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Abstract
The Earth's general atmospheric circulation in the tropics and subtropics is simply described. Intense heating by the sun at the equator causes air to rise and spread out polewards in the upper troposphere. As this air moves toward the poles it cools and begins to descend back to the Earth's surface at 200 -300 north and south of the equator. Upon reaching the Earth's surface this air either returns to the equator or moves polewards. Where air rises in this circulation, low air pressure forms and there is intense instability and condensation of moisture with subsequent heavy rainfall. Where air descends, high air pressure forms with intense evaporation, clear skies and stability. This tropical circulation of air is termed the Hadley cell and the high pressure that forms encircles the globe coincident with the great sub-tropical deserts. Australian climate is dominated by this circulation cell and the deserts that form as a consequence. The Hadley cells migrate annually with the apparent movement of the su n north and south of the equator.

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THE SOUTHERN OSCILLATION AND CLIMATIC EFFECTS IN AUSTRALIA

Edward Bryant

INTRODUCTION

The Earth's general atmospheric circulation in the tropics and sub-tropics is simply described. Intense heating by the sun at the equator causes air to rise and spread out polewards in the upper troposphere. As this air moves toward the poles it cools and begins to descend back to the Earth's surface at 20°-30° north and south of the equator. Upon reaching the Earth's surface this air either returns to the equator or moves polewards. Where air rises in this circulation, low air pressure forms and there is intense instability and condensation of moisture with subsequent heavy rainfall. Where air descends, high air pressure forms with intense evaporation, clear skies and stability. This tropical circulation of air is termed the **Hadley cell** and the high pressure that forms encircles the globe coincident with the great sub-tropical deserts. Australian climate is dominated by this circulation cell and the deserts that form as a consequence. The Hadley cells migrate annually with the apparent movement of the sun north and south of the equator.

Secondary circulation also exists in the sub-tropics, and in this respect the Indian monsoon is by far the largest annual feature. Here intense heating in the northern hemisphere summer shifts from equatorial regions to the Indian mainland. Air is sucked into the Indian subcontinent from adjacent oceans and landmasses to return via upper air movement either to southern Africa or the central Pacific. In the northern hemisphere winter, or our summer, this intense heating area shifts to the Indonesian-Northern Australian 'maritime' continent.

There is also another major secondary circulation which does not exist on an annual basis but varies at three-to-five year intervals. It is termed the **Southern Oscillation.** In general, low air pressure tends to be centred for several years throughout the year over the Indo-Australian region (Figure 1a). In contrast, an area of high pressure develops over the equatorial ocean west of South America. The heating in the Indo-Australian region causes air to rise and move in the upper troposphere to the east Pacific. The high pressure off the Peruvian coast owes its origin to cold water which cools the air above and causes it to descend. Air from this region then moves across the Pacific as weak easterlies to the region of heating in the western Pacific Ocean. The weak easterlies also blow warm surface water across the Pacific Ocean where it piles up in the Coral Sea offshore from Australia. As a result, sea-level is slightly depressed off the South American coast and raised in the Coral Sea. The easterlies also cause upwelling of cold water along the South American coast, and this cold water reinforces the cooling of the air. There is thus a feedback mechanism between atmosphere and ocean that enhances the perseverance of the circulation. Cold water in the eastern Pacific Ocean creates high pressure which induces easterly air flow that causes upwelling of cold water along the coast that cools the air. This system is very stable and is termed the Walker circulation after the Indian meteorologist who first recognised its identity at the beginning of the twentieth century.

Sometimes this circulation is abnormally strong and heavy rainfall occurs over the western Pacific landmasses. This was the case in 1974-75 and 1983-84, and the result was flood conditions in eastern Australia. For yet unknown reasons this circulation periodically breaks down and high pressure becomes established over the Indo-Australian area while low pressure develops over warm water off the South American coast. The easterly winds abate and are replaced by westerly winds in the tropics. The rainfall belt shifts to the central Pacific and drought replaces normal or heavy rainfall in Australia. Such conditions persisted in the Great Drought which affected most of Australia between 1979 and 1982 (for an illustration of rainfall deficits in Wollongong during this period, see Cox, 1983). What is more important, extreme climate changes can occur worldwide as a result of these reversals. These climatic changes can be responsible for such minor occurrences as increased frequencies of snake bites in Montana and funnel-web spider attacks in Sydney. More significantly, they may even generate extreme economic and social repercussions including the demaging of national economies, the fall of governments and the deaths of thousands through starvation, storms and floods (Canby, 1984).

EL NINO–SOUTHERN OSCILLATION EVENTS

While we are not clear as to the causes of abnormal oscillations, we now have an accurate picture of how they behave. It appears that a major reversal begins with the movement of warm water in the western Pacific towards the central Pacific (Figure 1b). This movement of water coincides with the movement of the Indo-Australian heating centre eastwards. Some believe that weakening of the Indian summer monsoon allows this shift to take place. Others believe that the Hadley cell weakens first of all, or that the strong east-west flow generated by the Hadley cells over Australia is replaced by abnormal south-to-north flow along the east Australian coast. This flow pushes the tropical heating centre eastwards. The most likely time for this shift to occur is during the annual change of seasons when the tropical heating area is migrating from the Indonesian-Northern Australian 'maritime' continent to the Indian sub-continent. As warm water shifts eastwards the rainfall region moves from the western Pacific to normally drier central Pacific islands. Cyclones which normally form in the Coral Sea now ravage Tahiti, Tonga and Hawaii which are usually unaffected by such intense storms. Accompanying this shift is the strengthening of westerly winds in the topics and the weakening of easterlies. This has two effects (Figure 1c). Firstly, the warm water which has piled up in the west Pacific Ocean has nothing to hold it there, and now surges across the Pacific to the eastern side in about one month's time. Secondly, sea-level increases in the east Pacific, and the cold water at the surface maintaining the high pressure cell off the South American coast is swamped by a 50-100 metre depth of warm water. As low pressure replaces high pressure over this warm water, the easterlies fail altogether because there is no pressure difference across the Pacific to maintain them.

The appearance of warm water along the Peruvian coast usually occurs by Christmas. This warming is an annual event and is termed the **El Niño** which in Spanish refers to the 'Christ Child'. This annual warming becomes exaggerated with sea surface temperatures increasing 4-6° above normal and remaining that way for several months. Until a few years ago the El Niño appearance was thought to be the trigger mechanism for a climatic oscillation; however it is now clear that most El Niño events appear several months after warming in the central Pacific has been initiated. Because the extreme El Niño events are so well documented back to the 1700's, these climatic changes are now termed **El Niño-Southern Oscillation,** or for brevity, **ENSO** events. The warm water of the El Niño forces fish feeding off plankton to migrate to greater depths or causes vast fish kills. Guano-producing birds feeding off anchoveta die in their thousands and the anchovey and fertiliser industries in Peru collapse. The warm water along what is normally an arid coastline leads to abnormally heavy rainfall causing floods in the normally arid Andes rainfall region and drought in southern Peru, Bolivia and northeastern Brazil. Warm water coalesces from the central Pacific to South America and slowly spreads into the northern Pacific (Figure 1d). This movement of water causes intensification of the winter low pressure cell off the Aleutian islands in the North Pacific Ocean. As

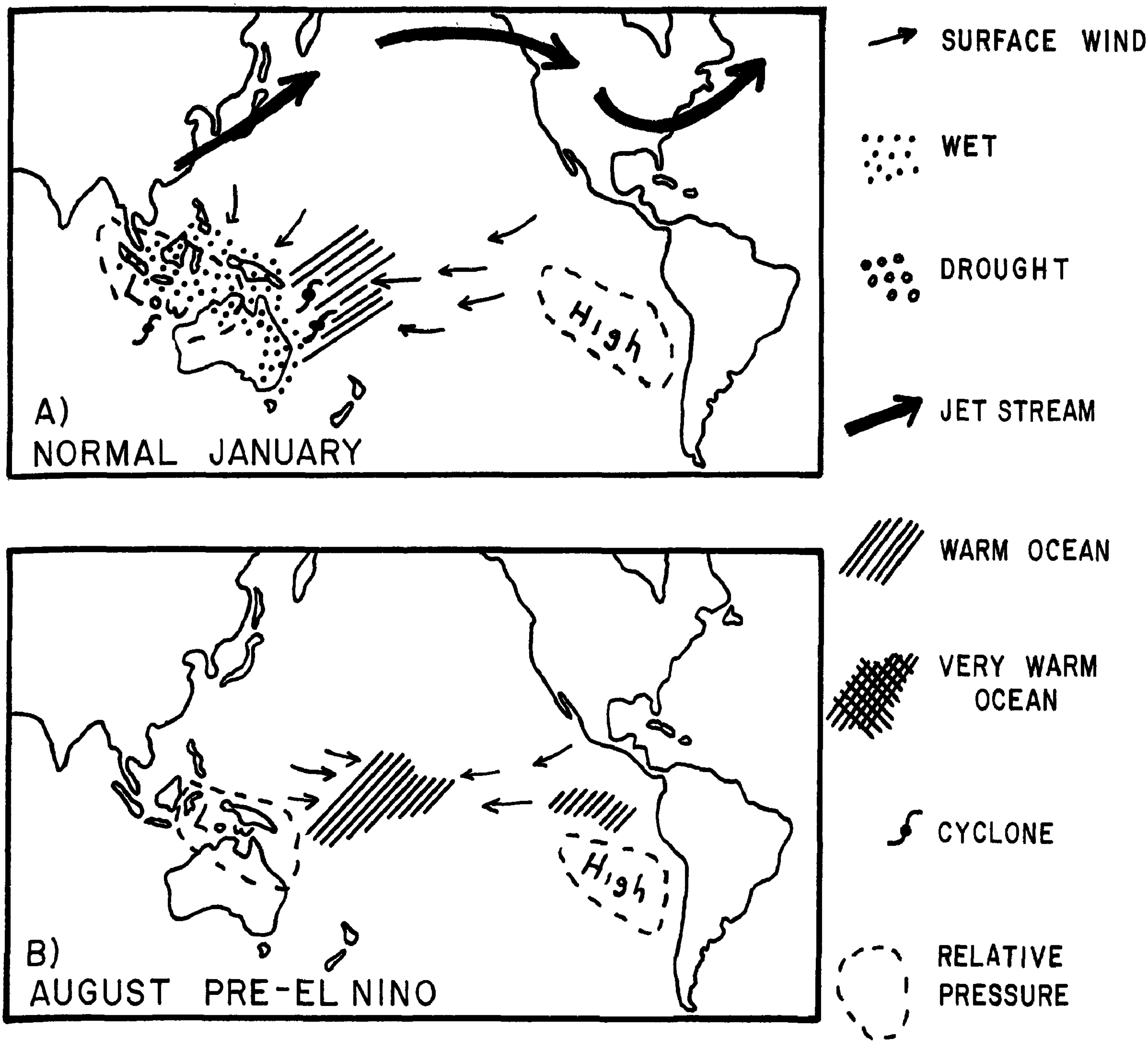

Figure 1: Idealized representation of the evolution and effects of an El Niño-Southern Oscillation event. Note that the 'high' and 'low' air pressures are relative to each other and may not necessarily represent high and low pressure cells in the general air circulation.

a result waves generated by extreme coastal storms in the 1982-83 ENSO event wreaked havoc to the luxurious homes built along the Malibu coastline of California. The intense release of heat by moist air over the central Pacific Ocean causes the westerly jet streams in the upper atmosphere to shift equatorwards. Any shift in the jet stream path across the Rocky Mountains of America leads to dramatic changes in climate across the continent. The 1982-83 ENSO event caused heavy rainfall in the southern United States, record-breaking mild temperatures along the American east coast and heavy snowfalls to the southern Rocky Mountains. In contrast, however, the 1976-77 event caused record-breaking low temperatures and heavy snowfall in the eastern half of North America because that event sent jet streams looping north of the Rocky Mountains into Arctic regions.

THE EFFECT ON LANDMASSES AROUND THE INDIAN OCEAN

Most descriptions of ENSO events concentrate upon the Americans, but the greatest devastation occurs in southern Africa, India, Indonesia and Australia. (At present drought in the African Sahel region, which includes Ethopia and Sudan, appears unrelated to the Southern Oscillation). An El Niño-Southern Oscillation event can cause failure of the Indian monsoon and drought in Indonesia. In recent years these countries have established distribution infrastructures which prevent major droughts from causing starvation on as large a scale as they once did; however the 1982-83 event caused the Indonesian economy to stall as the country shifted foreign reserves towards the purchase of rice and wheat. The effect was the same in southern Africa. Here many grain exporting countries became importers during

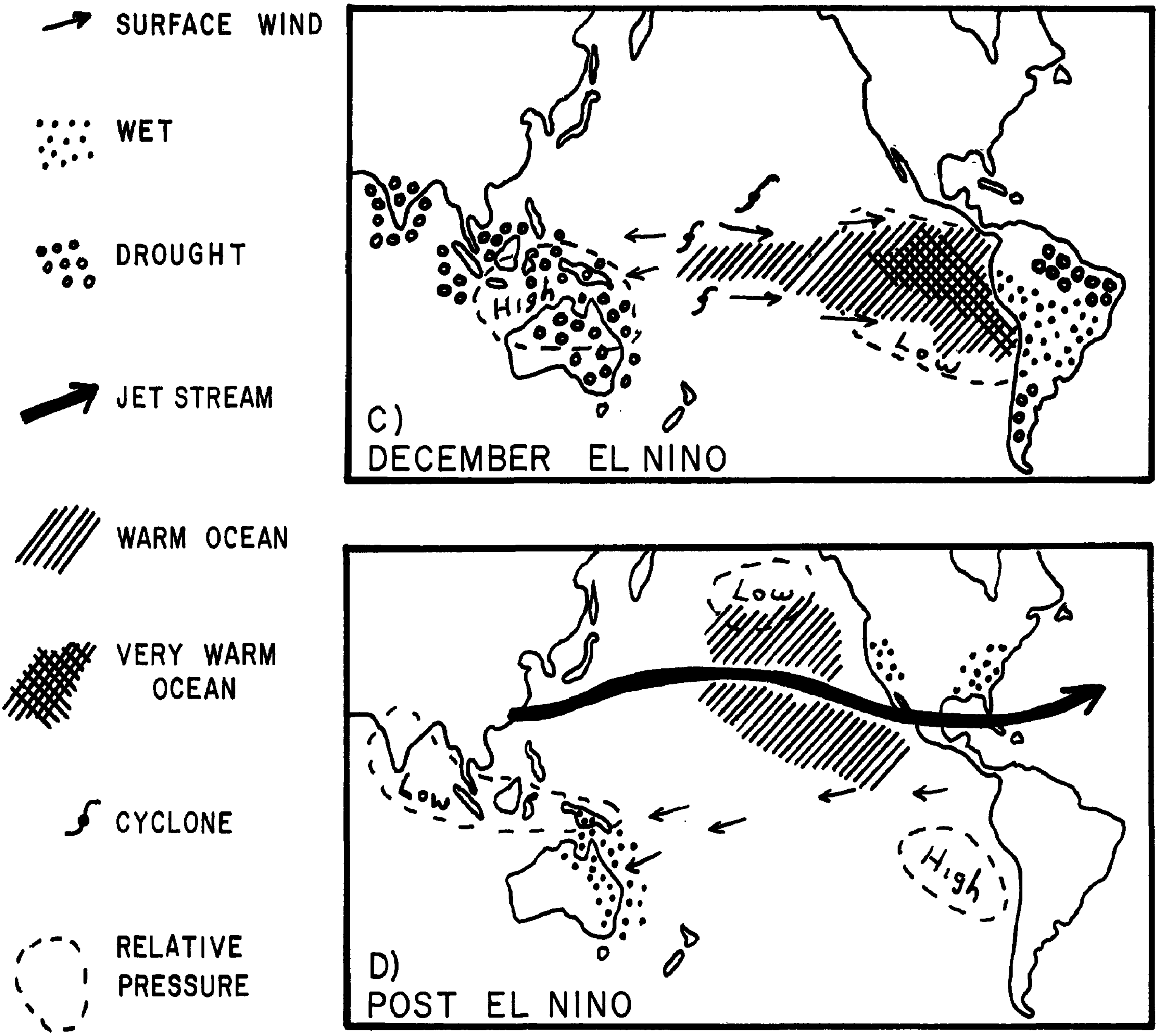

Figure 1 (continued)

the last drought. However it was in Australia that damage was the greatest. The event which took place between May 1982 and March 1983 coincided with the driest period of the recent drought—the worst drought this country has experienced. Approximately $2000 million was erased from the rural economic sector as sheep and cattle stock were decimated by the extreme drought conditions. The resulting lack of capital expenditure in the rural sector drove farm machinery companies such as International Harvester and Massey-Ferguson into near-bankruptcy. Dust storms blew thousands of tons of topsoil away and finally, in the last stroke, the Ash Wednesday bushfires of February 16th 1983, now viewed as the greatest conflagration observed by man, destroyed another $1000 million worth of property in South Australia and Victoria. These events and their recession-boosting effects did little to help the re-election chances of the Fraser government in March of 1983.

It is now realized that ENSO events account for a significant proportion of climatic change around the Pacific Ocean at the three-to-five year interval. Figure 2 shows the magnitude of the Southern Oscillation between 1851 and 1974 as measured by the pressure difference between Darwin (normally a low pressure area) and Tahiti (centred in the high pressure area). Positive values indicate that the Southern Oscillation is in its normal phase with low pressure over the Indo-Australian landmasses and high pressure over the east Pacific. Negative values indicate the reverse—an ENSO event. Sixty-eight percent of the strong or moderate ENSO events between 1851 and 1974 produced major droughts in eastern Australia. Sixty percent of all recoveries after an ENSO occurrence led to abnormal

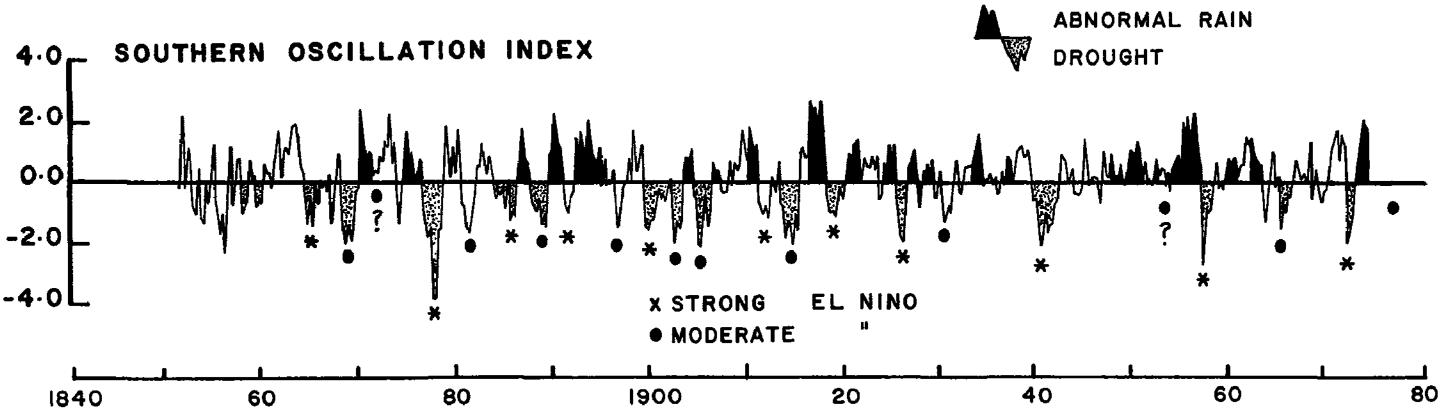

Figure 2: **Plot of the Southern Oscillation Index** (the difference between pressures at Darwin and Tahiti). Positive values indicate normal conditions, negative values indicate an El Niño-Southern Oscillation episode. East Australian floods are shaded in black and droughts are shaded in stippling.

rainfall and floods. In more recent memory, the floods of 1974-75 in eastern Australia were associated with the return to normal circulation after the 1972-73 ENSO event. The heavy rainfall we experienced in 1983-84, including the Dapto Flood of February 1984 (see Nanson and Hean, 1984) and the Sydney thunderstorms of November and December 1984 also fall into this category. These periods of heavy rainfall and floods can produce severe beach erosion such as that which occurred during the May-June storms of 1974 (Bryant and Kidd, 1975). Because of the association between Southern Oscillation behaviour and the timing of droughts and floods in Australia, much research is now being directed towards the prediction of such abnormal conditions. At present we have a lead time of approximately two months in the prediction of rainfall; however while we can forecast the timing of rain we have no idea as to the amounts which may fall. Since ENSO events and associated droughts in Australia take several months to become established, we have little chance yet of forecasting the occurrence of these episodes.

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POSTSCRIPTS

1) The snake bites in Montana during the 1982-83 ENSO event were caused by the snakes following their food source (mice) from dry, unpopulated hill country to wetter and more densely populated lower elevations. The increased number of funnel-web spider attacks in Sydney was caused by spiders moving from flooded holes after heavy rainfall broke the 1982-83 drought.

2) At the time of writing (January 1985) it appears that another small ENSO event has taken place with a return to drought in eastern Australia, severe cold in the eastern United States and displacement of tropical cyclones eastwards to Fiji and into the central Pacific Ocean.

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