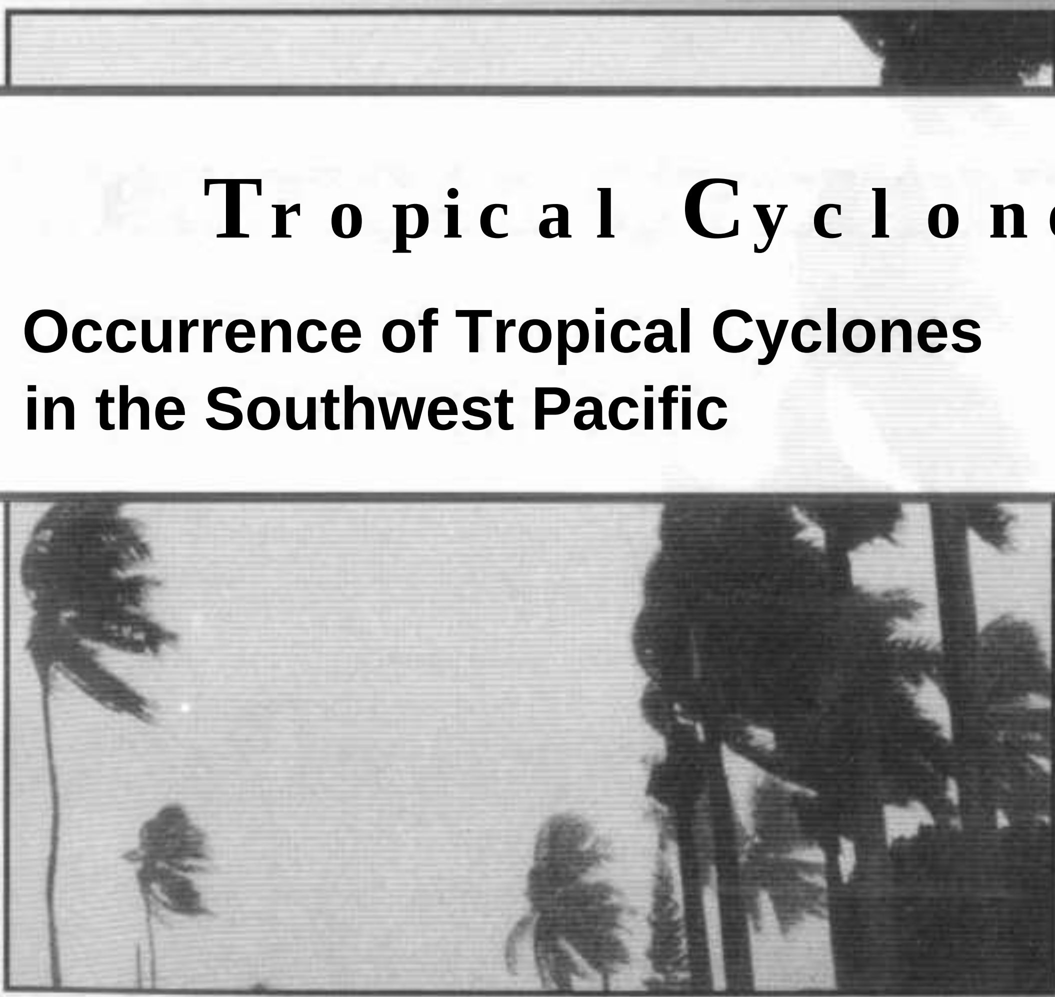
Dangerous Climatic Change -1996

Tropical Cyclones

Occurrence of Tropical Cyclones in the Southwest Pacific



GREENPEACE International

Occurrence of Tropical Cyclones in the Southwest Pacific Region 1920-1994

GflsemeAar

REPORT

1996

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EXECUTIVE SUMMARY

This report examines the occurrence and intensity of tropical cyclones that have occurred in the southwest Pacific for the period 1920-1994. A newly compiled database has been used to accomplish the analysis. Seventy-four seasons of data are analysed, but as it is unlikely that all historical occurrences have been detected, particular emphasis has been placed on analysing data for the past 30 years. The project aims to detect any variation in the number and intensity of tropical cyclones and to ascertain if any changes detected result from climate change due to human activity.

A large interannual variability is shown, with the seasonal occurrence ranging from 2 to 16 tropical cyclones per season, 8 being the average occurrence. Since the mid-1950s the seasonal average is 9.4, prior to that the seasonal average is 6.4. This change in the average is most likely due to the incomplete reporting of tropical cyclone occurrences prior to the Second World War. The data for the past 30 years show a slight increase in tropical cyclone numbers but this increase is not statistically significant.

Each tropical cyclone has been allocated an intensity based on its maximum wind speed; however, meteorological data required to allocate intensity are not available for many occurrences prior to the 1950s. The data available for the past 30 years show some conflict for the tropical cyclones in the higher categories. Whilst one of the statistical tests does show a significant increase in intensity, this result is viewed with caution due to the conflicting meteorological data.

Sunrise in the Pacific. The seasonal occurrence of tropical cyclones over the past 74 seasons ranges from 2 to 16, with the average being 8.

Statistical analysis shows that during strong El Niño or La Niña seasons, there is a significant increase in tropical cyclone numbers. The mean increase for strong El Niño seasons is 14% and 27% for strong La Niña seasons. It is also shown that the variance, of the annual tropical cyclone numbers increases as the absolute magnitude of the SOI increases, therefore there may be occasional strong El Niño or La Niña seasons during which a low number of tropical cyclones occur. The periodicity of tropical cyclone activity increased from 6-8 years prior to the 1950s, to 2 and 3-5 years since the 1950s. These shorter periodicities are generally associated with ENSO and a QBO-type signal.

This report presents mixed results. Whilst there is no significant change in seasonal tropical cyclone occurrence, and only a possible increase in intensity, there has been an increase in the occurrence of strong ENSO years. If the periodicity of the strong ENSO years becomes more frequent, it is possible that an increase in tropical cyclone numbers may occur. At this stage, it is not possible to state that any changes to the climate regime are due to the natural climate system or to human activity.

INTRODUCTION

Approximately 80 tropical cyclones form annually throughout the world, their formation being confined to those tropical ocean basins shown in Figure 1. About two thirds of these tropical cyclones produce wind speeds of 118 kilometres per hour or greater (Frank, 1987) and have the potential for causing extreme damage. In the southwest Pacific, tropical cyclones are classified according to the wind speed they attain. For example, a tropical cyclone with a wind speed between 118-166km/h is known as a hurricane, a tropical cyclone with a wind speed greater than 167km/h is a major hurricane.[1] In order to avoid confusion, the term tropical cyclone is used throughout this report to refer to those tropical circulations which attain wind speeds of at least 118 km/h during their lifespan.

In the past decade, storms and tropical cyclones worldwide have led to unprecedented damage. The consequences of tropical cyclones in the southwest Pacific have caused great damage and as Pacific island countries become more developed, their vulnerability to the impact of tropical cyclones grows; any increase in number or intensity of tropical cyclones will have greater repercussions than they would have otherwise. The consequences of recent tropical cyclones in the southwest Pacific are well documented. Although they occasionally bring much-needed rain to particular islands, more often they are associated with catastrophic impacts on island environments resulting from their high winds, torrential rain, and storm surges — for example, Cyclone Val (1991) caused US$250 million damage in Western and American Samoa.

The perceived worldwide trend in increased "storminess" has intensified the debate linking a rise in mean global temperature with an increased number of extreme climatic events. It is the aim of this report to uncover any connections between mean global temperature rise and patterns of tropical cyclone occurrence and intensity in the southwest Pacific Basin by:

1. identifying any changes in the frequency and intensity of tropical cyclones in the southwest Pacific from 1920 to the present,

2. identifying any relationships between tropical cyclones frequency and El Niño-Southern Oscillation (ENSO) events, and

3. considering possible links with any identified changes in the frequency and/or intensity of tropical cyclones in the southwest Pacific and the changes projected under an anthropogenic climate change regime.

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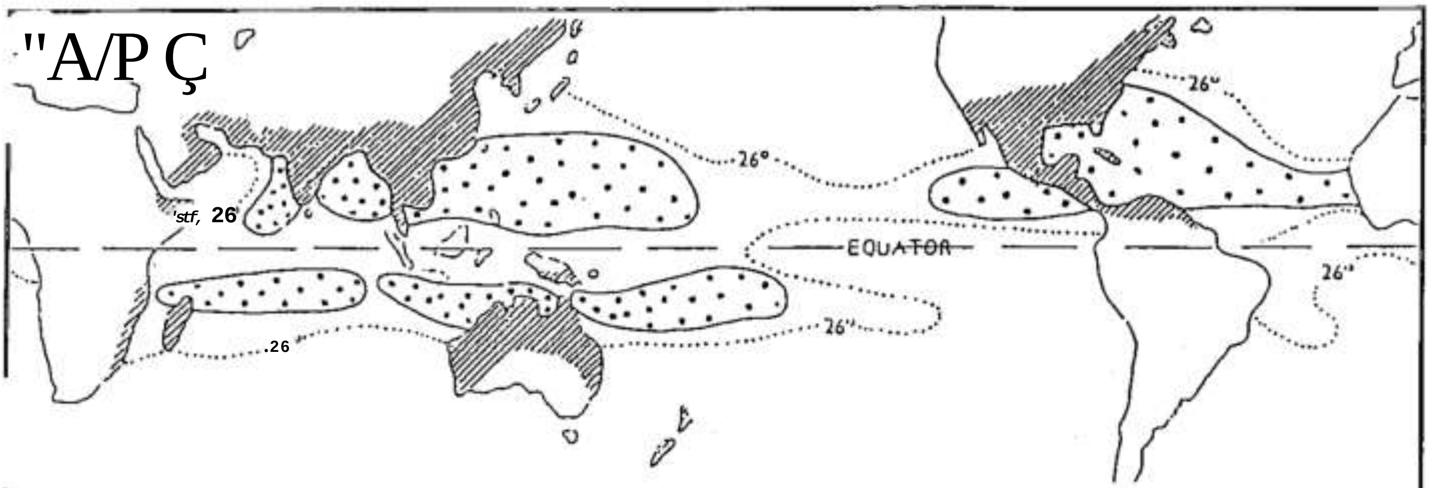
[1] Tropical cyclone classification in the southwest Pacific.
(Revell, 1981. P3)

	knots	km/h
Below gale	<34	<62
Gale	34-47	62-88
Storm	48-63	89-117
Hurricane	>63	>117
Major hurricane	>90	>167

With the aid of a newly compiled database, this report examines the historical record to determine any past trends in tropical cyclone occurrence and intensity. Given the short period of time for which a complete data set on tropical cyclone occurrence is available, as well as the occasional difficulties experienced in the determination of tropical cyclone status, this examination is simpler in theory than in practice. Owing to these limitations the analysis considers tropical cyclones which occurred in the seasons 1920/21-1993/94 but examines more particularly those occurrences of the past 30 years.

Figure 1: Areas of formation of tropical cyclones.



Areas of formation of tropical cyclones

Land areas affected by tropical cyclones

The limit of 26° C sea surface temperature.

Source: Adapted from Crane 1990, after Gray 1968

The text is divided into three major parts. Part 1 contains a description of the newly compiled data and a brief introduction to a few theoretical aspects related to tropical cyclone activity. Part 2 describes the temporal characteristics and impacts of the data and gives a comprehensive descriptive summary of major findings. Part 3, the annexe section, contains the detailed results of individual analyses and a description of the methodologies used in this study.

PART I

DATA USED FOR THIS STUDY

This database includes all those tropical cyclones which have formed south of the equator from the Gulf of Carpentaria in the west (selected tropical cyclones) to the limit of tropical cyclone formation in the east (French Polynesia). Those tropical cyclones which formed in the Gulf of Carpentaria and subsequently tracked towards the east coast of Queensland, north Australia, have been included in the database. Those tropical cyclones which formed in the Gulf of Carpentaria and tracked towards the west of Australia have not been.

Occurrences of tropical cyclones and storms in the southwest Pacific were first collected by Dobson in 1853; the next major list was compiled in 1925 by Visher. A major historical survey by Kerr (1976), includes the thirty years, 1939-1969. Since 1969, decadal surveys of tropical cyclones in the southwest Pacific have been published by Revell (1981), for the seasons 1969-1979 and Thompson *et al.* (1992), for the seasons 1979-1989. Lists of tropical cyclones are also compiled by meteorological services within individual Pacific Island countries. The New Zealand Meteorological Service (NZMS) has compiled a list of tropical cyclone occurrences, 1939-1994 which is also held by the National Institute of Water and Atmospheric Research (NIWA). The National Oceanic and Atmospheric Administration (NOAA), 1994 has produced a global list of tropical cyclones which includes a southwest Pacific section.

In 1994 Ana Maria d'Aubert, under the auspices of Dr Patrick Nunn at the University of the South Pacific, Suva, compiled a list of tropical cyclone and storm occurrences (1558-1970). This is a compilation of occurrences, with a number of listings according to country affected rather than specific tropical cyclone occurrences. For the present study this list has been edited to eliminate double counting of tropical cyclones and to exclude those storms believed not to have been tropical cyclones.

The list of tropical cyclones has been supplemented and extended to May 1994 with data compiled by meteorological agencies and the Natural Hazards Research Centre (NHRC), Macquarie University. Tropical cyclone databases compiled by the latter include those for Australia, Fiji, Vanuatu and Solomon Islands (NHRC, 1991, 1992(a), 1992(b): Radford and Blong 1991). These databases also contain information describing damage to buildings, infrastructure, agriculture *etc.* For many countries, scientific reports, newspapers, missionary and government records have been examined as well as meteorological data. The Australian data have been compiled from Lourensz (1977) and the Australian Bureau of Meteorology (BOM 1995). The latter is a tropical cyclone database for Queensland spanning the years 1909-1995 and currently being enhanced and updated.

Discrepancies in the number of occurrences of tropical cyclones occur. As part of the Australian area of responsibility overlaps into the southwest Pacific, there are some tropical cyclones which have affected the east coast of Australia and do not track into the NZMS area. As a result they may not be included in the NZMS database — for example, cyclones Pierre and Tanya (1985) and Becky (1968). Longworth (1993) lists 19 named tropical cyclones which are not included in the NZMS database.

Assigning alternate men's and women's names to tropical cyclones has been routine since 1973 and assigning a name commonly implies that tropical cyclone status has been reached. The determination of tropical cyclone status is sometimes difficult but has been facilitated by the use of satellite imagery. Despite this, there were 7 unnamed cyclones during the decade November 1979 to May 1989. They are described as minor and their classification of tropical cyclone status is open to debate (Thompson *et al.* 1992). Obviously, if status can be problematic even when satellite images are available, it is much more difficult to be confident that all tropical cyclones from the pre-satellite era did reach that status.

The final database contains 593 tropical cyclones which occurred during the 74 seasons, 1920/21 to 1993/94. Information relating to the meteorology of the tropical cyclones has been included and, for many of them, extensive information describing damage, cause of damage, health impacts and cause of death.

TROPICAL CYCLONE FORMATION

Tropical cyclones are revolving tropical storms with a closed circulation. The area of lowest pressure is the centre of the tropical cyclone — the eye, which is a region of warm subsiding air and is therefore generally calm with a clear blue sky above. The eyewall surrounds the eye and is the region of maximum wind speeds. For tropical cyclone status to be declared these wind speeds must be at least 63 kilometres per hour. Typically, the radius of the eye may reach 30 kilometres and the outer circulation may extend to a radius of 2,000 kilometres. In the southern hemisphere, tropical cyclones rotate in a clockwise direction and, as they move forward, the wind speeds are usually greatest in the front left quadrant of the tropical cyclone.

Specific conditions are required for the formation of tropical cyclones, which confine their formation to particular ocean basins (Frank, 1987). Figure 1 shows the pattern of global distribution of areas of formation and indicates those oceanic areas conducive to tropical cyclone development. The basic requirements for cyclone formation are as follows:

1. a significant level of cyclonic absolute vorticity (which is a function of the Coriolis force that has to be strong enough to allow the storm to curve, and does not occur until about 4-5° from the equator),

2. a sea surface temperature of at least 26.5°C with a warm water depth of at least 60 metres,

3. atmospheric conditions which allow the moist parcels of air to ascend, and

4. a weak vertical wind shear (different wind speed or wind direction in two adjacent vertical layers) over the pre-cyclone disturbance.

The last two conditions are met by the Equatorial Trough and the South Pacific Convergence Zone (SPCZ), which are the dominant climatic features of the southwest Pacific basin. It is within these zones that most tropical cyclones form. As the tropical cyclone moves over land or cooler waters, energy to maintain its form and strength is no longer available; however, heavy rain may still occur.

TROPICAL CYCLONE INTENSITY

Intensities are assigned to tropical cyclones according to the maximum wind speed or, if the wind speed is not available, the minimum atmospheric pressure attained by the tropical cyclone. Since the mid-1960s these attributes have been routinely estimated from satellite imagery.

Prior to the satellite era, the only method of determining the wind speed or atmospheric pressure was from direct measurement on the ground, supplemented with some aircraft and radar observations after about 1939.

As the measurements were rarely made in the eye of the cyclone, these recordings usually do not reflect the maximum which actually occurred, and the assigned intensity may be lower than in fact. However, they still may be within the range of the intensity assigned to the cyclone.

In some instances there are conflicting reports of maximum wind speeds and/or minimum pressure assigned to a particular tropical cyclone by different meteorological agencies and also within the same agency. In those cases, the maximum wind or minimum pressure has been used to assign the intensity.

There are a number of scales available to assign intensities (also called categories in this report) to tropical cyclones. For this, study, the Australian Cyclone Severity Scale (BOM 1990) has been used. The intensities in this scale range from 1 to 5, where 1 is the lowest intensity and 5 is the highest. Table 1 lists the intensities with their associated wind speeds and central pressures and the damaging effects attributed to each intensity.

All of the 593 tropical cyclones included in the database have been assigned an intensity. Intensity 1 has been assigned to those tropical cyclones which did not have reported wind speeds or atmospheric pressures. Some earlier tropical cyclones may not have achieved category 1 status and therefore should not be included; others, according to damage reports resulting from them, may have achieved a higher intensity and so should be assigned a higher category.

Table 1: Australian Cyclone Severity Scale

Category	Maximum Wind Gust (km/h)	Central Pressure (hPa)	Potential Damage	Effects
1	<125	983-994	Minor	Negligible house damage; damage to some crops, trees and caravans; craft may drag at moorings
2	125-169	971-982	Moderate	Minor house damage; significant damage to signs, trees and caravans; heavy damage to some crops; risk of power failure; small craft may break moorings
3	170-224	946-970	Major	Some roof and structural damage; some caravans destroyed; power failure likely
4	225-279	920-945	Devastating	Significant roofing loss and structural damage; many caravans destroyed and blown away; dangerous airborne debris; widespread power failures
5	>280	<920	Extreme	Extremely dangerous with widespread destruction

Source: Australian Bureau of Meteorology 1990

IMPLICATIONS OF TROPICAL CYCLONE OCCURRENCES

Each country in the southwest Pacific basin is at risk from some degree of social and economic damage and disruption as a result of tropical cyclones. Those countries which are closer to the equator — Solomon Islands, Kiribati, Tuvalu and Tokelau — are not affected as frequently as, say, Fiji or Vanuatu. Cook Islands and French Polynesia, situated at the eastern limit of tropical cyclone formation, tend only to be affected during El Niño years, probably as a result of the eastward shift of the convergence zones. During 1982/83, a strong El Niño season, 6 tropical cyclones formed in the eastern part of the basin, affecting French Polynesia.

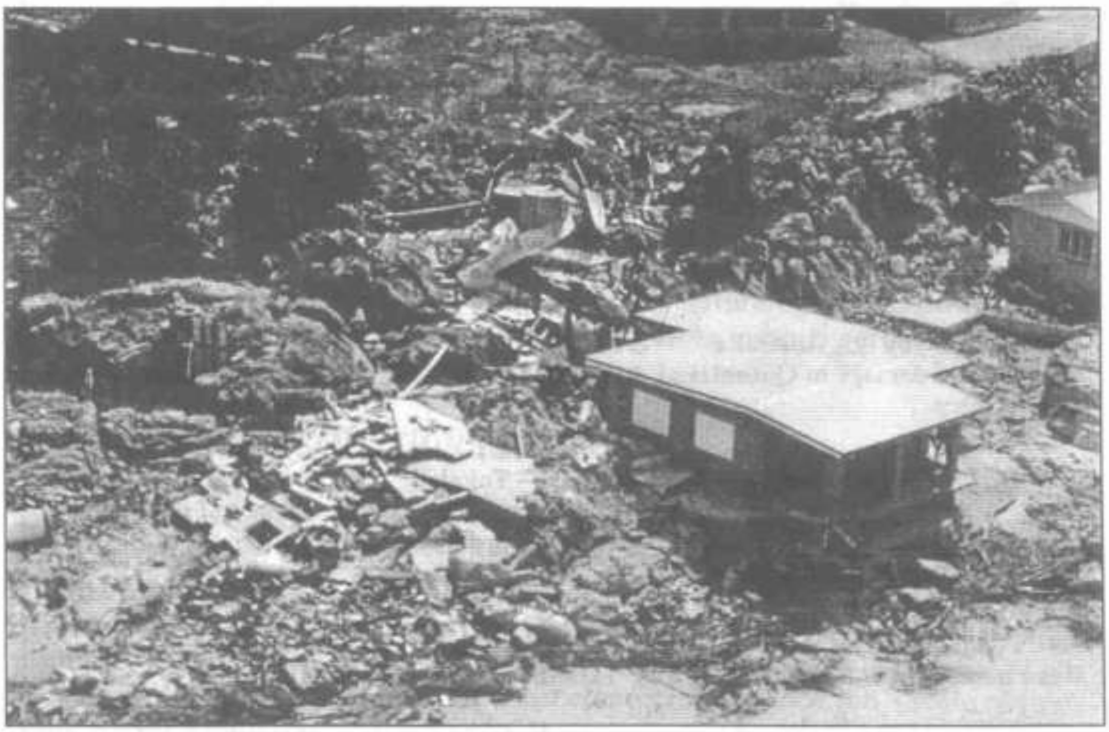
Table 2 gives an overview of a number of more recent tropical cyclones and illustrates some of the attributes which influence the amount of damage and injury resulting from tropical cyclones. The category of the tropical cyclone, the countries affected and the type of impact are included in the table.

As the category assigned to tropical cyclones is based on wind speed, the potential damage resulting from agents other than wind is not directly represented by the category; such agents include storm surge, high seas and high rainfalls which result in flood, landslide and water penetration of buildings. With increasing development and expanding populations, some of these impacts will become more important — for example, an increased demand for housing forces building onto more marginal areas which may be prone to landslides or floods. Loss of infrastructure and damage to commercial buildings and their contents have a detrimental impact on business, whilst damage to the environment and hotels impacts on the tourism industry.

Less intense tropical cyclones, that is, those with lower wind speed, do cause damage and injury which is not reflected by the assigned category. Cyclone Gisele (1968) and Bola (1988) tracked as far south as New Zealand and through interaction with mid-latitude circulation caused considerable damage by wind and flooding, although by then they had lost their warm-core tropical character. Rough seas resulting from Cyclone Gisele led to 57 deaths when an inter-island ferry foundered in Wellington Harbour. Cyclone Wally (1980) had probably not attained category 1 status when 840 mm (33 inches) of rain fell in Suva and surrounding areas, causing severe landslides and floods along the south coast of Viti Levu, Fiji.

There are a number of other aspects which determine the impact of a tropical cyclone; these include the forward speed, size and path of the tropical cyclone. Cyclone Val (1991) was slow moving as it passed directly over Western and American Samoa. The slow movement increased the time available to cause damage and, as its path was directly over the islands, the impact was greater than if it had been further out to sea.

On occasions, tropical cyclones occur in pairs, the second following swiftly after the first. For example, about 48 hours after Cyclone Eric (1985) had caused severe damage in Fiji, cyclone Nigel followed a track just slightly north of Eric's path, thus compounding the damage.



Storm surge damage by Tropical Cyclone Aivu, *Wunjunga, Queensland, 1989.*

Table 2: Tropicalcyclones, intensity, countries affected and some aspects of the cyclone and the damage incurred. [Australian Cyclone Severity Scale (the intensity) is in parentheses]

1968 *Gisele (2)* **New Zealand**
Rough seas in Wellington Harbour caused the "Wahine" to founder with the loss of 57 lives.

1980 *Wally (1)* **Fiji**
Severe floods and landslides resulting from 840mm (33 inches) of rain falling in Suva in 4 days. Occurred one week after Cyclone Joni.

1983 *Lisa (1) Nano (2) Nisha (3) Rewa (3) Veena (3) William (2)* **French Polynesia**
Six tropical cyclones occurred in one season causing damage within 30 of the 40 inhabited islands. Veena was the most damaging tropical cyclone for 20 years.

1985 *Eric (3) and Nigel (3)* **Fiji - Vanuatu - Tonga**
Two cyclones within days of each other. Severe impact on Fiji. Total insurance damage in Fiji and Vanuatu A$134 million (1995 dollars). Crop damage in Tonga.

1986 *Cyclone Namu (3)* **Solomon Islands**
Occurred in May, generally considered outside the cyclone season. 90% of the population in the Central Division affected. Floods and landslides washed away entire villages in the Guadalcanal highlands. Ill people dead, 61 resulting from landslides.

1987 *Cyclone Uma (3)* **Vanuatu**
Rough seas and storm surge destroyed 40 boats in Port Vila Harbour. 95% of buildings damaged in Port Vila, mainly due to high winds. Loss of power and water supplies.

1990 *Cyclone Ofa (4)* **Samoa — Tonga — Niue**
Every village damaged in Western Samoa. Storm surge obliterated parts of some communities, reshaped the coastline and created islands of coral debris near the reef line. Damage to buildings and infrastructure in Tonga. Mountainous seas in Niue, boulders of coral smashed through the wards of the hospital.

1990 *Cyclone Joy (4)* **Australia**
A$68 million damage in Queensland due to floods and high winds. $32 million loss to coal industry.

1991 *Cyclone Val (4)* **Samoa — Cook Islands — Tokelau**
Passed directly over Western and American Samoa. The slow movement of the cyclone increased its impact. Estimated US$250 million damage (1991 dollars). 16 deaths. Seawall damage in Cook Islands

1992 *Cyclone Fran (4)* **Wallis & Futuna — Fiji — Vanuatu — New Caledonia**
Major damage to buildings in Port Vila. Extensive water damage to buildings.

1993 *Cyclone Kina (3)* **Fiji**
Severe flooding. Communications cut and destruction of crops, livestock and infrastructure. High tides and heavy seas blocked the mouths of major rivers. Three major bridges destroyed.

EL NIÑO - SOUTHERN OSCILLATION (ENSO)

The El Niño - Southern Oscillation (ENSO) is an ocean-atmosphere phenomenon that strongly influences the climatic conditions in the Australia-Pacific Ocean region (as well as other parts of the world). It is based on contrasting anomalous climatic conditions between the Australian region and the eastern Pacific Ocean and it can cause extensive droughts and floods throughout the region. As the name suggests, ENSO consists of two components — the atmospheric Southern Oscillation (SO) and the oceanic El Niño — which are dynamically coupled. Linked by their ability to exchange heat, the atmosphere and ocean influence the strength of the large-scale Walker Circulation in the Pacific Ocean region (Walker, 1923). Any small changes occurring in one part of the coupled system can thus have implications for the entire region. The strength of ENSO is measured by the Southern Oscillation Index (SOI) which, in its most basic form, is expressed as the mean monthly atmospheric pressure difference between Tahiti and Darwin, expressed in standard deviation form. For example, a value of -2 during an El Niño event means two standard deviations below the mean pressure difference. When the SOI is negative (known as El Niño), the Australian region (north and east) and the adjacent southwest Pacific islands (for example, New Caledonia) tend to experience anomalously dry conditions, whereas the central region of the Pacific Ocean, for example Kiribati, record anomalously high rainfall. The conditions are reversed during periods of positive SOI, referred to as La Niña in this report, and also known as anti-El Niño (for example, McBride and Nicholls, 1983; Ropelewski and Halpert, 1987).

Our understanding of the ENSO processes is only partial and relatively recent (for example, Bjerknes, 1969; Rasmusson and Carpenter, 1982; Ropelewski and Halpert, 1987). However, the gradual progress made in this area has led to the development of the first ENSO models (for example, Zebiak and Cane, 1987) and allowed us to link ENSO to the variability of various atmospheric and oceanic variables, amongst them the activity of tropical cyclones. While it is possible to link ENSO to tropical cyclone activity in limited areas, like the Australian region (for example, Nicholls, 1984), the western Atlantic (Gray, 1984) or the northwestern Pacific (Chan, 1995), the relationship is weaker when larger ocean areas are considered. This is due to the transient nature of ENSO and the overall equalising effect of the different signals coming from various parts of the ocean.

QUASI-BIENNIAL OSCILLATION (QBO)

Many climatic variables such as sea surface and air temperature, cloudiness or wind strength are known to display quasi-regular short-term and long-term fluctuations with a range of periods (for example, Barnett, 1991). The more prominent and better described climatic oscillations are those of 40-50 days (for example. Madden and Julian, 1971) and the quasi-biennial pulse (for example, Trenberth, 1980). In the tropics, the most common low-mode (on a scale of years) atmospheric oscillations are generally those associated with the SO and the QBO (for example, Ropelewski *et al.,* 1992). Although the mechanisms of these phenomena are not yet fully understood, these events occur in quasi-regular intervals with periodicities in the range of 2-7 years and 2.2 years, respectively (for example, Philander, 1983; Ropelewski *et al.,* 1992). It has been shown that the

QBO, which is sometimes described as the pacemaker of interannual variability, has a period slightly in excess of 2 years and is a global phenomenon (for example, Ropelewski *et al.*, 1992 ; Jury *et al.*, 1994).

Although the QBO is traditionally associated with the variability of the upper level winds in the tropics (for example, Landsberg, 1962), it is now known that other variables, such as atmospheric pressure, temperature or even crop yields (for example, Trenberth, 1980; Zolotokrylin, 1985; Ropelewski *et al.*, 1992) sometime display a QBO-like behaviour. Depending on the variable, the latter signal may or may not be in phase or directly related to the QBO of the winds.

Solomon Islands — damage caused by Tropical Cyclone Namu, *May 1986.*

ENHANCED GREENHOUSE EFFECT

Climate change can be generally associated with one or both of two distinctly different components: the natural long-term variability of the climate and the anthropogenic contribution to the natural greenhouse effect of the Earth. The former component relates to the natural long-term fluctuations of the global temperature and the atmospheric CO_2 content, which has been more or less stable for the past 10,000 years (Raynaud *et al.*, 1993). The latter component is caused by man through increasing emissions of greenhouse gases into the atmosphere. Gradually, these emissions will enhance the natural greenhouse effect of the Earth by absorbing more of the outgoing longwave radiation and re-emitting it back to Earth. While the natural greenhouse effect makes the global temperature 33 degrees warmer than it would be without any atmosphere, the relatively recent (last 200 years) anthropogenic increase in greenhouse gas concentrations is expected to raise the mean temperatures even further. Climate model simulations suggest that this increase will be in the order of a couple of degrees during the next century (Houghton *et al.*, 1992). Warmer air and sea surface temperatures (SSTs) are not only expected to raise the sea level (due to thermal expansion of the oceans and by melting of glaciers and land ice sheets), but also to alter the current atmospheric and oceanic circulation patterns.

With respect to tropical cyclogenesis, the warmer SSTs could, theoretically, lead to longer cyclone seasons, more intense cyclones and more cyclones overall. However, it is not clear whether the effect of the warmer SSTs will be offset by a different behaviour of ENSO or by a concurrent mid-tropospheric warming which would make the atmosphere more stable (Holland *et al,* 1988). The results of model simulations are, so far, similarly inconclusive. Some model simulations have indeed shown an increase in tropical cyclogenes is parameters under enhanced greenhouse conditions (for example, Broccoli and Manabe, 1990; Ryan *et al.* 1992), but the crucial ocean components of these models were extremely simplified.

PART 2

TROPICAL CYCLONE FREQUENCY

The occurrence of tropical cyclones in the Southern Hemisphere is referred to as seasonal rather than annual since their occurrence spans the end of one calendar year and the beginning of the following year. The season is generally considered to be November to April with few occurrences in September, October and May.

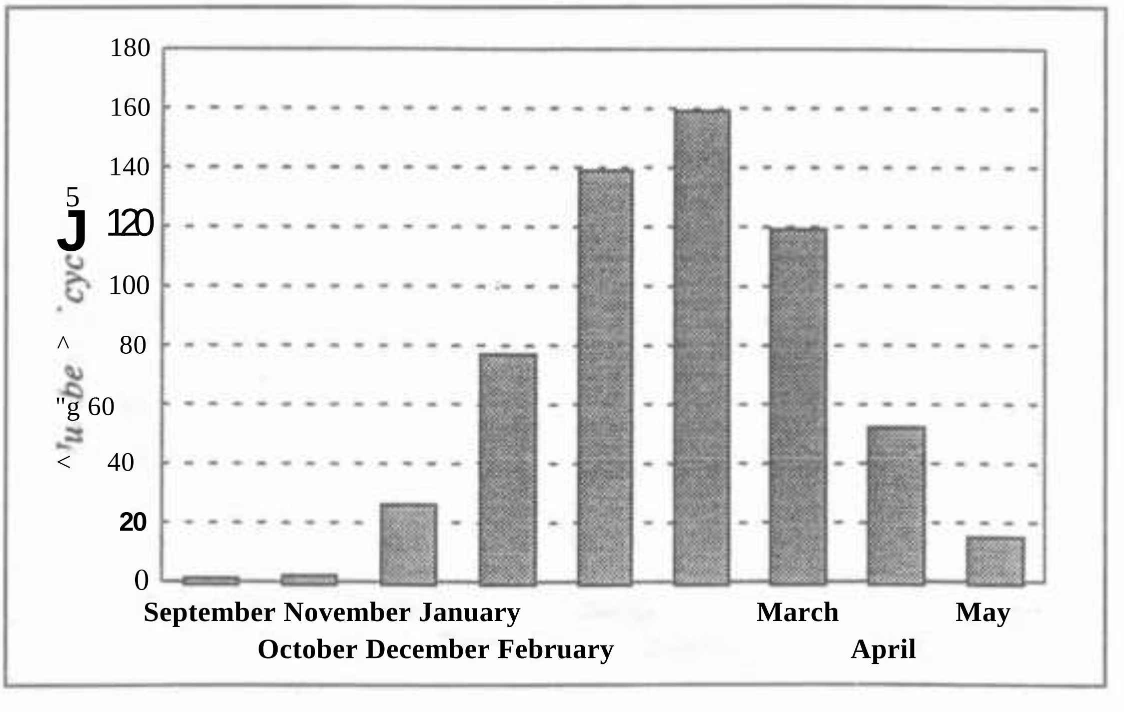
Monthly occurrences

Monthly occurrences are based on the date that a tropical cyclone was first noted to have formed; the month of occurrence is known for 590 of the 593 tropical cyclones in the database. Figure 2 shows the monthly occurrence since the 1920/21 season. The one September occurrence was in 1924 which caused damage to some ships to the west of New Caledonia; the two October occurrences were in 1970 and 1972. Both the October tropical cyclones affected Fiji, Nora (1970) being a minor occurrence. Tropical Cyclone Bebe (1972) was at the time considered to be the most devastating to have affected Fiji, and its effects in Tuvalu were reported as the worst since the 1891 cyclone.

Of the 15 May occurrences in the record, five occurred between 1982 and 1989, one in 1991 (Lisa) and one in 1993 (Adele).

The preferred months of occurrence are December to March with a total of 83% recorded during those four months. 27% of the recorded tropical cyclones occurred in February.

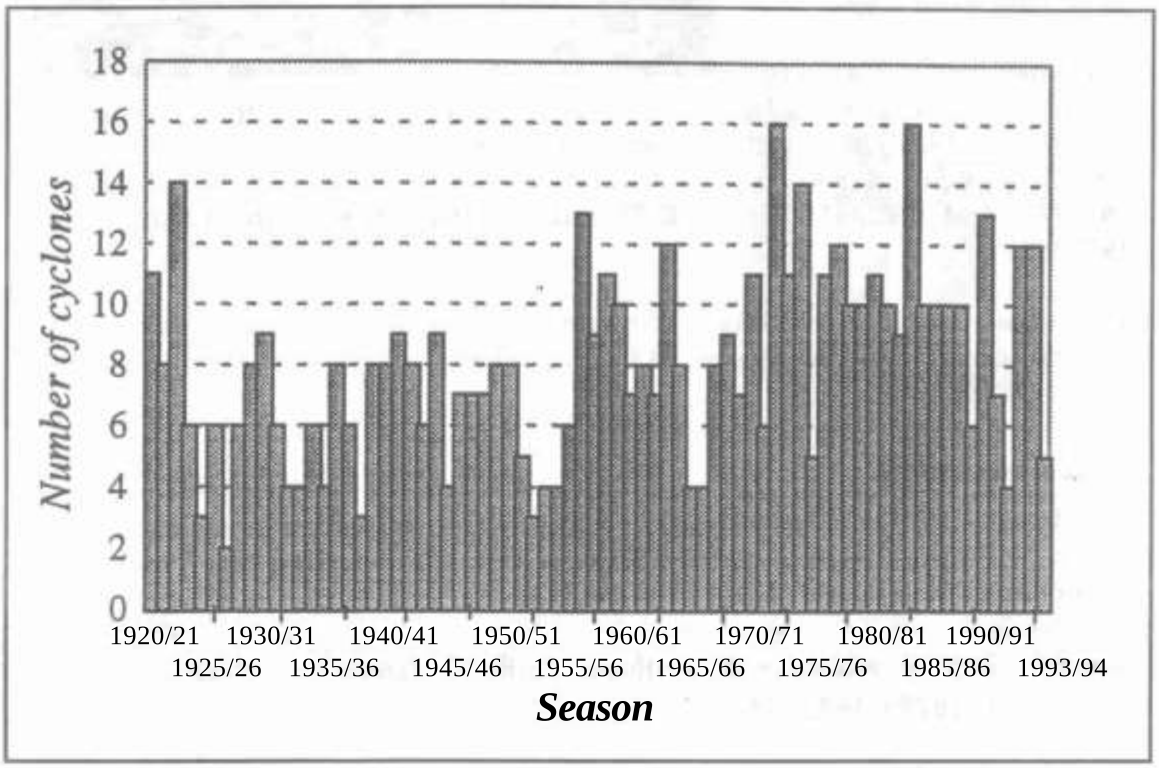
Figure 2: Tropical cyclones in the southwest Pacific — monthly occurrence 1920/21-1993/94



Seasonal occurrences

Figure 3 shows the number of tropical cyclones which have occurred each season since 1920. The average number of tropical cyclones per season is 8; the season 1955/56 marks the beginning of an average occurrence of 9.4 per season, with 6.4 per season being the average prior to then.

Figure 3: Tropical cyclones in the southwest Pacific — seasonal occurrence 1920/21 to 1993/94



There is an apparent dip in the number of occurrences between the early 1920s and the mid 1950s. There were 11 tropical cyclones in 1920/21 and 14 during 1922/23. The 1922/23 season has been documented by Twentyman (1923) the then harbourmaster at Suva. He reported this season to have been the most interesting hurricane season that he had experienced during his twenty years residency in Fiji, owing to the large number of occurrences. In the seasons 1922/23-1955/56 there were no more than 9 tropical cyclones in any one season.

Prior to World War II, tropical cyclones were detected and reported by ships at sea and by land stations. During and following World War II, further detection methods became available resulting from the increased use of aircraft, surface and radar observations. Since the advent of satellites in the 1960s the detection of tropical cyclones is considered complete and intensity has been more accurately estimated.

The temporal spread of tropical cyclones by season from the beginning of 1920 to 1994 shows a seasonal occurrence as low as 2 (in 1926/27) and as high as 16 (in

1971/72 and 1982/83).

Whilst the 1926/27 figure may be considered low due to a lack of detection, note that only 4 tropical cyclones were recorded during 1990/91, a satellite era season.

House damage caused by Cyclone Althea, *Townsville, Queensland, December 1971.*

Since the advent of satellites there have been a total of 10 seasons when 6 tropical cyclones or less have occurred: 3 occurrences in 1924/25, 1937/38 and 1951/52, 4 in 1964/65, 1965/66, and 1990/91; 5 in 1974/75 and 1993/94 and 6 during 1970/71 and 1987/88.

There have been 4 occasions in the entire record where 14 or more tropical cyclones occurred in one season: 14 in 1922/23 and 1973/7 4, 16 in 1971/72 and 16 in 1982/83.

Decadal occurrences

The decadal frequency of tropical cyclones is shown in Figures 4 and 5. The graph in Figure 5 was generated from a data set including the 7 marginal cyclones recorded by the NZMS from the 1980s.

Figure 4: Tropical cyclones in the southwest Pacific — decadal occurrence 1920/21-1993/94

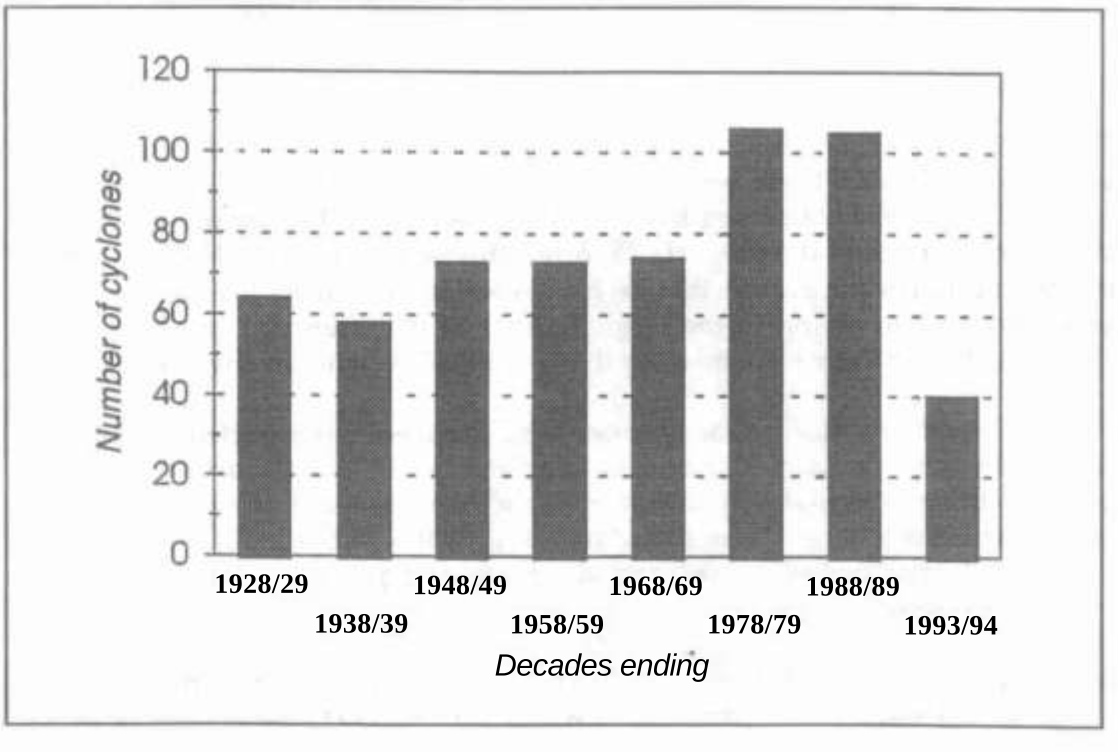


Figure 5: Tropical cyclones in the southwest Pacific — decadal occurrence 1920/21-1993/94 (including the 7 unnamed cyclones)

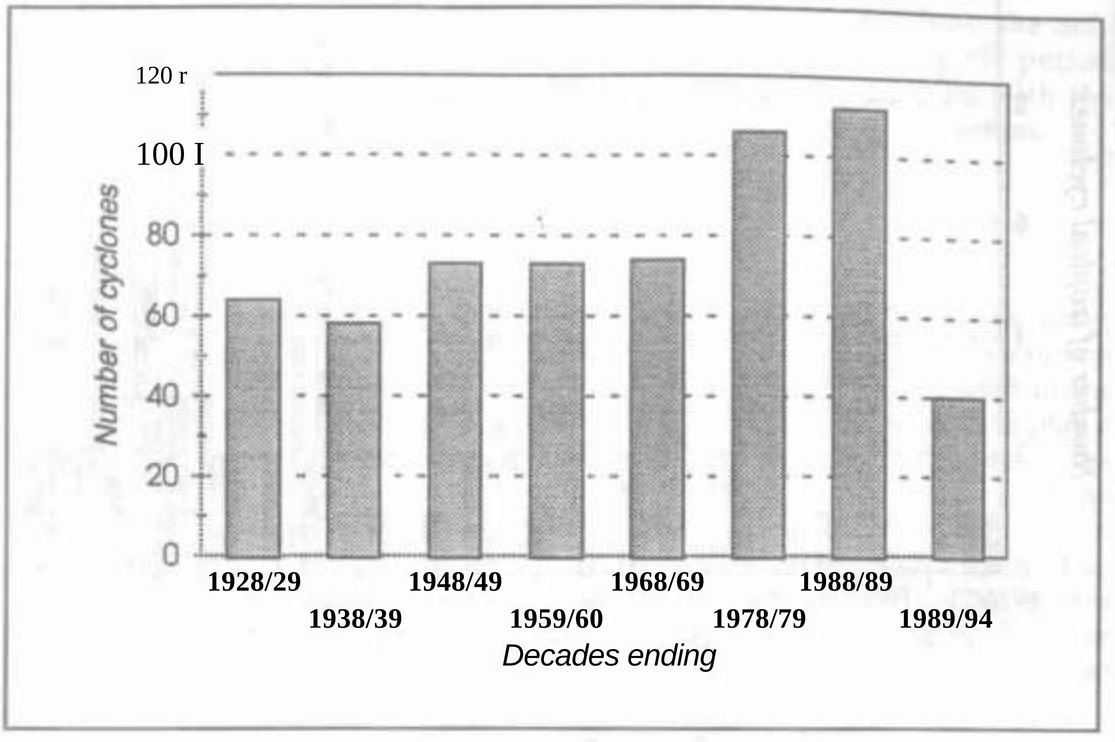
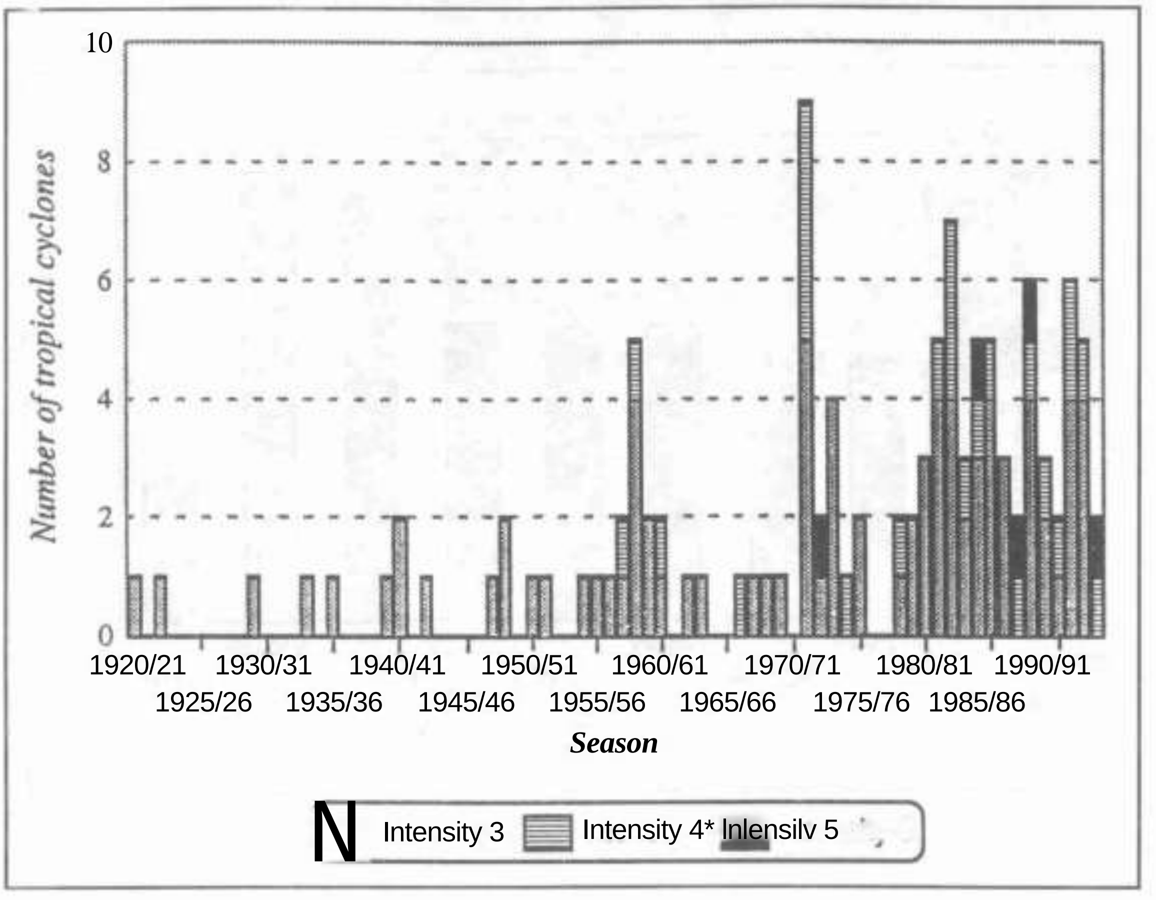


Figure 4 shows that the number of tropical cyclones recorded for the decades prior to the 1970s is between 58 to 72. In the decade ending 1978/79 the number increased to 106 and 105 occurred during the 1988/89 decade. This latter figure increases to 112 when the 7 unnamed tropical cyclones (Thompson *et al.* 1992) are included (see Figure 5).

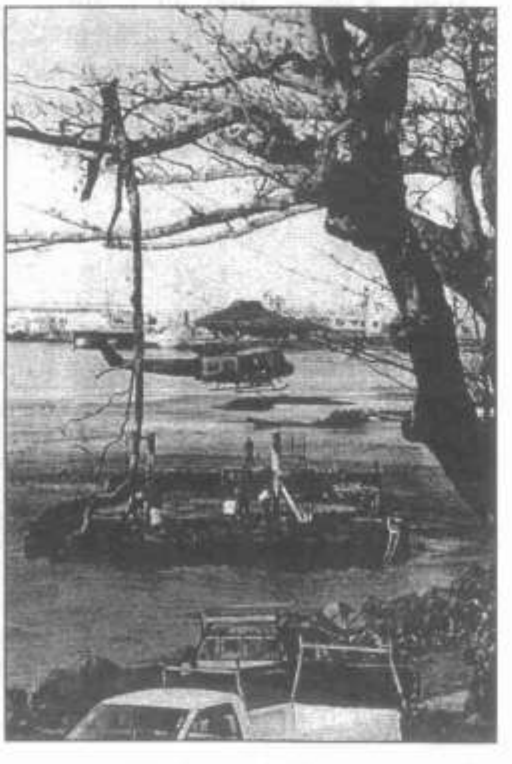
INTENSITY

Tropical cyclones of all intensities have been observed in the southwest Pacific basin. Figure 6 shows all those tropical cyclones since the 1920/21 season which have been allocated an intensity of 3 or greater. Due to the lack of meteorological data in the early decades, there are few reported occurrences of tropical cyclones with intensities greater than category 1 or 2 and none with intensities equal to or greater than category 4 until the 1957/58 season.



Of the 593 tropical cyclones which occurred in this period, 113 (19%) achieved an intensity of 3 or greater. 83 (14%) achieved intensity 3, 25 (4.2%), intensity 4 and 5, and (0.8%) intensity 5.

There are five tropical cyclones of intensity 5 represented on the graph. Of these, only one, Cyclone Bebe (1972), does not have conflicting reported meteorological data.
For example, Cyclone Anne (1988) has a maximum wind speed of intensity 3 (185km/h) reported by the NZMS, a maximum wind speed of intensity 4 (259km/h) reported by NOAA and a minimum pressure of intensity 5 (898hPa) also reported by NOAA. Another example is Cyclone Val (1991). This cyclone was intensity 3 according to NZMS data and intensity 4 according to NOAA.



An Iroquois helicopter lifting a motor off a barge — Tropical Cyclone Val, *Western Somoa, December 1991.*

The one outstanding season is 1970/1971, a strong La Niña season, when a total of 9 tropical cyclones occurred which were assigned category 3 or 4.

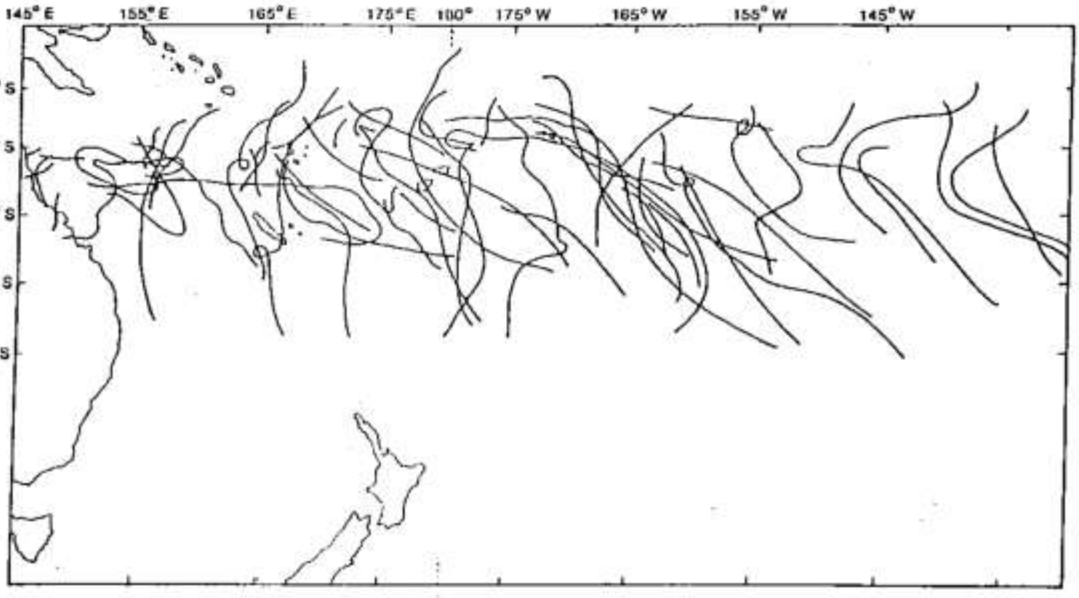
As described in Appendix D, the intensity of the tropical cyclones is the only variable in this study that shows a significant increase during the period 1964/65-1993/94. Owing to the intrinsic difficulties associated with the estimation of this parameter, this result has to be used with extreme caution.

ENSO AND QUASI-BIENNIAL OCCURRENCES (QBO)

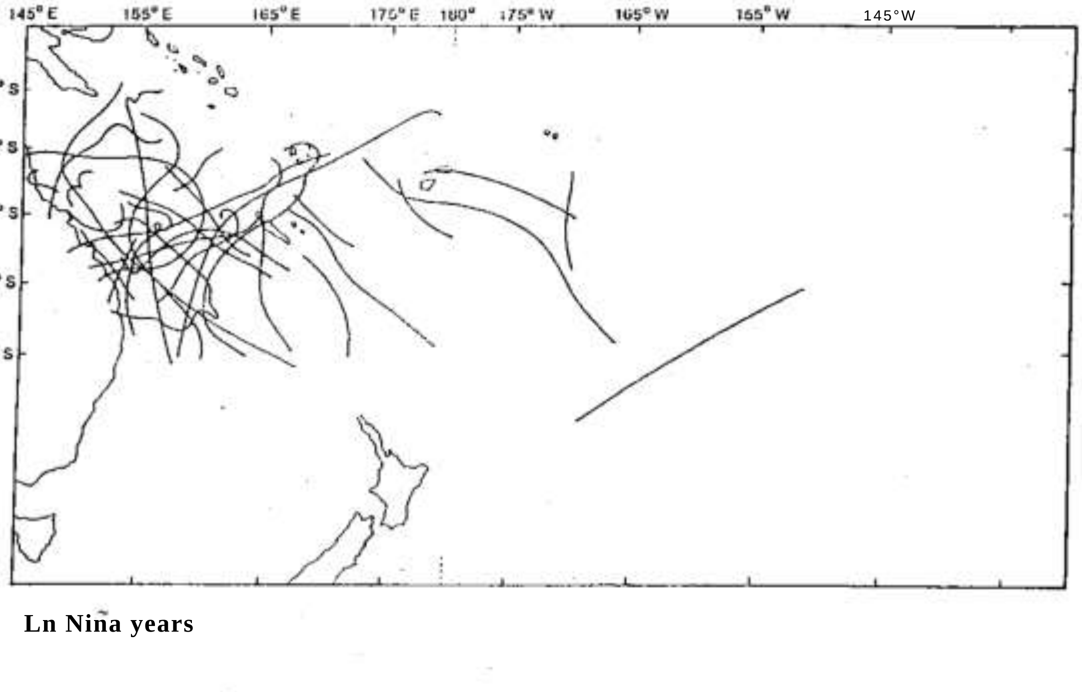
ENSO and the Quasi-Biennial Oscillation (QBO), a strong biennial periodicity, strongly influences the state of the tropical atmosphere (for example, Rasmusson and Carpenter, 1982; Ropelewski *et al.,* 1992). This influence is reflected in the time series of many climatological variables (Appendix C) and appears to play a certain role in tropical cyclogenesis (Gray, 1984). With the exception of the period prior to 1950, the newly compiled time series of tropical cyclone occurrence shows a strong quasi-biennial periodicity, as well as periodicities in the order of 3-5 years. These periods can be associated with a QBO-type and an ENSO signal, respectively . It appears that during the more recent decades this quasi-biennial signal has become more prominent and that it is even stronger when the 7 unnamed cyclones are included in the analysis. A more detailed description of this phenomenon can be found in Appendix C.

The relationship between ENSO and the seasonal numbers of tropical cyclones is more complex. While the SOI shows a strong relationship with the tropical cyclone activity in limited areas (for example, Nicholls, 1984), the signals from various regions of the Pacific Ocean cancel each other out and the correlations between the monthly (and 3-monthly) SOI and the net change in overall tropical cyclone activity in the entire southwest Pacific are close to zero.

Figure 7 shows the composite of tropical cyclone tracks for selected El Niño and La Niña years as compiled by Hastings (1990). This figure, which shows a strong displacement of tropical cyclone tracks, indicates that, generally, ENSO may have a somewhat larger influence on the location of tropical cyclogenesis than it has on the actual seasonal numbers of tropical cyclones in the entire southwest Pacific. However, the newly compiled data set shows that the mean occurrence of tropical cyclones during years of strong La Niña was 27% higher than their mean occurrence overall. Similarly, a 14% increase was noted for periods of strongly negative SOI. This finding has been partially confirmed by the study of Basher and Zheng (1995) who found a 28% increase during years of strong ENSO. The 27% increase for periods of strong positive SOI reported in this study is significantly higher than the mean tropical cyclone frequency for periods of weak El Niño and La Niña episodes, and hints at a real enhancement of tropical cyclogenesis during periods of extreme positive SOI values. However, as shown in Appendix B, the variance of the annual tropical cyclone numbers increases with the absolute magnitude of the SOI so that occasional La Niña and El Niño episodes can be marked by low tropical cyclone numbers. Detailed results of the categorisation of tropical cyclone activity according to the magnitude of the SOI can be found in Appendices A and B.



El Niño years



La Niña years

Source: Hastings, F.A., 1990

LONG-TERM TREND

It is often perceived that the seasonal frequencies of tropical cyclones are gradually increasing. While it is true that a greater number of tropical cyclones did occur in the last few decades (Figures 3 to 5), this may in part be due to improved reporting. While the mean seasonal numbers of tropical cyclones for the past 30 seasons (1964/65-1993/94) show a very slight increase the significance tests performed on these time series do not support the hypothesis of an increasing trend. In contrast to this result the trend of the entire time series (1920/21-1993/94) shows a significant increase in mean seasonal frequencies; however, as explained in Appendix D, this increasing trend can be attributed mainly to the rather sharp increase in tropical cyclone numbers in the early 1950s, which may be due to improved observations during the 1950-1960 period. The statistical methods used in obtaining these results are described in Appendix A, while the details of the trend analysis can be found in Appendix D.

SUMMARY

This report describes the general characteristics and impacts of tropical cyclones in the southwest Pacific, as portrayed by a newly compiled tropical cyclone data set for the period 1920/21-1993/94. The sequences of tropical cyclone numbers were examined with respect to five major points; the general characteristics and quality of the data, the interannual variability, the relationships with ENSO, the periodicity and QBO-like occurrences, and the characteristics of long-term trends.

General characteristics and quality of the data

The problems and uncertainties associated with the compilation of such a data set, as well as the occasional difficulties arising from the assignment of the tropical cyclone (as opposed to tropical storm) status were described. Storms other than tropical cyclones have not been included in this project, although the role of the storms which did not fit clearly in either of the two categories, but which almost made tropical cyclone status, has been investigated. A study into the frequency of tropical storm occurrence may be a worthwhile adjunct to that of tropical cyclone occurrence.

interannual variability

The 593 tropical cyclones contained in this database display a large interannual variability ranging from 2 to 16 cyclones per season. The time series shows a sharp increase in tropical cyclone activity in the early 1950s, rising from an average of 6.4 tropical cyclones per season prior to 1955/56 to 9.4 per season since 1955/56, which may possibly be attributed to a postwar increase in observational activity. However, the most significant improvement in data quality and full areal coverage has only been achieved since the early 1960s following the introduction of meteorological satellites. Thus, special attention has been paid to the analysis of the higher-quality data available for the last 30 years of the period under examination.

Relationships with ENSO

With regard to ENSO, it has been shown that the total seasonal number of tropical cyclones in the entire southwest Pacific and the monthly (weak and strong) SOI values are only very weakly linked. While not significant, these results are not in disagreement with the findings of other authors (for example, Nicholls, 1984; Basher and Zheng; 1995) who found significant correlations between the SOI and tropical cyclone activity in limited areas of the southwest Pacific. As shown by Hastings (1990) and Basher and Zheng (1995) tropical cyclogenesis in the southwest Pacific displays an ENSO-related shift and, overall, the signals from various regions tend to cancel each other out. However, the indication is that the numbers of tropical cyclones occurring during very strong El Nino and La Nina years are significantly higher than those developing during periods of weaker SOI. The mean tropical cyclone numbers for strong La Nina seasons is 27% higher than the average for the whole series, while the mean for strong El Nino seasons is 14% higher. Thus, while strong La Nina and El Nino episodes can usually be linked with a higher tropical cyclone activity in the entire southwest Pacific, the same relationship does not seem to be applicable as a general rule for all (weak and strong) ENSO episodes. However, as the variance of the annual tropical cyclone numbers increases with the absolute value of the seasonal SOI, it is also possible that during individual El Nino and La Nina seasons the response may be a decrease in tropical cyclone number (in contrast to the overall mean increase).

Periodicity and QBO-like occurrences

Currently, the seasonal activity of tropical cyclones displays a rather strong periodicity of about 2 and 3-5 years. However, prior to the 1950s the dominant periods were somewhat longer, in the order of 6-8 years. The recent shorter periodicities, which are generally associated with ENSO and the QBO-type signal, hint at a combined influence of strong ENSO events and other, not yet fully understood, atmospheric and oceanic oscillations on the development of tropical cyclones in this region. Should the strong ENSO years become more frequent, as suggested by the unusual behaviour of the SOI during the past 4 years, then it is possible that more tropical cyclones might develop in the SW Pacific basin.

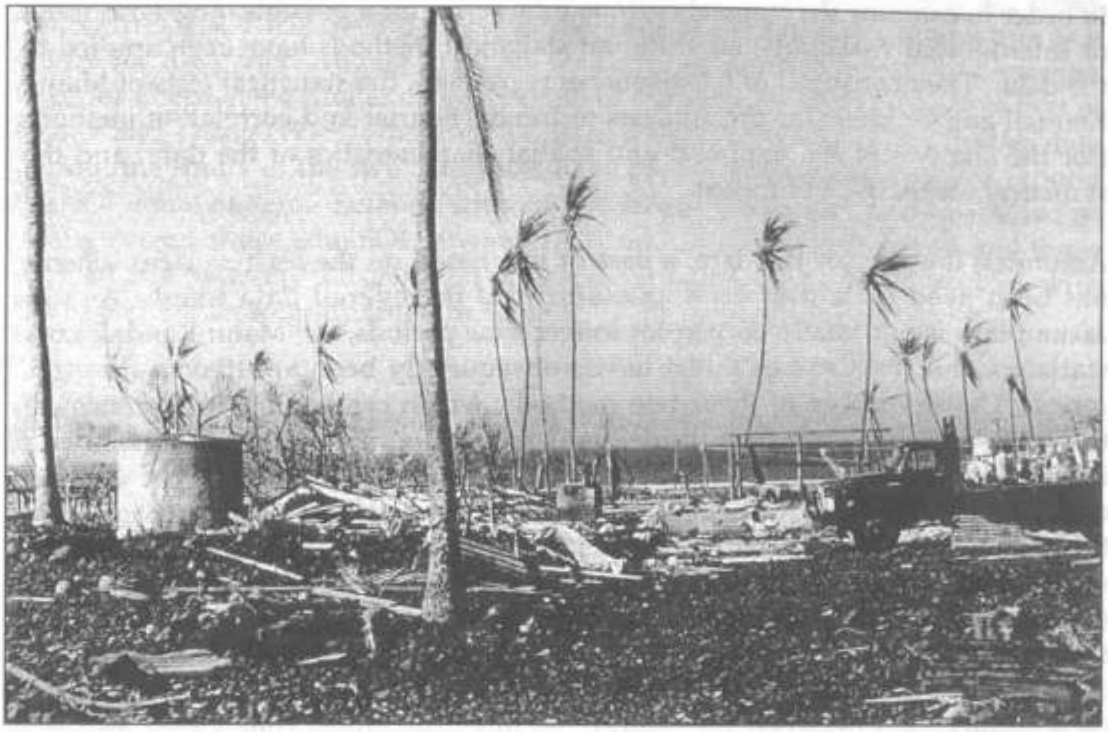
Characteristics of long-term trends

The somewhat faster and stronger pulsation of tropical cyclone activity during the past 3 decades could be an indication of a changing climate regime. This result is in contrast to the statistically insignificant increasing trend in tropical cyclone numbers during the same period. (Note that the trend for the past 74 seasons shows a significant increase, which may be due to an increase in reporting of tropical cyclones since the early 1950s).

Conclusion

Analysis of the 30-year data set shows that there is no significant increase in tropical cyclone occurrence in the southwest Pacific . The significant increase in intensity cannot be viewed with confidence as the results may well be due to some inaccuracies in the dataset. At this stage, it is not possible to say whether the changes detected relating to the increase in strong ENSO seasons can be attributed to a natural climate cycle or whether they are the result of human activity.

This report highlights the difficulty in obtaining accurate results relating to tropical cyclone activity and climate change with the data available. The results presented have been analysed from a 74 year dataset but only the past 30 years of data is considered accurate. A longer time series should increase the precision of the results. Apart from looking to the future by continuing to monitor occurrences each season, it may be possible to increase the accuracy of data relating to past occurrences, such as is currently being carried out for the east coast of Australia.



Western Samoa in the aftermath of Tropical Cyclone Val, *December 1991.*

PART 3

Appendix A

METHODS

In order to examine the tropical cyclone time series for a possible long-term trend or interdecadal variability, six different statistical methods have been applied to the data. They consisted of least-squares regression, the statistical tests of Mann-Kendall and Cramer (for the analysis of trend), Fourier and correlation methods (for the analysis of the temporal and spatial characteristics of the data) and the statistical comparison of means.

Assuming linearity of the data, a best-fit line based on the least-squares scheme has been used for a first brief assessment of the overall data trend. As this assumption is not totally correct for longer time periods, the Mann-Kendall rank statistics and the Cramer's test have subsequently been applied to the time series. The advantage of these two methods, which can test the randomness of the data against a possible non-linear trend, lies in their robustness and independence from the Gaussian normal frequency distribution of the original data. The Mann-Kendall method ranks the individual data values according to their magnitudes and uses these ranks for computation of the statistics for the series. Irrespective of the characteristics of the original time series, the rank statistics values are always nearly normally distributed and can be tested against the probability points of a Student's t-distribution. The same significance test can also be performed with the result of the Cramer's statistics which are based on a comparison between the overall mean of the entire time series and the means of various sub-periods of the same series. A more detailed description of these methods can be found in Mitchell *et al.* (1966). In both cases the statistics have been compared with the 95%, and the 99% probability points, for the two-tailed test and the appropriate number of degrees of freedom (38 and 28) respectively.

As some of the peaks and troughs in the time series seem to appear at quasi-regular intervals the data have also been subjected to a Fourier analysis (a mathematical method for detection of the most prominent periodicities in the data). This analysis has been applied to the entire data and several selected sub-periods. Because the autocorrelation coefficients for the respective sub-series were all very low ($|0.0|$ - $|0.2|$), the data have been regarded as free of persistence and the results of the Fourier analysis were treated as "white noise" spectra. The statistical significance of the spectra, the "null continua" and the respective 95% confidence levels were calculated according to the method described by Mitchell *et al.* (1966).

The overall relationship between the seasonal variability of tropical cyclone numbers and the large-scale patterns of atmospheric circulation in the Pacific Ocean region has been examined with the help of correlations with the SOI. The SOI, which has been used in its three-monthly mean form (centred on the middle month), is defined here as the normalised pressure anomaly difference between Tahiti and Darwin multiplied by 10 (Climate Monitoring Bulletin, 1995). The correlations have been calculated for lags of 0 to -12 months (SOI leading the tropical cyclone frequencies).

Furthermore, the seasonal activity of tropical cyclones has been classified according to the mean seasonal magnitude of the SOI, and the differences between the means of various categories have been tested for significance. This has been achieved by the use of the appropriate statistical test pertaining to the comparison of two means and the Student's t-distribution (Mitchell *et ah,* 1966). The seasonal SOI has been defined as the arithmetic mean of the monthly SOI values for the period August to March (prior to and during the cyclone season). In order to achieve a similar categorisation of the extreme ENSO events to that of Basher and Zheng (1995), who used a different form of the SOI and a shorter data period, the limits of the five categories have been chosen symmetrically around the SOI value of zero. Seasons with an SOI larger than I 6.0 I were classified as strong events, those with SOI between I 6.01 and 12.01 as weak events and those with an SOI between -2.0 and +2.0 as near-zero signals. The five categories with the respective seasons are listed in Table 3.

Table 3: Tropicalcycloneseasons 1964/65-1993/94 categorised according to the magnitude of the mean SOI value (August-March)

<-6	'6 to -2	-2 to+2	+2 to +6	>+6
1965/1966	1968/1969	1967/1968	1964/1965	1970/1971
1972/1973	1969/1970	1978/1979	1966/1967	1971/1972
1977/1978	1976/1977	1983/1984	1974/1975	1973/1974
1982/1983	1979/1980	1984/1985	198171982	1975/1976
1986/1987	1980/1981	1985/1986		1988/1989
1991/1992	1987/1988			
1992/1993	1989/1990			
	1990/1991			
	1993/1994			

TROPICAL CYCLONE NUMBERS AND THE SOUTHERN OSCILLATION

The relationship between the SOI and the numbers of tropical cyclones in the southwest Pacific region has been examined in several previous studies. Revell and Coulter (1986), Hastings (1990) and Basher and Zheng (1995) demonstrated that tropical cyclogenesis in the southwest Pacific displays a distinct shift during extreme phases of ENSO (northeastward during El Nino and southwestward during La Niña), while the overall cyclone numbers are somewhat less affected. The figures presented by Basher and Zheng (1995) suggest that, while the SST and SOI can be useful predictors of the tropical cyclone activity in limited sectors of the southwest Pacific, the signals tend to cancel each other out when the analysis is extended to the whole basin area.

In contrast to these studies, which concentrated on the predictability of the tropical cyclone activity in limited areas, this investigation focused on the large-scale and long-term change characteristics of the newly compiled data set. In agreement with the results of the previous studies, the correlation coefficients between the mean 3-month SOI values and the tropical cyclone numbers from the entire southwest Pacific were all near zero between lag 0 to lag -12 months. This result confirms the findings of the previous studies (for example, Basher and Zheng, 1995) and indicates that the correlations between the SOI and the tropical cyclone activity from different parts of the Pacific Ocean tend to cancel each other out. This type of overall correlation cannot be used as an indicator of tropical cyclone activity in the entire southwest Pacific. For this reason another approach has been taken and the total tropical cyclone activity has been analysed with respect to extreme phases of ENSO. Following the example of Basher and Zheng (1995) , we have categorised the tropical cyclone seasons according to the magnitude of the seasonal value of the SOI and compared the characteristics of the different classes. The results of this classification are summarised in Table 4.

Table 4: Number of seasons, mean and variance of annual tropical cyclone numbers(l 964/65-1993/94) categorised according to the mean seasonal SOI magnitude(August-March)

Seasonal mean SOI	<-6	-6 to -2	-2 to +2	+2 to +6	>6	TOTAL
Number of seasons	7	9	5	4	5	30
Annual Mean	10.70	8.11	9.80	6.50	12.00	9.42
Variance	13.95	8.61	0.20	5.67	14.50	8.59

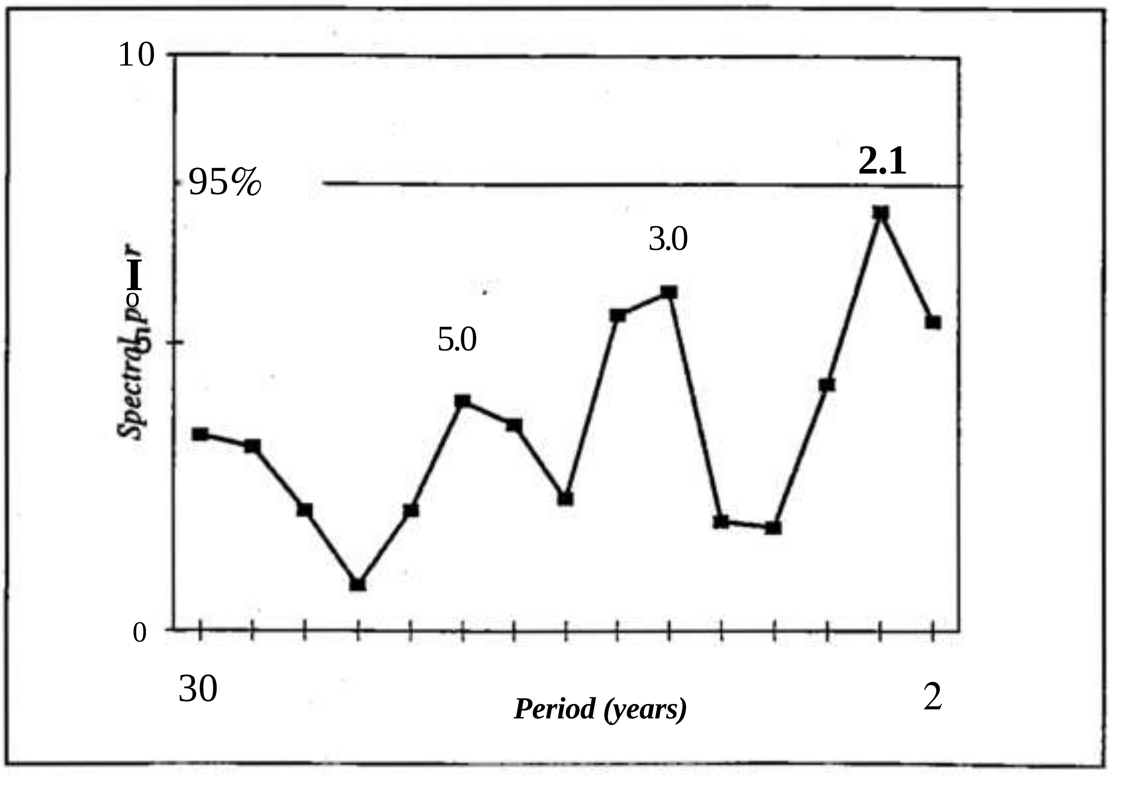
The results of this intercomparison suggest that tropical cyclone activity is somewhat enhanced during seasons marked by large SOI values and suppressed during periods of small SOI. As shown in Table 4, those seasons with highly positive mean SOI display the highest overall mean frequency of tropical cyclones (12 cyclones/season). This mean is significantly higher (99% significance level) than the mean for the weakly positive or weakly negative SOI categories and also higher (95% significance level) than the average mean of the three middle categories with SOI values between -6.0 to 6.0. The mean number of tropical cyclones in this strongly positive SOI category is 27% higher than the average for the whole series, while the mean for the strongly negative SOI category is 14% higher. The other SOI categories yield -14% (weakly negative), +4% (near-zero) and -31% (weakly positive) results. These results are somewhat different than the 28% (strongly negative SOI category) and -16% (near-zero SOI category) obtained by Basher and Zheng (1995) who used a different database and a different type of SOI. However, as shown in Table 4, it is not only the mean tropical cyclone number that increases with a large magnitude of the SOI, but also the variance. Thus the inclusion of another one or two El Nino or La Nina seasons may alter the results.

Damage caused by Tropical Cyclone Namu, *Solomon Islands, May 1986.*

PERIODICITY OF THE TROPICAL CYCLONE TIME SERIES

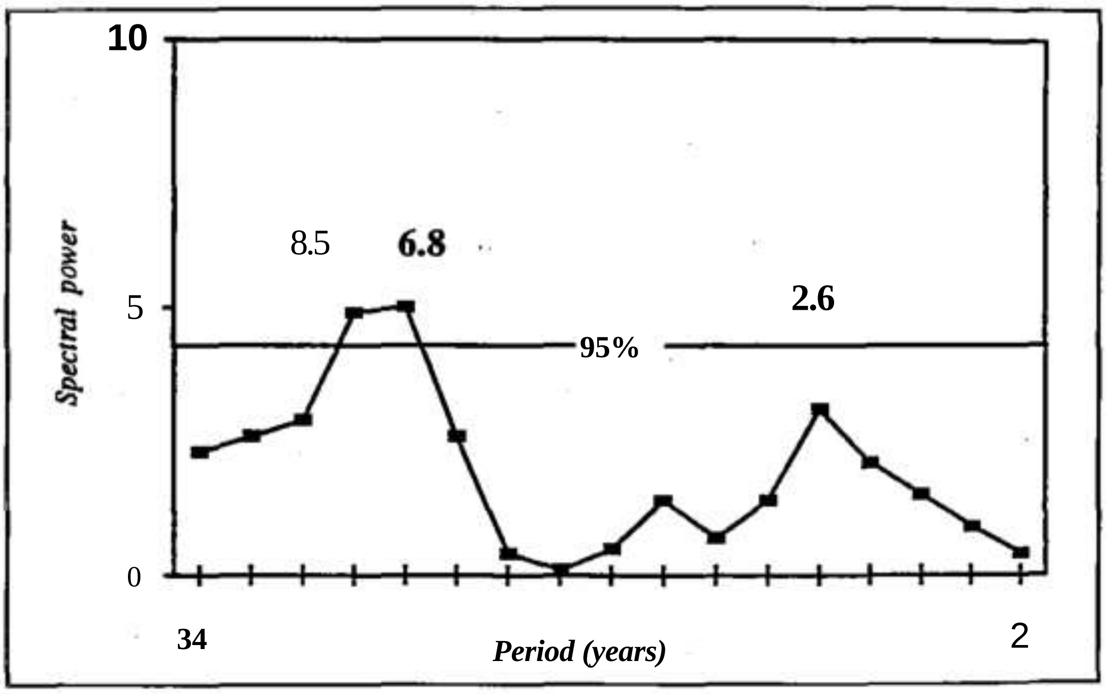
In order to examine the tropical cyclone frequency data for any dominant oscillations, the 1964/65-1993/94 as well as the 1920/21-1993/94 time series have been analysed with the help of the Fourier analysis. (The inclusion of the long time series into this analysis seems to be more justified than its examination for any long-term trend, as the error associated with the observations of cyclones is likely to be a systematic one. Thus, the total seasonal numbers of cyclone observations during earlier periods might be more inadequate than the registration of the actual intervals separating two maxima of tropical cyclone activity). The analysis has been performed on both the original time series and the data set with the 7 unnamed cyclones. The inclusion of the 7 unnamed cyclones did not alter the general shapes of the spectra, but, in some instances, made the amplitude associated with the QBO-type signal stronger (that is, more significant).

Figure 8: Periodogram for annual tropical cyclone numbers in the southwest Pacific 1964/65-1993/94. (The 95% significance level is denoted by a horizontal line, the dominant periods in bold)



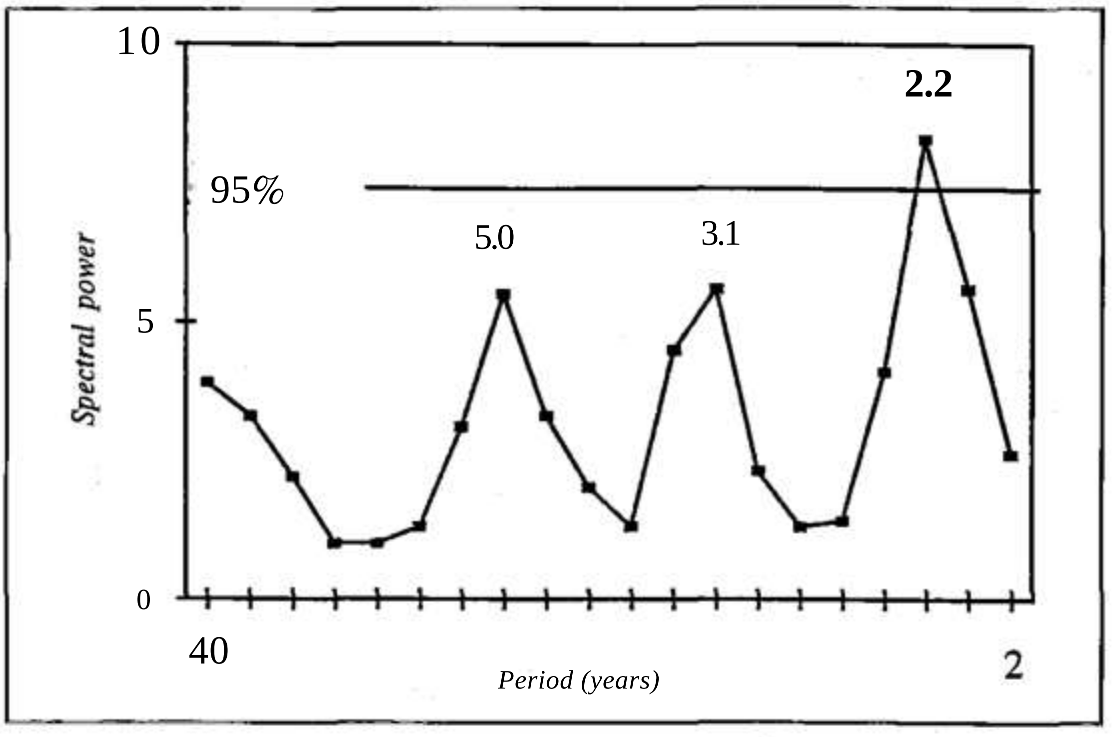
As shown in Figure 8, the periodogram for the 1964/65-1993/94 time series of tropical cyclone occurrence displays maximum peaks at the previously mentioned periods of approximately 2.1, 3.0, and 5.0 years. In contrast to Figure 10, the three peaks for these particular periods remain just below the 95% confidence level. These periodicity peaks are those of the QBO-type signal and ENSO, which influence the large-scale atmospheric circulation over the Pacific Ocean and can play an important role in tropical cyclogenesis. While ENSO may influence the heat content of the oceanic mixed layer and the atmospheric humidity, the QBO-like behaviour is possibly partly caused by the varying strength of the tropospheric shear required for cyclone formation. The link between the tropical cyclone activity and these two types of oscillation is not confined to the Pacific Ocean Basin, it has also been observed in other parts of the world (for example, Gray, 1984).

Figure 9: Periodogram for annual tropical cyclone numbers in the southwest Pacific 1920/21-1953/54 . (The 95% significance level is denoted by a horizontal line, the dominant periods in bold)



The periodogram for the 1920/21-1993/94 period displays a similar characteristic with a dominant periodicity of slightly more than two years (not shown). However, when divided into two shorter sub-periods of 1920/21-1953/54 (Figure 9) and 1954/55-1993/94 (Figure 10), the major periodicities of the sub-sets differ. Keeping in mind the difficulties associated with the compilation of the pre-war data, it appears that prior to 1953/54 the cyclone activity maxima were separated by, on average, longer intervals than after 1953/54.

Figure 10: Periodogram for annual tropical cyclone numbers in the southwest Pacific 1953/54-1993/94, including the 7 unnamed tropical cyclones. (The 95% significance level is denoted by a horizontal line, the dominant periods in bold)



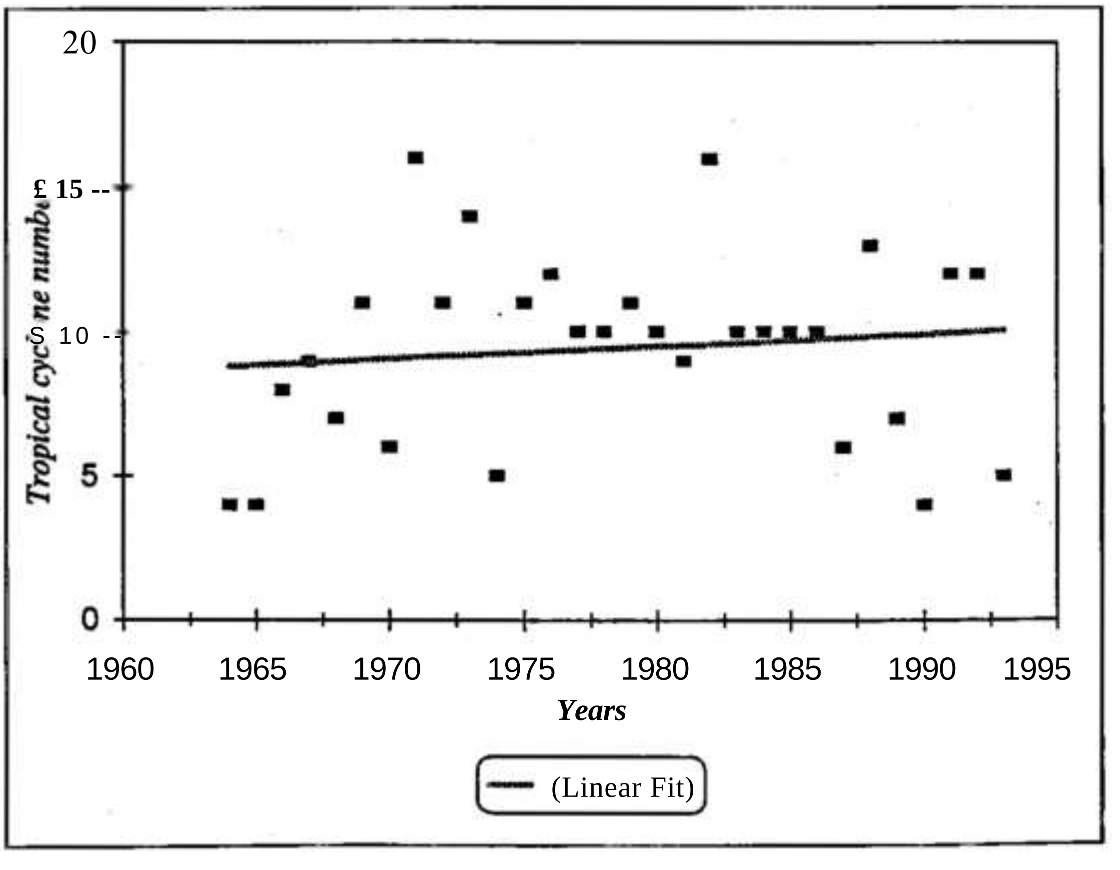
As shown in Figures 9 and 10, the respective amplitude maxima can be found between 6-8 years for the period 1920/21-1953/54 and around 2 years for the period 1954/55-1993/94. This change in periodicity prior to 1953/54 shows similarities with the fluctuations of the strength and periodicity of the Southern Oscillation (for example, Allan, 1988; Kuhnel *et al.*, 1993). In the absence of any significant long-term trend in the mean seasonal number of tropical cyclones this result suggests that, while the mean seasonal activity increases only insignificantly, the current climate system might reach extreme conditions more frequently than was the case half a century ago. However, the nature of the data does not allow us to determine the exact cause of this change in periodicity. The difference could be a function of the data quality, or due to a natural long-term fluctuation of the climate and, possibly, of ENSO (which is known to occur more frequently every 50 and 90 years, [Anderson, 1992]) or due to a real anthropogenic climate change.

LONG-TERM TREND OF THE TROPICAL CYCLONE TIME SERIES

a) PERIOD 1964/65-1993/94

As shown in Figure 11, a best-fit line based on the method of least-squares has been fitted to the tropical cyclone data for the period 1964/65-1993/94. The data display a considerable scatter and the slope of the best-fit line is rather small (0.04, or 0.02 when the 7 unnamed cyclones are added). As indicated in Figure 11, this slightly increasing trend is caused mainly by the two coincidentally very low tropical cyclone numbers at the beginning of the selected time series. To test the strength of the increasing trend the data has been subjected to the significance tests of Mann-Kendall and Cramer. Although both tests render positive values, the magnitudes of these statistical parameters are not large enough to surpass the appropriate 95% or 99% significance level points. The inclusion of the 7 unnamed tropical cyclones does not alter this result. Thus, the sequence of the annual tropical cyclone numbers for the period 1964/65-1993/94 has to be considered as random and the hypothesis of a long-term increasing trend in the time series cannot be substantiated.

Figure II: Scniterplot and best-fit line for tropical cyclone numbers 1964/65-1993/94



The results of the above-described significance tests look somewhat different when these methods are applied to tropical cyclone intensity. The slope in the regression equation increases to 0.12 and the Mann-Kendall rank statistics renders a significant result (at the 95% level). However, this finding is not confirmed by the Cramer's comparison of means, which remains not significant.

b) PERIOD 1920/21-1993/94

As explained by Holland (1981) in the context of the quality of tropical cyclone data for the Australian region, accuracy of the data prior to the 1960 period (that is, prior to the introduction of meteorological satellites), is generally considered inadequate for research purposes. A similar consideration is assumed to be valid for the time series presented here. However, it has been deemed useful to apply the same statistical methods to the 74 season time series, if only to highlight where the inadequacies of these new data may lie. Due to the substantially different frequencies prior to the 1955/56 season (for example, Figure 3, this report) the 74 season time series does not display any linearity. The trend prior to 1955/56 is actually decreasing, whereas after 1955/56 it is increasing.

The Mann-Kendall and Cramer's tests render highly significant results, but only when the sharp increase in frequencies (following the 1955/56 season) is fully included in the analysis. As the results for the data segments which precede or follow the 1954/55 season remain not significant, the significance of the overall trend can be uniquely attributed to the sharp rise in frequencies from 1 955/56. This increase in tropical cyclone activity is unlikely to be caused by a different behaviour of the climatic system and may be attributed mainly to improved observations of tropical cyclones (for example, Lourensz, 1977; Holland, 1981).

The Pacific island of Kiribati.

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