO.

Recent work has also uncovered a relationship between the QBO and MJO during the summer months, such that the MJO has a larger amplitude and is better predicted when the QBO winds are easterly compared to when the QBO winds are westerly. The reason for this relationship is currently being investigated.

ENSO (averaging 3.5 years).

The Southern Oscillation can be seen in Figure 7.4 to be by far the strongest influence, and has already been described in Chapter 3. ENSO events are defined based on the sea surface temperatures in Nino-3.4. The Niño 3.4 index and the Oceanic Niño Index (ONI) are the most commonly used indices to define El Niño and La Niña events.

BoM definitions of an El Niño are given on page 13. Other USA definitions characterise an El Niño by a five consecutive 3-month running mean of sea surface temperature (SST) anomalies in the Niño 3.4 region that is above (below) the threshold of +0.5°C (-0.5°C). This standard of measure is known as the Oceanic Niño Index (ONI).

IPO and PDO

The Inter-decadal Pacific Oscillation (IPO) and the Pacific Decadal Oscillation (PDO) reflect longer-period oscillations in ocean temperatures in the Pacific. The PDO appears to reflect conditions more in the north of the Pacific Ocean but may just be a northern expression of the IPO, a near-global ENSO-like pattern of variability.

When the IPO raises temperatures in the tropical Pacific Ocean, ENSO has less influence on rainfall in some regions of Australia; when the IPO lowers temperatures in this ocean region, ENSO has increased influence. Since 1920, there have been two warm IPO phases (1924–1944 and 1977–1998) and two cold phases (1945–1976 and 1999–present). This effect could

account for the weak signal of the SOI in the 1930s and 1940s.

The IPO may be able to be used to identify large changes in 5–7-year rainfall patterns in Australia, especially in Queensland, and to pick up the start of a lengthy period of wetter or drier climate. However, currently there is only limited consensus on the topic of decadal to multi-decadal variability as the data sets are not long enough.

Antarctic Circumpolar Wave

The Antarctic Circumpolar Wave (ACW) is a coupled ocean–atmosphere wave contained in the Antarctic Circumpolar Current (or West Wind Drift) that flows continuously eastward around the Southern Ocean over an eight year circle.

The ACW is now generally rejected as being a statistical artifact and is viewed as part of a global ENSO wave. More recently, high latitude climate research has moved towards the Southern Annular Mode.

Southern Annular Mode (SAM)

The Southern Annular Mode (SAM), also known as the Antarctic Oscillation (AAO), describes the north–south movement of the westerly wind belt that circles Antarctica dominating the middle to higher latitudes of the southern hemisphere.

The changing latitude of the westerly wind belt influences the strength and position of cold fronts and mid-latitude storm systems and is an important driver of rainfall variability in southern Australia (Figure 7.5).

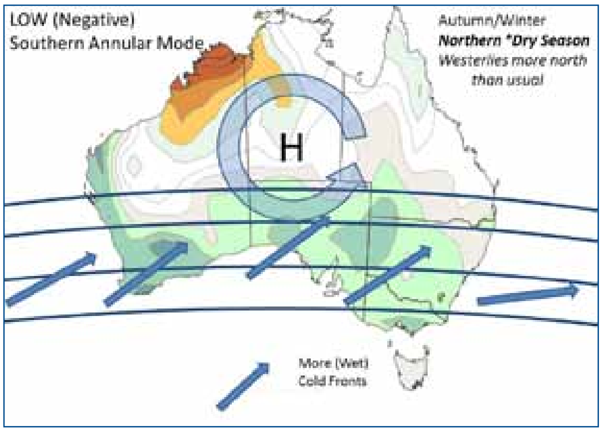


Figure 7.5. When the SAM is negative, westerly winds over southern Australia result in more low pressure systems and storms.

When the SAM is negative the belt of westerly winds expands northward over southern Australia, resulting in more (or stronger) storms and low pressure systems.

Conversely, when the SAM is positive, the belt of these strong westerlies moves southward towards Antarctica. The resulting weaker westerly winds and higher pressures mean that cold fronts do not penetrate over southern Australia. During autumn and winter, a strong positive SAM results in lower rainfall in southern Australia as the cold fronts and storms are further south.

In spring and summer, a strong positive SAM can mean that the easterly winds from the northern half of high pressure systems bring moist air from the Tasman Sea over southern Australia. This moisture can turn to rain as the winds hit the coast and the Great Dividing Range.

In recent years, a high positive SAM has dominated during autumn–winter, and has been a significant contributor to the 'big dry' observed in southern Australia from 1997 to 2010.

Latitude of the subtropical ridge.

The subtropical ridge (STR) is the belt of high pressure as part of the Hadley Cell with a mean position of 30°S in the Southern Hemisphere. The ridge moves south during our summer, and northward during our winter (Figure 7.6).

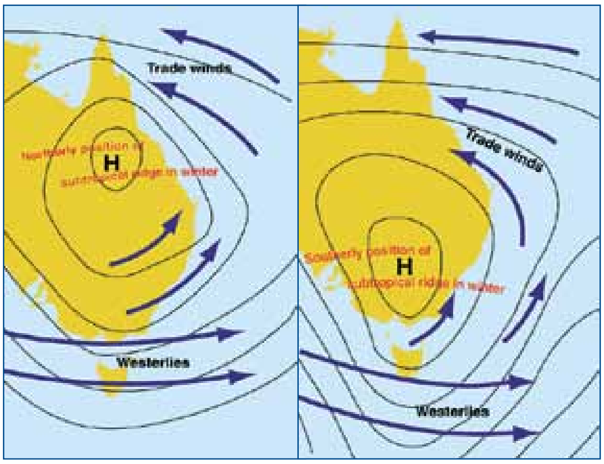


Figure 7.6. The latitude of the subtropical ridge in any particular winter affects the direction of prevailing winds and subsequent rainfall in Victoria and the mid coastline of eastern Australia.

While the high pressure cells pass by at an average latitude for any particular season, this can vary between years. During winter/spring, the subtropical ridge may lie as far north as central Queensland, but five years later could be far to the south towards Tasmania.

The cells of high pressure reflect subsidence of cool dry air, and often extend into the upper atmosphere as upper highs. The cells influence the direction of prevailing winds, moisture uptake from the ocean and subsequent rainfall especially during winter.

The regions that appear to be most affected are those at the northern and southern extents of the position of the cells, namely around 25°S (central Queensland) and around 37°S (southern Victoria). It is now thought that the levels of the pressure within the cells may be as important as their latitude.

Volcanic activity

Major volcano eruptions push millions of tonnes of dust and sulphur aerosols into the troposphere. This volcanic haze is carried around the world and intercepts incoming solar radiation. After major eruptions, air temperatures cool quickly by about 0.1 to 0.2°C for a couple of years but then return to normal.

The eruption of Mount Tambora on Sumbawa Island in Indonesia in 1815 led to global cooling and the 1816 'Year Without a Summer' in the northern hemisphere.

Over the last 130 years, eleven strong ENSOs have coincided with volcanic eruptions. There is less effect on sea surface temperatures, and apparently little on rainfall or surface air pressure.

General Circulation Models

Dynamical models

Dynamical models use mathematical equations describing the physical laws governing the behaviour of the climate system. These laws include Newton's laws of motion, the laws of thermodynamics which tell us how temperature will behave, and transport or conservation equations for water vapour and mass. If measurements are available to specify the spatial distributions of temperature, wind, pressure and water vapour over the globe then, in principle, the set of mathematical equations (known as the 'primitive equations') can be solved to specify the state of the system (or the climate) at some future time.

Dynamical models can be of varying complexity. They can range from simple idealisations of the atmosphere to the movement forward of high-resolution representations of the state of the atmosphere at all heights over the entire globe. The more complex models include the complex Numerical Weather Prediction (NWP) models used for daily weather forecasts, and General Circulation Models (GCMs) used to study climate change.

Coupled models

The dynamical models used to make seasonal climate forecasts and to predict the future state of ENSO are known as 'Coupled' or 'Atmosphere–Ocean' Models (Figure 7.7).

Figure 7.7. GCMs divide the oceans and atmosphere at various depths and altitudes.

The two separate dynamic models for the atmosphere and the ocean (Figure 7.8) are 'coupled' as they drive one another.

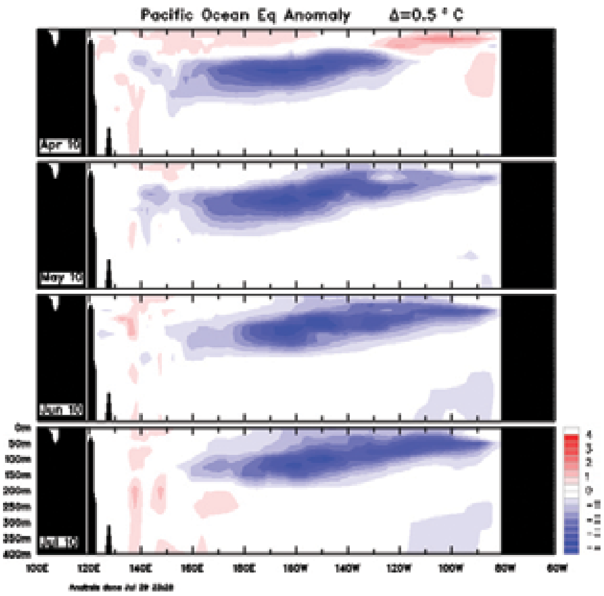


Figure 7.8. Sub-surface ocean temperatures – example of depth and location of cold and warm water across the equatorial Pacific

As the atmospheric model moves forward in time, the changes in the low level winds (next to the sea surface) act as a force to drive the ocean model. As the ocean model moves forward in time, the changes in sea surface temperature act as an engine for the atmosphere model through the eddy fluxes of heat and water vapour from the ocean into the atmosphere (Figure 7.9).

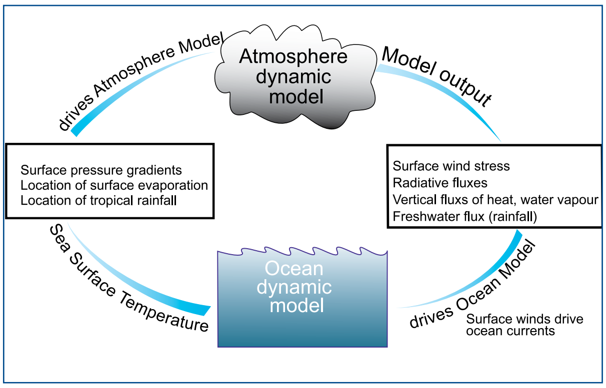


Figure 7.9. Coupled circulations of the atmosphere and ocean

Simpler models have been used, for several years, to predict the sea-surface temperature structure in the eastern tropical Pacific, and hence to give extra warning of either a warming (El Niño) or pronounced cooling (La Niña), but for more accuracy models now have to include ENSO modifiers such as the IOD, IPO and QBO.

GCMs can now provide more accurate forecasts especially for periods longer than the three months usually indicated by SOI or SST patterns. However, there is still a problem with down-scaling from a global or continental forecast to something more useful for individual property management decisions at the local level (Figure 7.10).

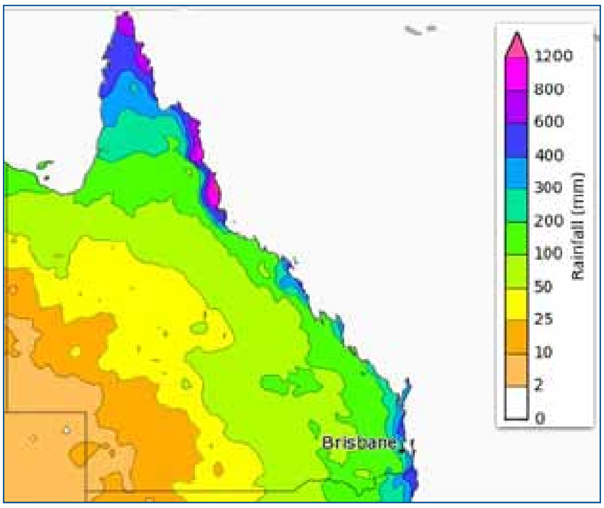


Figure 7.10. Example of a BoM seasonal forecast map generated by POAMA model showing level of regional detail

Ensemble forecasts

The atmosphere is a ‘chaotic system’. Being dynamic, it is highly sensitive to the state of the system at the beginning of a GCM calculation. However, the dynamical equations are controlled by more slowly changing boundary conditions, such as the sea surface temperature, the heat content above the oceanic thermocline (the ‘subsurface heat content’), amount of moisture in the soil and the seasonal march of the sun. Thus we can predict the probability of average rainfall or average temperature over longer periods of one or two months.

The probability distribution of the seasonal forecast is obtained by running the coupled model up to fifty times with different start points to produce what is known as a dynamical ensemble. (Figure 7.11).

The different model forecasts, all with slightly different initial states, are called members of the ensemble.

Ensembles have been used, for several years, to predict the sea-surface temperature structure in the eastern tropical Pacific, and hence to give extra warning of either a warming or pronounced cooling. Ensemble forecasts of SST can be used to generate an SOI that is

then used to generate climate forecasts from the concurrent relationship with long-term historical climate data.

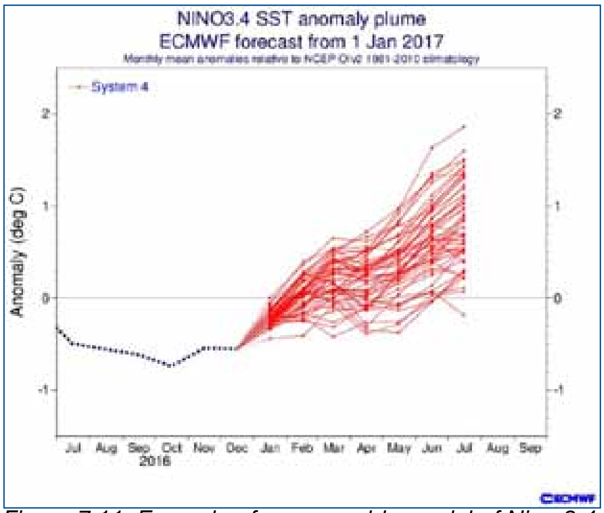


Figure 7.11. Example of an ensemble model of Nino 3.4 from ECMWF

International GCMs

Most of the major international meteorological centres currently run ensemble forecasts for the coming 3–12 months.

The seasonal forecasts of sea surface temperature anomalies for the Pacific and Indian Oceans from each model can be seen on the BoM website each month (Figure 7.12).

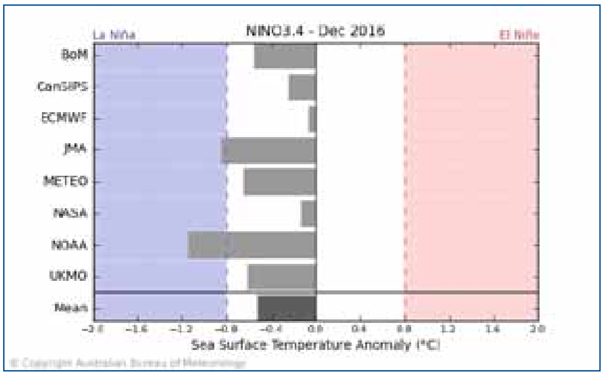


Figure 7.12. Example of ENSO forecasts from international GCM models; critical SST anomaly is 0.8°C.

POAMA and ACCESS

The current GCM run by BoM – POAMA (Predictive Ocean Atmosphere Model for Australia) – is being superseded by a more powerful model named ACCESS (Australian Community Climate Earth-System Simulator).

The ACCESS project is a partnership between the Bureau, CSIRO, Australian universities and overseas agencies, particularly the UK Met Office (UKMO). BoM is incorporating local output from the UKMO coupled ocean-atmosphere model in the ACCESS framework.

The use of the most up-to-date observed conditions of the ocean, land and atmosphere allow each forecast to begin from a more accurate starting point and so improve accuracy in the forecast ensembles.

While POAMA's monthly forecasts currently have a 250-kilometre resolution, ACCESS will provide 60-kilometre resolution (Figures 7.13 and 7.14).

This will better represent, for example, the Great Dividing Range which plays a key role in the spatial distribution of rainfall. It will also improve the representation of important large-scale climate drivers, like ENSO, potentially leading to better multi-week and seasonal forecast accuracy over Australia.

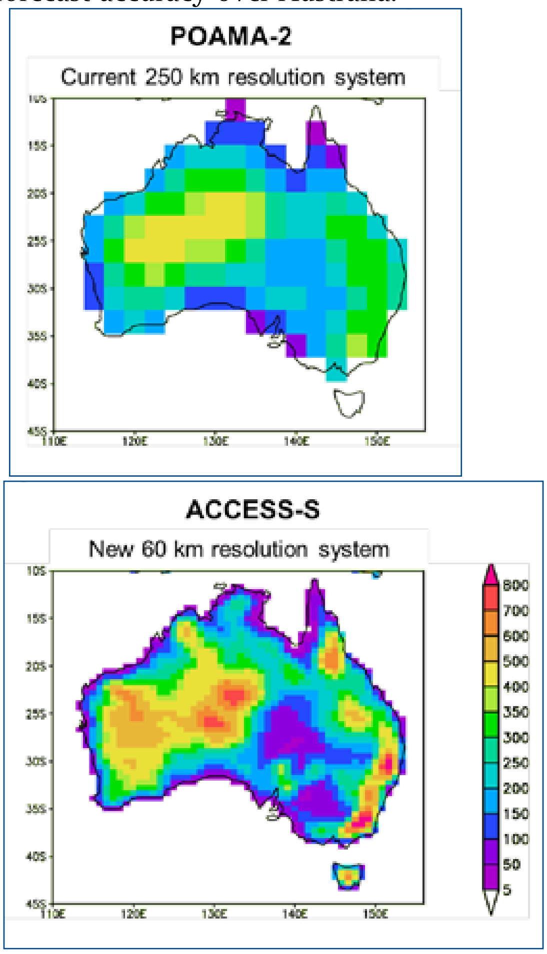


Figure 7.13. Example comparing POAMA and ACCESS resolution for topography

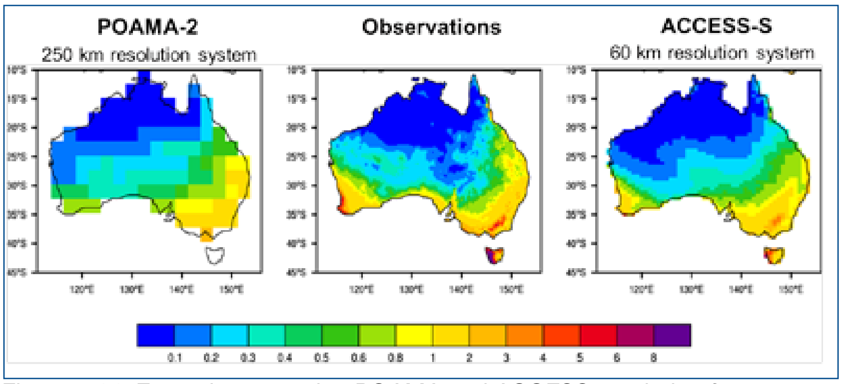


Figure 7.14. Example comparing POAMA and ACCESS resolution for mean rainfall (mm/day)

The main constraints are available supercomputer capacity and in users interpreting and communicating the forecast.

ACCESS-S atmosphere-only forecast data (daily rainfall, temperature, and solar radiation) can be down-scaled to a weather-station level of 12-kilometres, and so may soon be used to drive CropARM and NitrogenARM software for local crop decisions.

Climate change

Temperature

Over the last thousand years, the climate in the northern hemisphere (where historical records exist) has varied considerably – from a Medieval Warm Epoch (for example when Vikings colonised Greenland) to a 'Little Ice Age' between 150 and 450 years ago when many glaciers advanced and, for example, the River Thames in England regularly froze over (Figure 7.15).

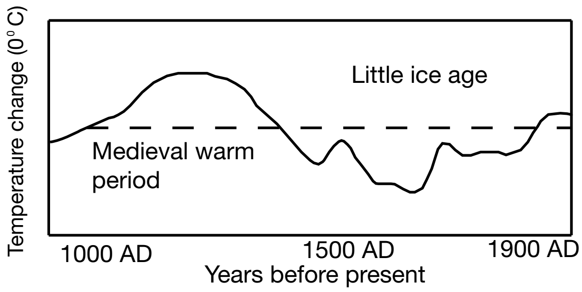


Figure 7.15. Northern hemisphere temperatures over the last thousand years

However, more recently global temperatures have risen 0.6±0.2°C. They have been higher during the last decade than in any decade in the past 100–140 years, and are predicted to rise exponentially (Figure 7.16).

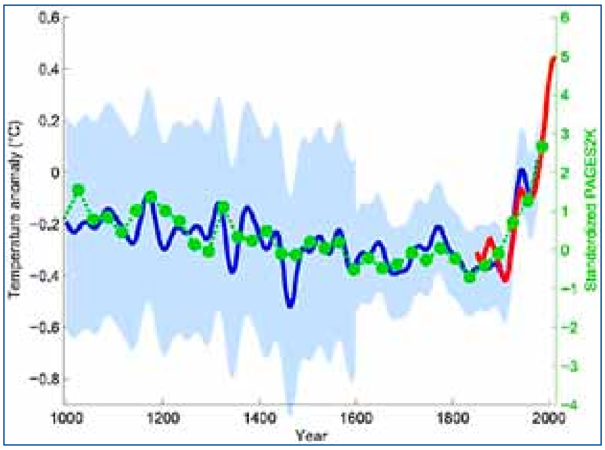


Figure 7.16. Moderate changes in temperatures across the northern hemisphere over the last millenium have been superceded by the exponential rise over the last century.

In the southern hemisphere, surface temperatures were stationary throughout the latter half of the nineteenth century and into the early part of the twentieth, reaching a global minimum around 1910. They then increased until 1945, remained stationary until the mid-1970s, before rapidly increasing again (Figure 7.17)

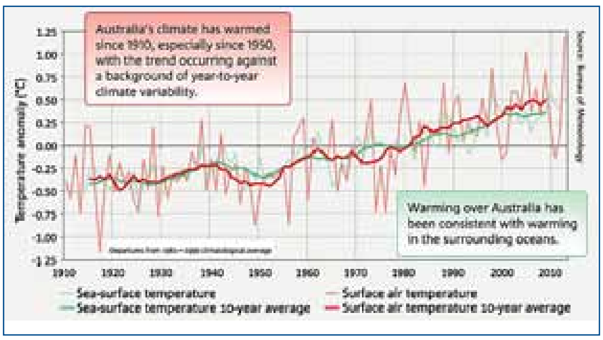


Figure 7.17. Changes in Australian temperature with the red line showing 10-year averages against a background of year-to-year variability

Aligned with the general rise in temperature are heat waves and more extreme rainfall events.

Some studies have attributed up to a third of temperature rises since 1970 to variations in solar radiation as solar particle eruptions and geomagnetic storms, but anthropogenic emissions such as carbon dioxide, methane, nitrous oxide and water vapour are commonly accepted as the prime cause.

Rainfall

Changes in rainfall in the Southern Hemisphere are less distinct. Some regions have been getting wetter, others drier.

'Drier' to a continent like Australia (Figure 7.18), which has rainfall marginal for agriculture over most of the land mass, could have profound consequences.

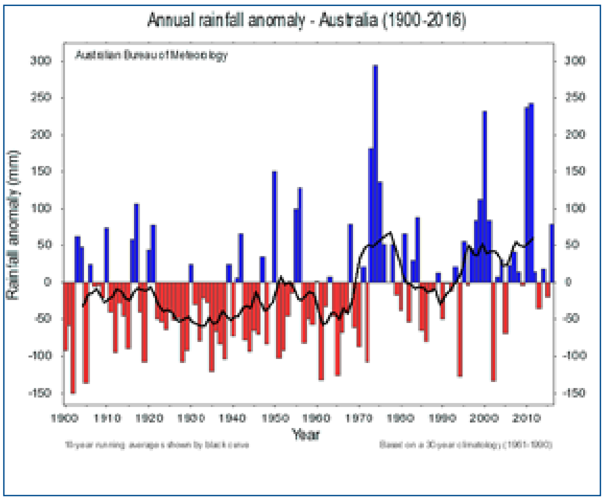


Figure 7.18. Variation in annual rainfall over Australia between 1900 and 2016 with the 10-year average shown as the black line.

The Australian climate is not constant – there have been significant variations in both average temperature and rainfall over large areas of the continent even during this short period, and larger variations over a longer time-scale.

Climate in eras before scientific records were kept can be estimated from 'proxy' sources (Chapter 3). These proxy sources suggest that there have been longer term or interdecadal variations in the strength of the IPO as well as the shorter-term ENSO cycle.

Any continued change due to emissions of carbon dioxide (CO_2) and other greenhouse gasses will probably not be steady and uniform; there will still be colder or wetter years and even decades under natural climate variability.

How large this enhanced greenhouse effect will be and where it will have most impact is still under investigation and discussion.

What is likely is that our climate will become even more variable.

Over the short-term, the best way for rural producers to manage climate change will be to manage climate variability.

Some risks and impacts for agriculture

Possible effects for primary producers in Australia include:

- Greater plant growth because of higher CO_2 levels, but this increased potential growth is limited by the low nitrogen levels in many Australian soils.
- More uneven pasture growth not offset by higher CO_2
- Longer droughts in our already marginal climate
- Worse floods, more bushfires
- Spread of cattle ticks and parasitic insects
- Upset flowering and fruiting of temperate trees
- Loss of habitats for native species

Risks are unevenly distributed and are generally greater for regions with already marginal rainfall.

Many adaptation and mitigation options can help address climate change, but no single option is sufficient by itself.

Effective adaptation and mitigation responses will depend on policies and measures across multiple scales: international, regional, national and sub-national.

Glossary of terms

ACCESS – Australian Community Climate Earth-System Simulator

Anomalies – deviations from the long-term mean.

Anti-cyclones – cells of high pressure associated with dry air, resulting in mainly cloud-free skies and little or no rainfall. Anticyclones move from west to east across Australia at 25–40°S.

APSIM – Agricultural Production Systems sIMulator – a crop growth model for tropical crops.

Average – average rainfall is calculated by dividing the total by the number of entries, i.e. the arithmetic mean. (cf. median.)

BoM – Bureau of Meteorology Australia

Blocking – A near-stationary high pressure system that occurs near south-eastern Australia. A 'cut-off' low pressure system can form on its northern flank to bring widespread rainfall.

Cell (Hadley) – a vertical circulation of the atmosphere in which warm air rises and cools, flows laterally at high levels, then descends. In the Hadley cell, air rises over the heat equator, flows toward the poles and descends after travelling about 25° of latitude.

ClimateARM – an interactive climate analysis tool

Coriolis effect – Moving air or water is deflected horizontally because the speed of rotation of the Earth's surface is faster at low latitudes than at high. The Coriolis effect acts to the left in the southern hemisphere, imparting a clockwise swirl into an area of low pressure. There is little Coriolis effect within 7° of the equator.

Cyclones – depressions, or areas of low pressure, associated with rising warm air and clockwise air circulation (anticlockwise in northern hemisphere). A tropical cyclone is an intense depression fed by very warm (over 28°C) waters, and by latent heat energy release in condensation. The wind is given its swirl by the Coriolis effect.

Deciles – rank a set of recorded rainfalls (monthly, seasonal, annual) into ten groups. The lowest 10% of falls belong to decile range 1, the next lowest to decile range 2 and so on, up to the highest 10% of recorded falls which belong to decile range 10. The top of decile range 5 is the median. cf. terciles that divide the ranking into three sets.)

Decision support models – computer models to assist decisions by simulating the effects of seasonal climate forecasts on the potential growth of a crop or pasture.

Droughts – droughts or severe rainfall deficits, occur when a 12-month period receives less rain than in the driest 10% of calendar years. In eastern and northern Australia, they are often associated with strongly negative SOI values, commonly referred to as an El Niño event or episode.

ECMWF – European Centre for Medium-range Weather Forecasts

ENSO – El Niño-Southern Oscillation is a composite term referring to the whole suite of events associated with these negative SOI episodes.

El Niño – the phase of the Southern Oscillation associated with the abnormal warming of a large area of the eastern equatorial Pacific Ocean.

GRASP – a tropical grass production model

GCM – General Circulation Model

Gyre – the anticlockwise (southern hemisphere) swirl of currents around an ocean basin, caused by the effect of the Coriolis force on prevailing winds.

Indonesian throughflow – flow of warm water from the western Pacific into the Indian Ocean

IPO – Interdecadel Pacific Oscillation with a cycle of 15–20 years. An IPO may modulate ENSO.

ITCZ – the Intertropical Convergence Zone is where the moist south-east trade winds meet the north-east trades of the northern hemisphere. It is a zone of heavy rain and thunderstorms, and constitutes a main source of tropical rain.

La Niña – now used to refer to the opposite of an El Niño, or events associated with positive values of the SOI. (Also anti-ENSO).

Median – median rainfall is calculated by ranking totals from highest to lowest. The middle figure is the median. Annual rainfall averages and medians are usually close but monthly averages may be well above the median in arid regions where the average is distorted by rare, but torrential, rainfall events. (cf. average.)

Model – a computer program designed to simulate what might happen in a situation.

Monsoon – the heavy summer rains in northern Australia, brought about by a moist inflow of air from the oceans to the northwest and northeast of Australia due to low pressure over the continent. (In Asia, monsoon traditionally refers to the wind.)

MJO – Madden-Julian Oscillation. Low-pressure waves sweeping west to east across the top end of the continent irregularly every 30–60 days (average 40 days), and triggering rainfall events.

Nino 3.4 – area of the equatorial Pacific Ocean most related to Australian climate forecasts

POAMA – Pacific Ocean Atmosphere Model for Australia

Probability – the chance of an event happening expressed as a percentage. A probability of 70% means the event can be expected to occur in 7 out of 10 years.

QBO – Quasi-biennial Oscillation - a stratospheric oscillation with a cycle of about 28 months but with unknown effect on ENSO.

Rainman StreamFlow – a comprehensive climate analysis tool for PCs

SAM – Southern Annular Mode. The latitude of SAM influences the position of fronts over southern Australia

SOI – Southern Oscillation Index measures the strength of the Southern Oscillation; Troup's Index compares the difference in atmospheric pressure between Tahiti and Darwin.

Southern Oscillation – a see-saw of atmospheric pressure anomalies between the Indonesian region and the eastern tropical Pacific Ocean

SST – sea surface temperature.

STR – Subtropical ridge

Synoptic – a synoptic chart shows the distribution of meteorological conditions over a region at a given moment.

Thermocline – a relatively shallow depth of water where a strong temperature change occurs between the ocean's warm surface water and the deeper, cold layers.

Tropical-extratropical interactions – often significant rainfall-producing events in which moist airmasses from the tropics link up with weather systems from higher latitudes.

Troposphere – the layer of the Earth's atmosphere in which our weather occurs; about 20 km high at the equator, and 10–15 km high at mid-latitudes.

TBO – Tropospheric biennial Oscillation that may modulate ENSO.

Tropopause – the upper limit of the troposphere before the stratosphere.

Trade winds – south-east winds blowing across the southern Pacific and bringing moist unstable air into the ITCZ. These weaken in an El Niño (cause and effect).

Upwelling – upward movement of deep (abyssal), cold water to the surface.

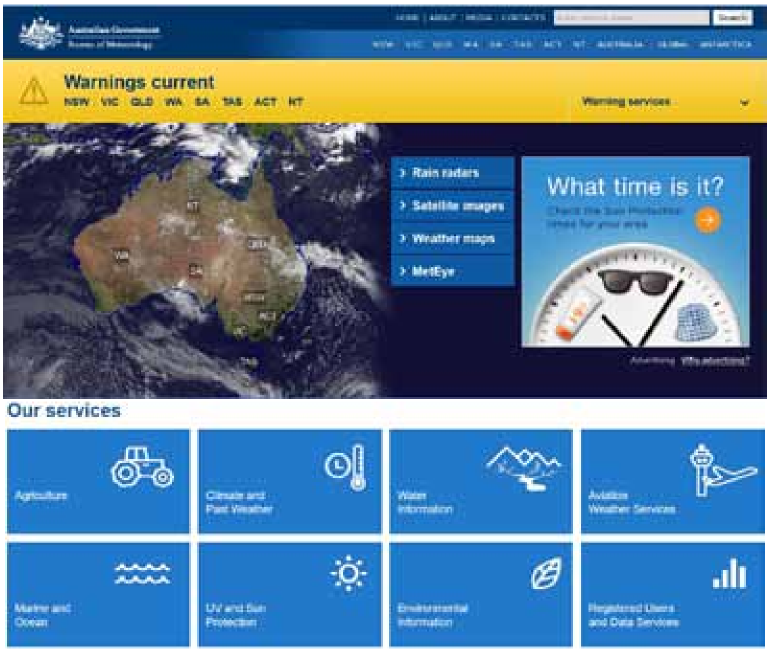
Walker Circulation – the cellular flow of air in a vertical plane over the equatorial Pacific Ocean. Warm, moist air rises over the Indonesian region and tropical western Pacific within the ITCZ, releasing rain. The air then moves at high altitude (12 000 m) to the east and descends over the colder water of the eastern Pacific.

Good sources of climate information on the Internet

There are now numerous publications and web sites dealing with ENSO and its world effects but fewer on the application of seasonal forecasting on agriculture.

For our Australian readers, we recommend that you initially explore three main Internet sites: the Bureau of Meteorology; the LongPaddock; and the Climate Kelpie.

Bureau of Meteorology web site – click on **Climate and past weather** for extensive information about the Australian and world-wide climate.
http://www.bom.gov.au/climate/



The Long Paddock – view sections and maps on the seasonal climate outlook, the current and past SOI, rainfall and pasture growth, drought, and AussieGRASS.
https://www.longpaddock.qld.gov.au/

Climate Kelpie: rounding up climate tools for Australian farmers.

Climate Kelpie, from the Managing Climate Variability R & D program, lists numerous sources of weather forecasts and provides links to the many decision support tools for different crops and production systems.

http://www.climatekelpie.com.au/manage-climate/decision-support-tools-for-managing-climate