THE CLIMATE AND WEATHER

OF

TUVALU

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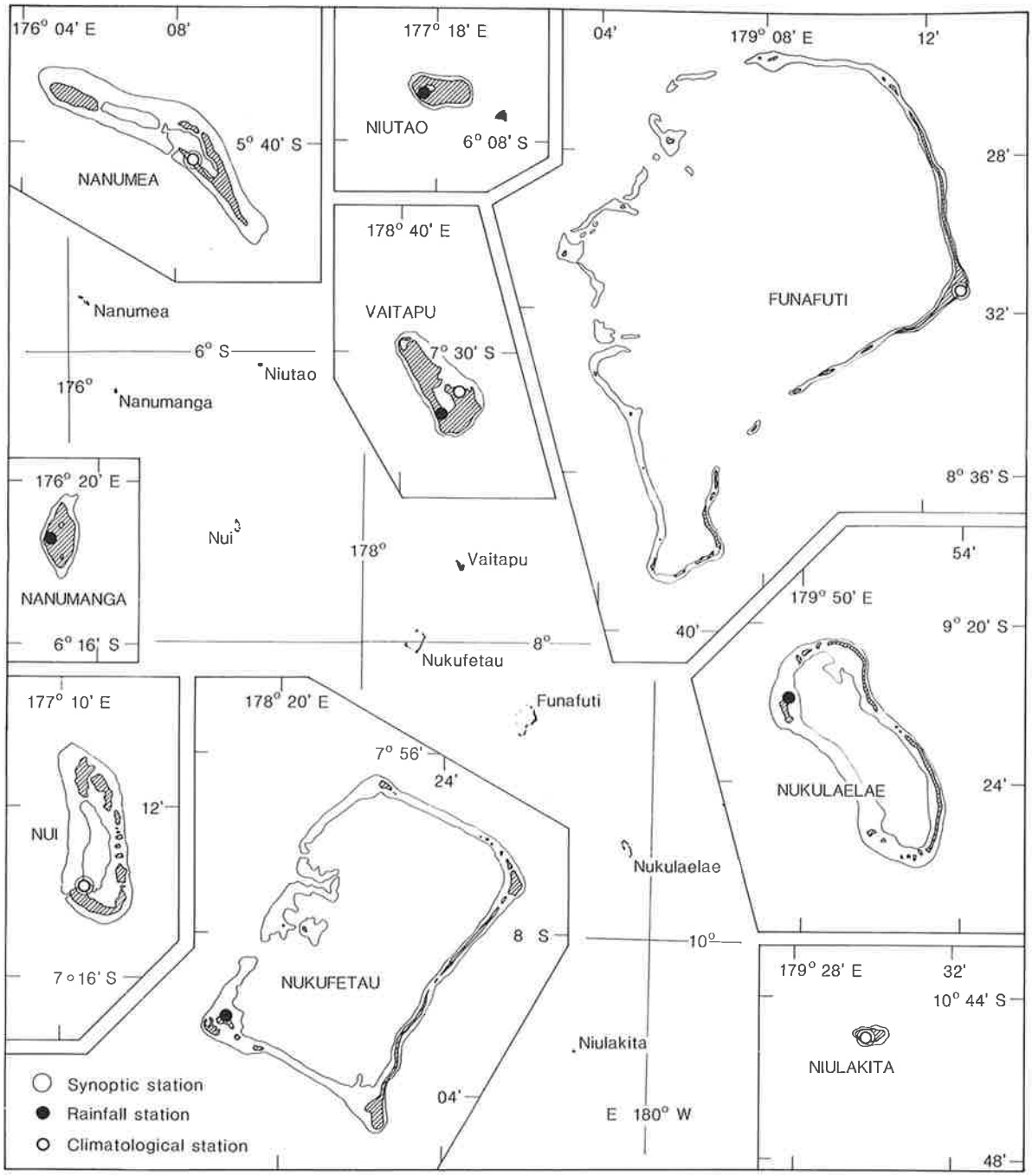

Fig.1(a) Location map

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Note to 188 Series

This publication is the sixth in a series on the climate and weather of specific South Pacific island groups.

This series replaces an earlier Meteorological Service series entitled: 'Climatological Notes - South Pacific Region', (N.Z.M.O. Series C), published in 1943.

The following titles have been published, or are in preparation:

(1) Climate and Weather of Niue (published)

(2) Climate and Weather of Southern Cook Islands (published)

(3) Climate and Weather of Northern Cook Islands (published)

(4) Climate and Weather of Tokelau (published)

(5) Climate and Weather of Tonga (published)

(6) Climate and Weather of Tuvalu (published)

(7) Climate and Weather of Western Kiribati

(8) Climate and Weather of Western Samoa

Cover - an outrigger canoe with asymmetrically cross-sectioned hull from the Caroline Islands (after a drawing by Louis Choris in 1815).

CONTENTS

THE CLIMATE AND WEATHER OF TUVALU

Summary

Tuvalu lies within the trade wind zone but on the edge of the South-west Pacific equatorial doldrum zone. Prevailing winds are from the easterly quarter and they occur most frequently between June and August. In most years from December to March, winds between west and north usually equal or exceed the easterlies in frequency.

Wind speeds over the surrounding oceans average about 10 knots. Strong winds are not common, being experienced about three percent of the time. Although tropical cyclones occasionally develop in close proximity to Tuvalu, they are most unlikely to become storms.

Rainfall in Tuvalu is high and reliable throughout the year. Sixty percent of the rain falls in the November-April period and it is in this wetter season that most of the heaviest falls are recorded. There is a significant inverse relationship between rainfall and the southern oscillation index, with the southern oscillation leading the rainfall response by several months. However abnormal rainfall anomalies seldom persist for longer than two months.

With the high levels of sunshine, evapotranspiration rates are also high, but in most years precipitation is sufficient to meet these requirements. Soil moisture deficits are most likely in the drier northern atolls.

1. INTRODUCTION

Tuvalu is a group of nine coral atolls or islands located in the South-west Pacific Ocean between 5° and 11°S, and from 176°E - 180°. All are low-lying, none of which rise above 5 metres. The islands and atolls extend over 650 km in a line from Nanumea in the north to Niulakita in the south (Fig. 1). The total land area is about 26 km^2, with the centre of government being at Fongafale on the atoll of Funafuti. The main cultivated food crops are coconuts, bananas, breadfruit, pandanus and taro. Copra is produced for export, but most of the people are engaged in subsistence agriculture and fishing.

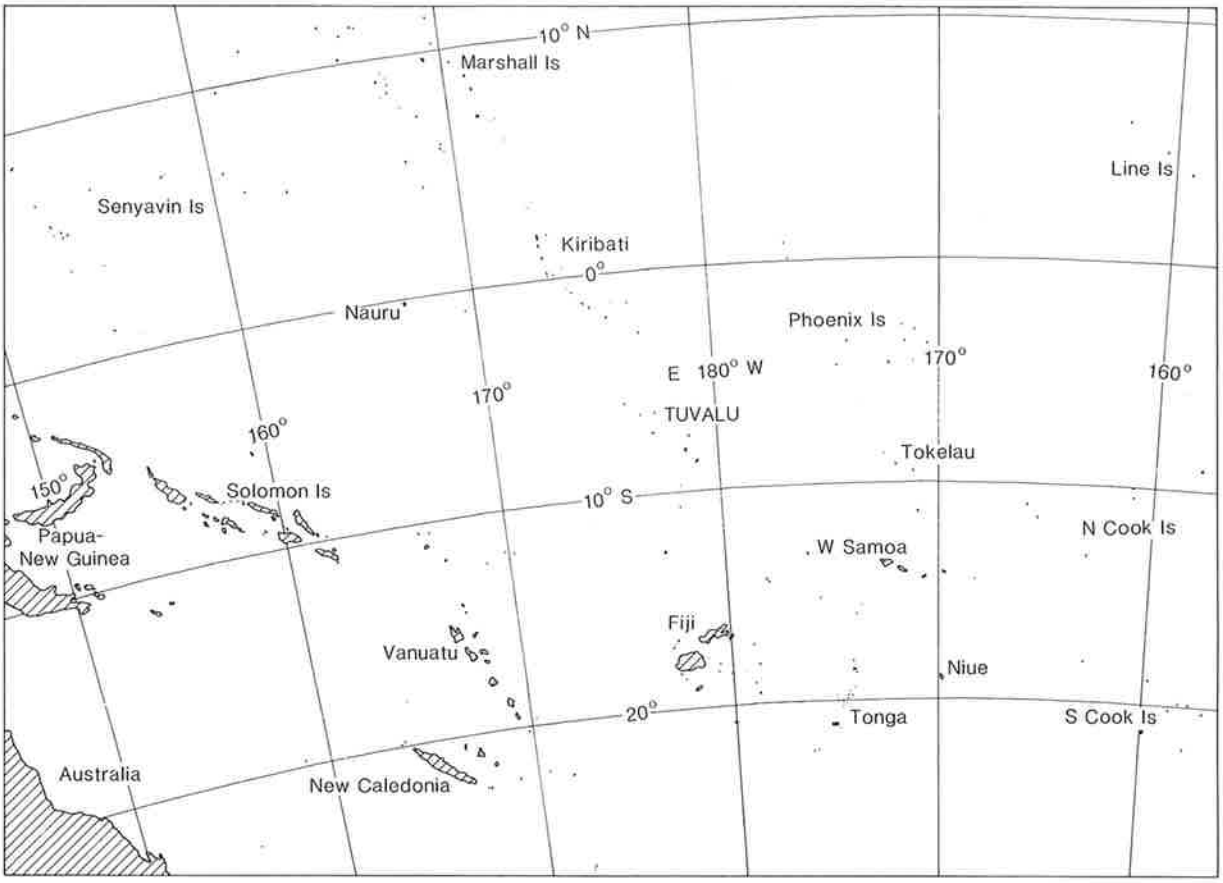

Fig 1 (b) Location of Tuvalu in the Pacific

Meteorological data used in this publication were mostly obtained from the New Zealand Meteorological Service's archives. Rainfall observations made in 1922 at Funafuti are the earliest known weather observations. Table 1 shows some information about the archived meteorological record. Synoptic weather observations are made six-hourly, four times a day beginning at midnight local time (1200 UT). Rainfall observations are made at 9 a.m. (2100 UT), while daily climatological observations are taken either at 6 a.m. (1800 UT) or 9 a.m. (2100 UT).

2. GENERAL CIRCULATION OF THE TROPICAL SOUTH PACIFIC

While there is much variability in the general circulation of the tropical South Pacific on both seasonal and even shorter time scales, the time-averaged state is characterised by four main features:

(i) Sub-tropical high pressure zone

A belt of high pressure spanning the South Pacific is centred on the latitudes 25°-30°S. Within this zone in the eastern South Pacific is a large semi-permanent anticyclone (the South Pacific anticyclone) centred near 90°-100°W. On the western margin of the high pressure belt, anticyclones move eastwards into the Pacific region from the Australia-Tasman Sea region.

Table 1 The Meteorological Record

Location	* Station Type	Data Period	Remarks
Nanumea	Climat/Synoptic	Jan	Sheltering in sector east via south to north
Niutao	Rainfall	Aug	Site exposure only fair
Wanumanga	Rainfall	Jan	Poor gauge exposure
Nui	Climat/Synoptic	Aug	Sheltering due densely wooded coconut palms
Vaitupu	Rainfall	Jan	Gauge surrounded by trees and buildings
Vaitupu Agmet**	Climat	Aug	excellent exposure
Nukufetau	Rainfall	Jan	Poor gauge exposure
Funafuti**	Climat/Synoptic	Jan	Site well exposed
Nukulaelae	Rainfall	Jan	Exposure good to east and west
Niulakita	Climat/Synoptic	Jan	Site sheltered from trade winds

* Climat: Stations making full climatological observations once daily.
Synoptic: Stations making observations of selected parameters primarily for use in weather analysis and forecasting, several times a day.
Rainfall: Station making daily rainfall observations.
** Climatological observations made at 9 A.M. (2100 UT).

(ii) Trade winds

On the northern side of the high pressure belt is an extensive belt where the winds blow consistently from the same general direction. These are the trade winds. They blow from the easterly quarter, but some in the western South Pacific have a more southerly component resulting from the eastward migration of anticyclones (Revell, 1981). The intensity of the South Pacific anticyclone influences the strength of the trade winds. Although the trade winds are normally moderate, they tend to be strongest from about May to October when the South Pacific anticyclone is most intense. Wind speeds at these times may reach 25 knots*.

* One knot equals 0.515 m/s or 1.85 km/hr.

A feature of the trade wind region is the frequent presence of temperature inversions between 1500 and 3000 metres. Above the inversion westerly winds predominate with dry subsiding air. The growth of convective clouds to high altitudes is inhibited as cloud tops rarely penetrate far into the inversion zone and showers are usually scattered and light. In the Tuvalu region where trade winds have travelled for great distances from regions of active subsidence, the inversion is generally nonexistent. With the decrease of atmospheric stability convection and heavy showers occur.

(iii) Equatorial doldrum belt and intertropical convergence zone

The equatorial doldrum belt (EDB) is a region of relatively light winds that is present all year round in the western Pacific Ocean. Lying within about five degrees of the Equator, the belt is a zone of high rainfall and great seasonal variability (Revell, 1981). During the southern hemisphere summer when the EDB is furthest south, there is usually a trough of low pressure extending from Northern Australia and into the Coral Sea on the southern fringe of the doldrums. This trough is known regionally as the 'monsoon trough'. The resulting light winds reflect in part alternating periods of easterlies and westerlies. Occasionally the 'monsoon westerlies' can be squally. Although the monsoon westerlies frequently blow as far as the date line, from time to time they spread to the Cook Islands. During the period from May to September the doldrum zone lies principally in the northern hemisphere, and in this period there is no Australian monsoon trough.

The zone between the convergence of the North Pacific and South Pacific trade winds is the intertropical convergence zone (ITCZ). It is characterised by an extensive area of cloud, which fluctuates in intensity over time. The ITCZ follows the passage of the sun, with a lag of about 3 or 4 months (Wyrtki and Meyers, 1975). The range in latitudes of the I7CZ is from 3°-10°N in the eastern central Pacific, and from 5°-15°N near America.

(iv) The South Pacific convergence zone

The South Pacific convergence zone (SPCZ) is an important feature of the South-west Pacific. It is an area of convergence between the low latitude easterly trade winds and the higher latitude south-easterly trades. It is a semi-permanent cloud feature of the southern hemisphere (Fig. 2).

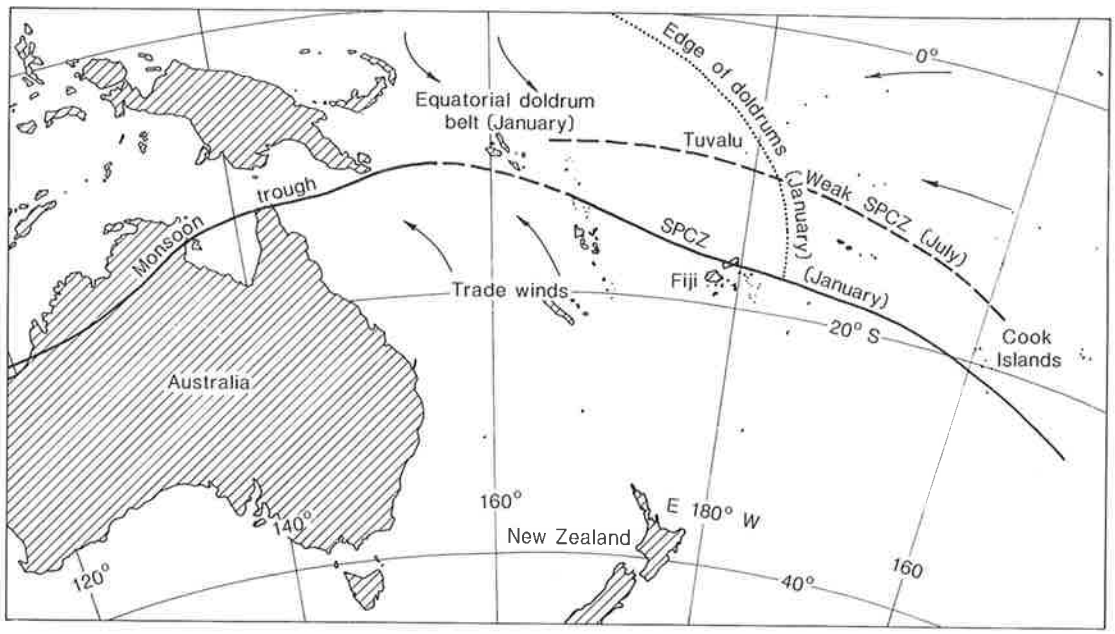

Fig. 2. Mean position of South Pacific convergence zone in January and July. Adapted from Wytrtki and Meyers (1975) and Hessell (1981)

The intensity of the SPCZ varies considerably. From time to time, troughs of low pressure develop on the zone, especially when upper-level westerlies are strong. Their development is accompanied by an increase in the width of the cloud band and a deterioration in the weather (Hill, 1963). Seasonal variation in the location of the SPCZ (Fig. 2) is generally small. During summer (November to April) the SPCZ lies from near Vanuatu and Northern Tonga to the Southern Cook Islands - it is well south of Tuvalu. The western edge of the zone becomes an extension of the monsoon trough of Northern Australia and the Solomon Islands. Although the westerlies associated with the doldrums on the northern side of the SPCZ frequently blow as far as the date line, they also spread further east.

In winter, the SPCZ is frequently very weak or inactive. Its mean position is from near Niulakita, the southernmost island of Tuvalu, to between the Southern Cook Islands and Society Islands (Fig. 2). A broad easterly or south-easterly trade wind flows over the tropical South-west Pacific.

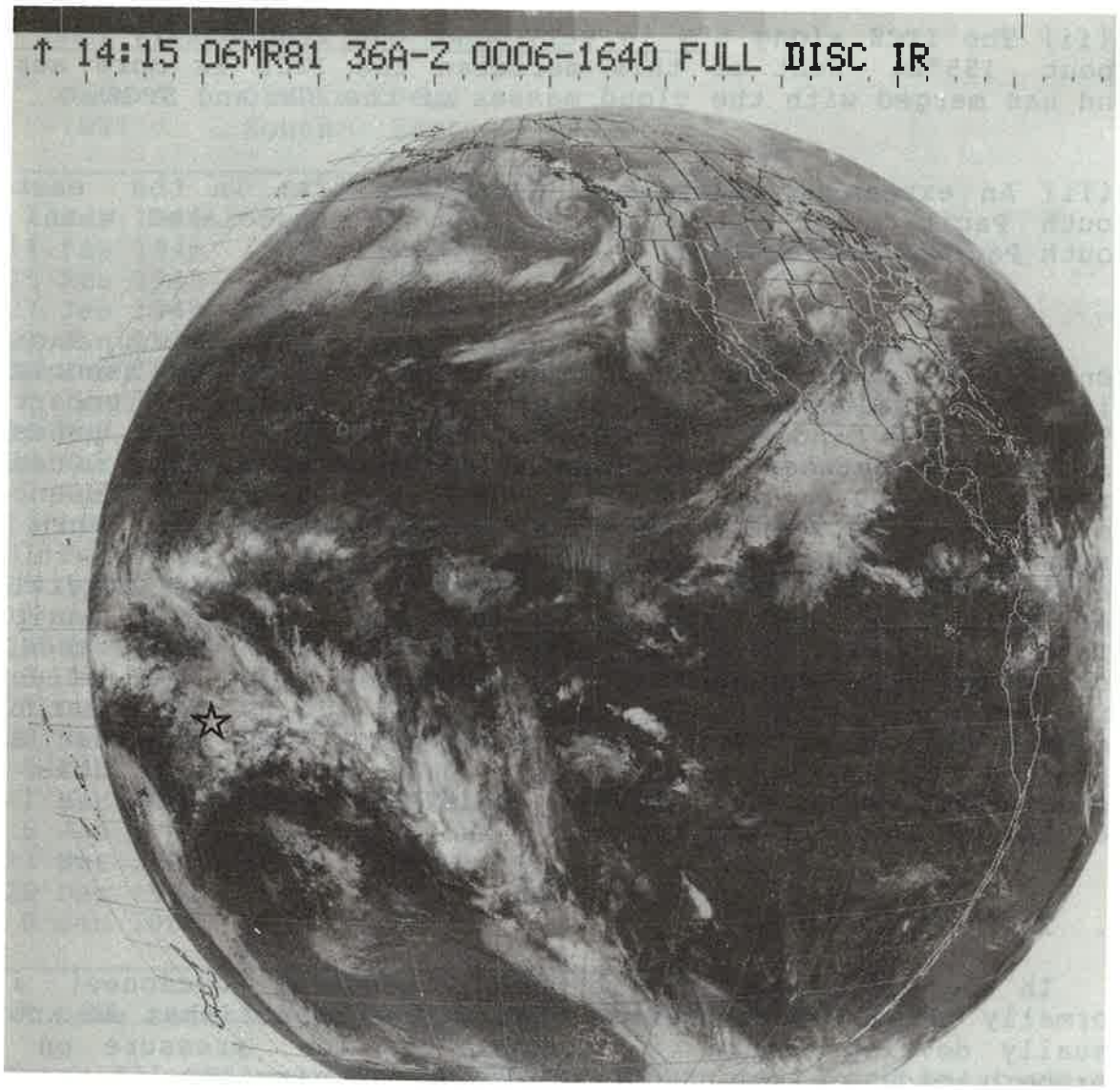

Fig. 3. Satellite view of Pacific Ocean on 6 March 1981. Note SPCZ lying north of mean position. A star marks the general location of Tuvalu.

Figure 3 shows a satellite view of the Pacific Ocean taken on 6 March 1981. This figure shows three important features of the tropical Pacific Ocean circulation.

(i) The extensive cloud band of the SPCZ is lying north of its mean position. Tuvalu lies under an extensive mass of cumulonimbus cloud on the western edge of the photograph.

(ii) The ITCZ along 5°N is very weak and fragmentary east of about 155°W. West of this meridian the ITCZ is more active and has merged with the cloud masses of the EDB and SPCZ.

(iii) An extensive relatively cloud-free area in the eastern South Pacific and along the Equator is associated with the South Pacific Anticyclone.

Spatial variation in the location of the South Pacific convergence zone has also been identified to be associated with the southern oscillation index (SOI) (Trenberth, 1976). This index represents the extent of a pressure oscillation between the Indian and South Pacific Oceans. Trenberth measured the SOI from the normalised differences in pressure between Papeete and Darwin (Australia). When the pressure is high in the Pacific, it tends to be low in the Indian Ocean, and the SOI is positive. Under such conditions the SPCZ lies west and south of its seasonal position (Trenberth, 1976). At the same time the ITCZ also tends to move away from the Equator. Tuvalu comes under the influence of a stronger South Pacific anticyclone, and as the equatorial doldrum belt moves west and north-west, the islands are affected by drier conditions. The SOI clearly has an association with the Tuvalu rainfall variability - see section on Rainfall and the SOI.

3. TROPICAL CYCLONES

In the South-west Pacific Ocean, tropical cyclones(i.e. normally classified as having wind speeds of at least 34 knots) usually develop within a trough of low pressure on the northern side of the SPCZ. Tropical depressions (i.e. wind speeds less than 34 knots) may form all year round, while tropical cyclones (i.e. wind speeds of at least 34 knots) are almost exclusively confined to the months November to April, which in the tropical South Pacific is regarded as the cyclone season. Tropical cyclones occasionally begin to develop close to Tuvalu, mostly south of latitude 9°S (Table 2), but it is very rare for them to become storms while in this area. There have been three known tropical cyclones to result in serious damage to Tuvalu. These occurred on 18 February 1891, 2 January 1958, and 19 October 1972. (This latter one was noteworthy since it occurred outside the normal cyclone season). There was also an unconfirmed report of widespread damage to Tuvalu in November 1957 (Kerr, 1976).

Table 2. Tropical cyclones in the Tuvalu region 1940-1985

Date * (UT)	Origin (Deg) South	East	SOI
4 Feb 1940	9.1	177.8	
14 Feb 1940	9.8	178.8	
25 Feb 1942	9.9	177.9	
27 Jan 1944	10.3	179.8	
21 Jan 1948	9.0	179.0	
22 Feb 1957	10.9	179.1	
1 Jan 1958	8.0	177.0	
28 Nov 1958	9.9	179.5	
29 Mar 1964	10.6	177.0	+ve
7 Apr 1967	11.7	179.1	
12 Dec 1967	10.5	179.5	
31 Feb 1972	10.0	177.5	+ve
19 Oct 1972	7.9	177.1W	
11 Dec 1976	11.5	176.5	
24 Nov 1977	5.9	176.9	
3 Jan 1979	5.1	176.1	
27 Dec 1979	8.0	175.0	
25 Mar 1980	9.5	175.0	
8 Feb 1981	9.0	178.0	
1 Mar 1981	10.5	177.0	
6 Jan 1982	9.0	178.5W	+ve
23 Mar 1983	10.0	179.0	
26 Dec 1984	9.1	178.2	
8 Jan 1985	11.0	180.0	

* Date refers to the time when first observed.

Note. All SOI values negative except those marked positive

Since 1940 there have been 23 occasions when tropical cyclones began to develop in the Tuvalu region. The table shows that nearly all developed when the SOI was negative. Revell and Goulter (1985) noted a close relationship between the origins of tropical cyclones and the SOI. The mean origin point of South-west Pacific tropical cyclones was north-east of the median position of 14°S 170°E for negative SOI, and south-west for positive SOI.

4. CLIMATE ELEMENTS

Wind

Tuvalu lies within the trade wind zone of the South-west Pacific and on the edge of the austral summer equatorial doldrum belt. (Fig. 2, 4). Predominant surface winds are from between northeast and southeast for about 55 to 65 percent of the time, but seasonal differences do exist (Table 3). East to south-east winds are most frequent between June and August, varying from about 60 percent of the time in the northern atolls of Nanumea and Nui, to over 75 percent on Funafuti and Niulakita. These wind directions are more than twice as frequent during the period from May to October, than at other times of the year. During this period, the doldrum zone lies predominantly in the

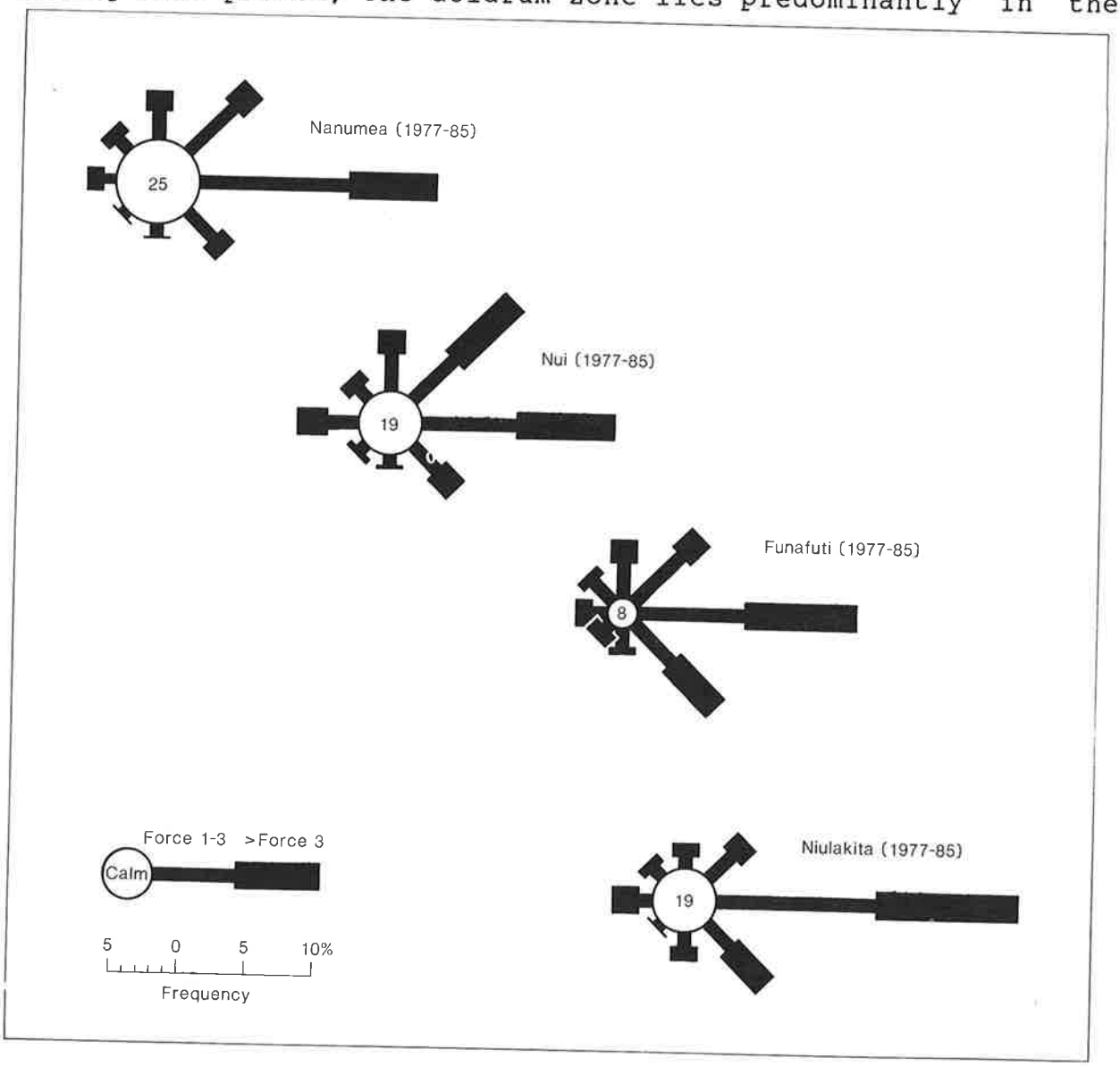

Fig. 4. Mean annual wind roses for Tuvalu . All observations are taken at 6 am except Funafuti which is recorded at 9 am.

Table 3. Seasonal wind frequencies (percent) and mean speeds (knots)

		Dec Jan Feb	Mar Apr May	Jun Jul Aug	Sep Oct Nov	Wetter	Drier	Annual
(a) Nanumea (6 a.m.) 1977-85								
Dir	N	13.8	7.7	1.8	4.8	11.9	2.3	7.0
(percent)	NE	14.1	14.3	9.7	10.7	17.1	10.3	13.6
	E	19.1	33.9	47.5	37.8	23.8	45.5	34.9
	SE	3.0	6.5	13.7	10.5	4.9	11.8	8.5
	S	2.1	0.7	2.0	2.4	1.7	1.9	1.8
	SW	1.6	0.2	0.5	1.2	1.0	0.8	0.9
	W	10.0	5.5	0.1	2.4	8.3	0.8	4.5
	NW	10.0	3.0	0.6	2.8	7.4	0.9	4.1
	Calm	25.6	28.2	24.2	21.5	23.9	25.8	24.9
Mean speed		8.3	7.2	7.8	7.7	7.9	7.5	7.7
Percent over 22 knots		4.1	1.5	1.7	1.2	2.9	1.3	2.1
(b) Nui (6 a.m.) 1977-1975								
Dir	N	14.6	9.3	3.2	8.2	13.2	4.6	8.8
(percent)	NE	16.9	13.4	15.8	18.0	16.8	15.3	16.0
	E	9.1	27.0	46.8	29.9	14.7	41.3	28.3
	SE	2.8	7.2	15.0	11.4	3.7	14.3	9.1
	S	2.2	2.0	2.1	2.8	2.4	2.2	2.3
	SW	3.5	1.7	0.5	0.7	2.6	0.6	1.6
	W	24.6	11.9	0.5	5.9	19.5	2.2	10.7
	NW	10.5	4.3	0.7	2.9	8.0	1.3	4.6
	Calm	15.7	23.0	15.5	20.2	19.0	18.2	18.6
Mean speed		9.8	8.1	9.9	8.2	9.0	9.0	9.0
Percent over 22 knots		3.5	1.9	4.5	1.3	3.0	2.7	2.8
(c) Vaitupu Agricultural (9 a.m.) 1981-1985								
Dir	N	29.3	22.1	9.9	15.6	28.3	10.6	19.2
(percent)	NE	20.2	22.7	24.3	27.7	21.8	25.7	23.8
	E	11.3	23.6	36.3	31.8	14.3	36.6	25.8
	SE	2.9	3.2	7.1	5.1	2.2	6.9	4.6
	S	5.1	8.4	12.5	9.2	5.3	12.0	8.7
	SW	4.9	7.1	5.6	4.6	6.5	4.5	5.4
	W	12.6	9.0	4.2	5.2	12.2	3.4	7.7
	NW	12.4	2.9	0.3	1.2	8.4	0.4	4.3
	Calm	11.3	0.9	0.0	0.0	1.1	0.0	0.5
Mean speed		8.0	6.6	7.6	7.8	7.4	7.8	7.6
percent over 22 knots		0.7	0.0	1.1	0.9	0.5	0.9	0.7

		Dec Jan Feb	Mar Apr May	Jun Jul Aug	Sep Oct Nov	Wetter	Drier	Annual
(d) Funafuti (9 a.m.) 1977-85								
Dir	N	16.0	9.1	2.2	7.8	14.2	3.5	8.7
(percent)	NE	17.0	13.2	10.0	16.1	16.8	11.4	14.1
	E	13.8	32.2	44.3	38.7	19.6	44.5	32.3
	SE	7.5	14.3	32.2	19.0	9.3	27.0	18.3
	S	4.8	3.5	3.6	3.8	4.4	3.5	3.9
	SW	4.8	2.2	0.8	1.8	3.8	1.0	2.4
	W	12.4	6.0	0.5	2.0	9.6	0.9	5.2
	NW	13.8	9.2	0.7	3.0	12.1	1.7	6.8
	Calm	10.0	10.3	5.7	7.2	10.2	6.4	8.3
Mean speed		9.4	8.8	11.9	9.5	8.9	10.9	9.9
Percent over 22 knots		2.7	2.0	6.3	2.6	2.3	4.5	3.4
(e) Niulakita (6 a.m.) 1977-1985)								
Dir	N	7.6	4.0	1.4	2.2	6.0	1.6	3.7
(percent)	NE	9.3	11.3	5.5	7.1	10.2	6.5	8.2
	E	17.9	38.9	65.3	54.3	26.0	61.8	44.7
	SE	6.5	6.4	15.5	12.5	6.3	14.1	10.4
	S	6.1	3.5	1.9	3.4	4.9	2.6	3.7
	SW	4.7	1.5	0.0	0.8	3.2	0.3	1.7
	W	13.6	6.4	0.3	1.4	10.2	0.7	5.2
	NW	9.6	3.0	0.2	0.4	6.5	0.2	3.2
	Calm	24.7	24.9	10.0	17.8	26.7	12.3	19.2
Mean speed		8.1	7.9	10.6	8.4	7.7	9.8	8.8
Percent over 22 knots		3.5	2.5	3.6	1.1	2.9	2.5	2.7

Note: Wetter period is from November to April and the drier period is from May to October.

northern hemisphere, and the trade winds blow largely undisturbed over the tropical South-west Pacific.

From December to May, and particularly between December and February, north and west winds associated with the doldrum belt/monsoon trough account for 35 to 45 percent of the wind; equalling or exceeding the frequencies of winds from the easterly quadrant. In about March or April there is a marked in the monsoon winds together with a sharp increase in the frequency of trade winds.

The frequency in which the wind blows within 40 degrees of the most frequent direction is called the wind constancy.

During March to August, the modal direction is 090°, and the constancy varies from about 45 percent in March to nearly 80 percent in July. From December to February, while 300° is the most frequent direction, the wind constancy is 30 percent. From September to November, 120° is the modal wind direction, and the constancy is about 65 percent.

The annual frequency of surface wind directions over the period 1973 to 1984 at Nanumea and Funafuti were correlated with an annual mean value of the SOI. Correlation coefficients are presented in Table 4. The table shows that while the SOI is positively associated with north-east winds, and to a lesser extent easterlies, it is also inversely related with south or south-west winds. This means that when the value of the SOI is low (i.e. negative), Funafuti and Nanumea are both likely to have above average frequencies of south and south-west winds, while there is a marked reduction in north-east and east winds.

During 1982, and a major El Nino episode, the SOI reached a record negative value, causing the frequency of south and south-west winds at Nanumea and Funafuti to be about three times and twice as frequent respectively. During this period both east and north-east winds reduced by about 35 percent at Nanumea and by 10 percent at Funafuti.

Table 4 also shows a strong inverse relationship at Nanumea between the SOI and calm conditions, but at Funafuti, there is a small non-significant positive correlation.

Table 4. Correlation between the SOI and wind direction frequency. Correlations over ± 0.53 are significant at the five percent level

Direction	Namuea	Funafuti
N	-0.08	0.02
NE	0.84	0.76
E	0.43	0.45
SE	0.42	0.20
S	-0.52	-0.86
SW	-0.55	-0.65
W	-0.13	-0.12
NW	-0.37	-0.12
Calm	-0.78	0.13

Monthly mean wind speeds, based on synoptic weather reports made several times daily are shown in Table 5. Buildings and trees surrounding the meteorological sites affect the wind speeds recorded. Oceanic winds around Tuvalu (see

section 5.1) average about 9.8 knots. Wind speeds on the atolls and island are slightly less; Nanumea probably being some 20 percent lighter than at sea. However seasonal winds (Table 3) indicate that the northern atolls of Nanumea and Nui have relatively uniform speeds all year round, but at Funafuti and Niulakita, there is a distinct maximum from June to September.

Table 5. Mean monthly wind speeds (knots)

Location	Jan	Feb	mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Nui	10	11	10	8	8	10	11	11	9	8	8	10	9.4
Funafuti	8	9	10	8	9	11	12	12	11	8	7	8	9.4
Niulakita	7	9	9	5	8	10	11	11	10	8	6	7	8.4
Nanumea	8	9	9	7	6	8	7	8	8	7	8	8	7.9

While winds over 22 knots occur between two and four percent of the time (Table 3), gale force winds (those having mean speeds over 33 knots) are relatively rare. On Funafuti, where there is an instrumental record, 13 gale episodes have been measured between 1978 and 1983; an average of two gales per year. Nearly 80 percent of all gales occurred with west or north-west winds during the South Pacific cyclone season, November to April.

Wind gust data for Funafuti shows that gusts over 33 knots are measured on 50-60 days each year. One extreme gust of 73 knots from the south-east was measured on 22 August 1984. A gust of at least this magnitude has a frequency of occurrence of about once every 25-35 years.

Diurnal variation of wind speed over the islands is given in Fig. 5. The maximum occurs in the middle of the day, resulting from an augmentation of the trade winds by a local sea-breeze regime. A wind speed minimum occurs at night-time.

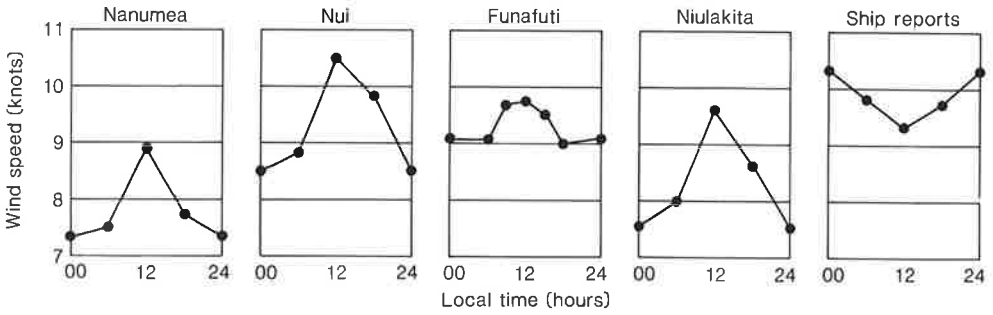

Fig. 5. Diurnal variation of wind. (Based on synoptic weather reports over period 1978-1985. However ship reports are over period 1951-1980)

The range of variation is between 5 and 15 percent of the mean speed.

In contrast, over the oceans, night-time winds are stronger than the daytime ones. This feature is typical of the trade wind regimes of the Pacific Ocean (Riehl et. al., 1951).

Knowledge of the characteristics of wind throughout the Pacific have grown in importance with the increasing awareness of the uses of wind as a resource, especially in the area of wind energy production. The potential of a location as an energy source is dependent on the prevailing mean wind speed and distribution since wind power is since wind power is proportional to the cube of the wind speed. From a theoretical or fitted distribution of wind speeds, another important wind energy consideration can be assessed; that is, the time at which the wind will blow at any given speed or between a specified range.

Table 6. Wind energy potential for Tuvalu

Loocation	V_m	Wind energy* $kWh/m^2/yr$	Hours per year between 6-30 knots
Nanumea	7.9	680	5912
Nui	9.4	1154	6635
Funafuti	9.4	1154	6635
Niulakita	8.4	821	6187
Ocean+	9.8	1305	6783

* Assumes a Weibull distribution with a shape factor of 2. Characteristic wind speed is 11 percent greater than V_m(Swift-Hook, 1979).

\+ Ocean refers to are 2.5 -12.5°S, 172°E-180°.

Annual wind energy potential for Tuvalu is given in Table 6. The total potential between 6 and 30 knots over the oceanic region is 1305 kWh/m^2/year which is nearly 50 percent larger than the estimates for the sheltered Nanumea site, but only 12 percent greater than at Nui and Funafuti.

Rainfall

Annual, seasonal and monthly rainfalls. Tuvalu lies to the east and north of the maximum rainfall region of the tropical South Pacific Ocean, in an area associated with both the cloud and convergent zones of the SPCZ and the Austral summer doldrum belt. Tuvalu tends to have considerably more rainfall than island groups further north (e.g. Kiribati) and south (e.g. Figi and Tonga). The annual rainfall

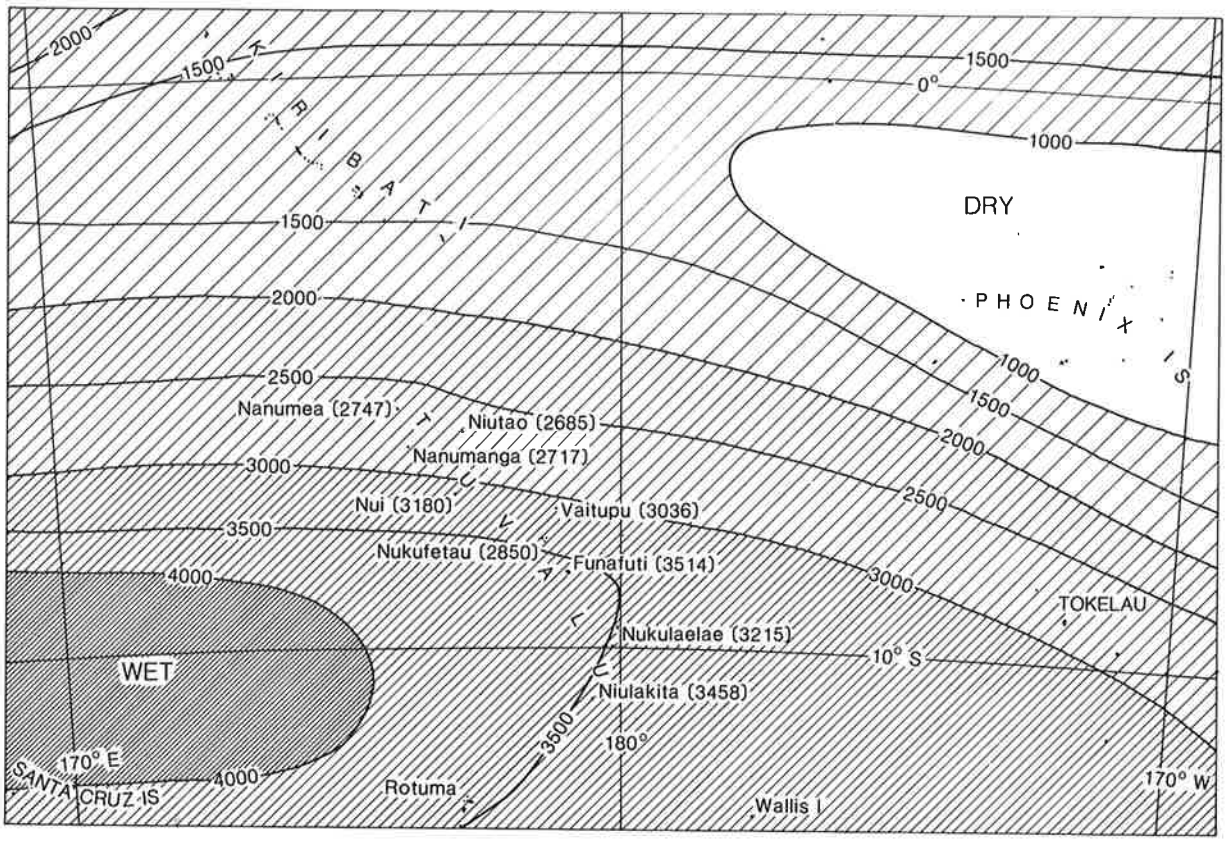

Fig. 6. Mean annual rainfall (mm) for Tuvalu and adjacent oceans, 1951-1980

for a standard 30-year period, 1951-1980 is shown in Fig. 6. (Normals are actual 30-year averages or have been estimated by comparison with adjacent stations.) Tuvalu's southern islands receive on average

Table 7. Monthly rainfall normals (mm), 1951-1980

Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Nanumea	360	249	292	249	206	181	190	212	163	165	187	292	2747
Niutao	337	259	261	234	193	186	198	189	169	171	225	263	2685
Nui	387	335	351	218	212	188	202	215	190	209	284	389	3180
Vaitupu	331	334	268	215	218	188	190	233	187	233	292	347	3036
Vaitupu Ag.	353	356	286	229	235	202	204	251	201	251	311	370	3249
Nukufetau	343	294	268	207	189	190	179	215	187	191	264	323	2850
Funafuti	409	350	314	248	253	224	239	285	208	268	311	405	3514
Nukulaelae	391	315	344	228	225	219	236	238	202	222	261	334	3215
Niulakita	384	329	358	253	237	223	239	232	236	311	308	347	3458

Table 8. Seasonal distribution of rainfall

Location	Time of year (mm) Nov-Apr	May-Oct	Percent of annual total Nov-Apr	May-Oct
Nanumea	1630	1117	59	41
Niutao	1579	1106	59	41
Nui	1964	1216	62	38
Vaitupu	1787	1249	59	41
Vaitupu Ag	1905	1344	59	41
Nukufetau	1699	1151	60	40
Funafuti	2037	1477	58	42
Nukulaelae	1873	1342	58	42
Niulakita	1979	1479	57	43

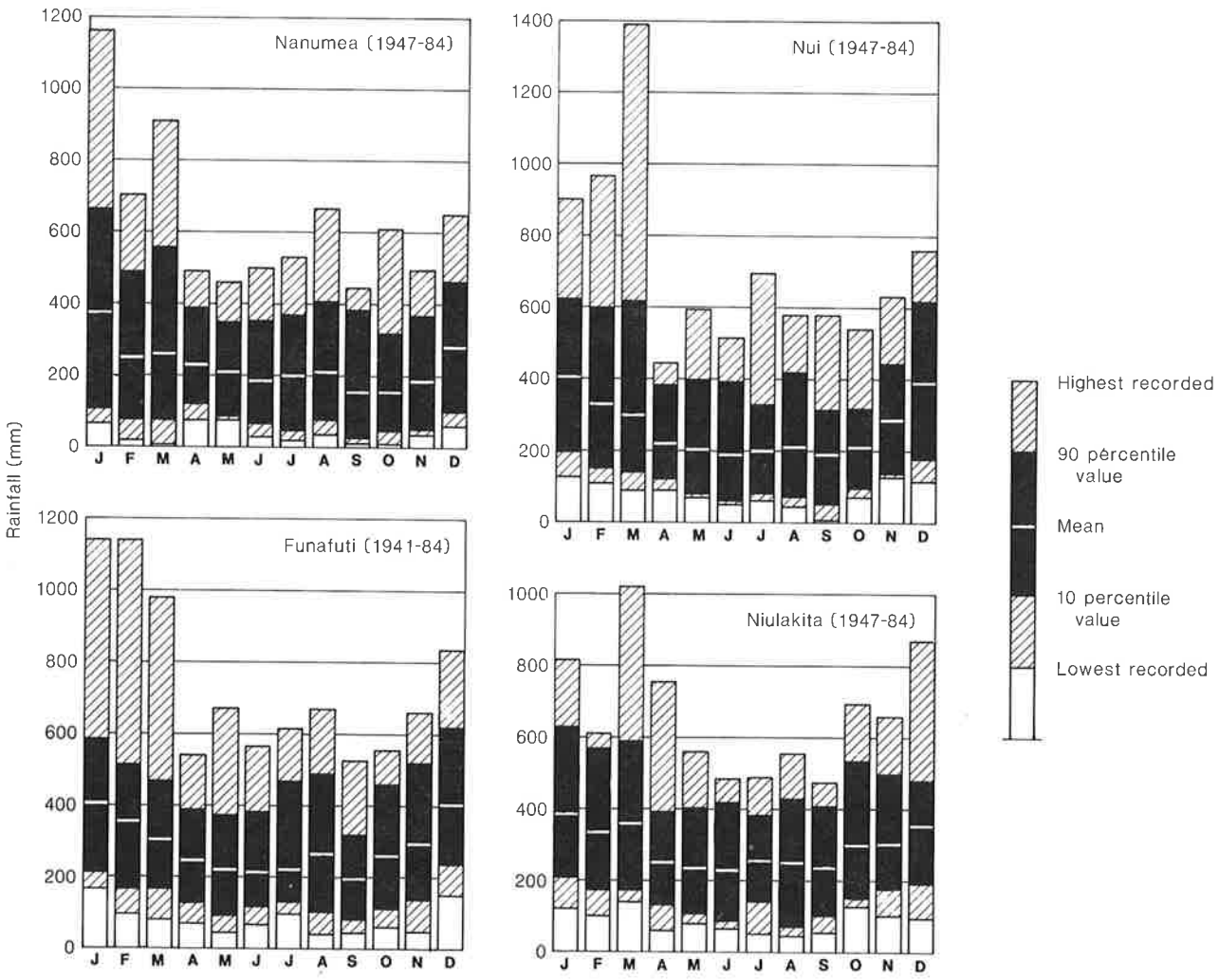

Fig. 7. Monthly rainfall variability on Tuvalu

Table 9. Monthly rainfall extremes of coefficient of variation (CV) for Tuvalu

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
(a) Nanumea												
Highest	1148	698	909	489	475	506	549	705	446	647	493	685
Lowest	66	22	6	75	75	29	21	35	8	8	36	60
CV*	57	58	68	41	47	58	61	66	77	81	63	53
(b) Niutao												
Highest	846	796	839	428	503	442	537	473	477	398	882	578
Lowest	42	12	32	52	22	28	8	23	5	6	44	32
CV	54	69	63	36	52	57	53	57	65	69	69	49
(c) Nanumanga												
Highest	1073	1054	1109	593	393	460	429	481	334	698	654	1152
Lowest	42	12	32	52	22	28	8	23	5	6	44	32
CV	84	81	74	55	63	61	57	60	52	77	58	72
(d) Nui												
Highest	890	963	1393	445	594	515	710	580	579	540	628	762
Lowest	123	109	71	65	68	52	60	43	7	71	123	117
CV	42	54	68	46	59	56	56	62	61	50	40	44
(e) Vaitupu												
Highest	1158	1110	912	496	506	372	478	666	468	557	591	659
Lowest	80	34	19	52	23	22	40	40	4	33	82	136
CV	61	61	63	49	50	40	52	62	60	52	45	36
(f) Funafuti												
Highest	1141	1139	976	539	670	566	617	670	523	554	661	637
Lowest	167	93	83	70	46	68	94	41	47	60	51	152
CV	45	52	48	47	53	47	49	56	49	45	45	40
(g) Niulakita												
Highest	816	611	1018	753	558	485	491	557	476	692	658	869
Lowest	120	101	141	62	81	44	43	46	43	123	101	92
CV	42	41	46	51	49	50	46	53	47	41	41	42

*CV is the ratio of the standard deviation to the monthly mean expressed as as percentage.

over 3000 mm of rain each year, but the amounts generally decrease moving towards the more northern atolls.

Monthly rainfall normals (for the period 1951-1980) are given in Table 7. Tuvalu has a high rainfall all year round, but within this there are distinct seasons of wetter and drier periods. The wetter period occurs from November to April when about 60 percent of the total annual rainfall is recorded,

while in the remaining six months, or drier period, about 40 percent occurs (Table 8).

The computed normals in Table 7 are similar to those presented by Meisner (1976), but cover the period 1910-1975. Nearly all normals were within five percent of each other.

Despite the close proximity to the very wet zone of the South-west Pacific, interannual rainfall variability is generally moderate (Table 9 and Fig. 7). The coefficient of variation in the table indicates relatively uniform values throughout the year, although atolls in the north of Tuvalu tend to have a larger variation than those in the south. Figure 7 presents actual recorded month by month variation for several atolls. At Funafuti for example, it is expected that in 90 percent of all Februarys the rainfall will have a value less than 536 mm, while in only 10 percent of the time will the value be less than 164 mm.

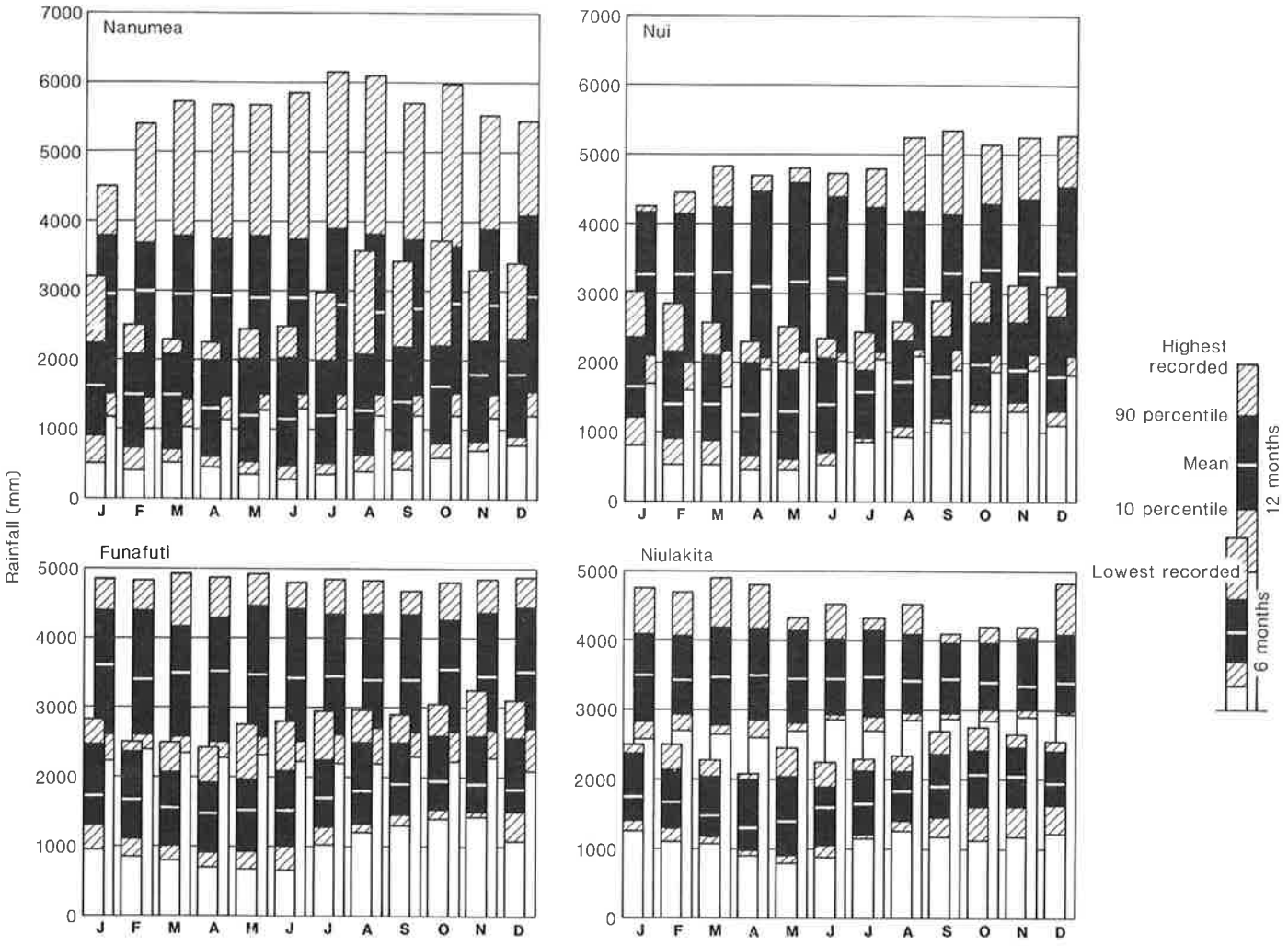

Fig. 8. Rainfall deciles for six and twelve consecutive months. The month shown on the diagrams is the start month

Rainfall deciles for consecutive months can be used to assess the risk of continued anomalous rainfalls. In Fig. 8 deciles are presented for six and twelve consecutive months. At Nui in 90 percent of the years (10 percentile) during a six month period beginning in January there will be at least 1172 mm of rainfall, but in 10 percent of all six month periods there will be on average at least 2349 mm. In the period of the record, the maximum six month total beginning in January is 3001 mm. A similar interpretation can be made with deciles over a 12 month period.

The likelihood of receiving a certain amount of rainfall each year can be useful in estimating the reliability of the rainfall resource, especially on atolls and islands totally dependent on the tank storage of rainfall. Table 10 give probabilities of receiving at least 3000 mm in at least four out of five consecutive years. The likelihood of two successive years receiving less than 3000 mm is also presented. On Funafuti for example, there is a 75 percent chance that four out of five years will receive 3000 mm, and only a 4 percent probability that any two successive years will have less than 3000 mm.

Table 10. Rainfall probabilities - Tuvalu

Location	Probability of receiving at least 3000mm each year	Probability of receiving at least 3000mm in 4 out of 5 yrs	Probability of 2 successive yrs receiving less than 3000mm
Nanumea	0.53	0.22	0.22
Niutao	0.52	0.21	0.24
Nanumanga	0.29	0.03	0.50
Nui	0.57	0.29	0.18
Vaitupu	0.69	0.51	0.10
Nukufetau	0.38	0.07	0.39
Funafuti	0.81	0.75	0.04
Nukulaelae	0.67	0.46	0.11
Niulakita	0.84	0.82	0.24

Rainfall and the SOI. Short-term climate fluctuations in the tropics, on six-monthly or yearly time scales, have been identified as being associated with the SOI. To assess the influence of the SOI on rainfall at Tuvalu, two rainfall indexes were computed for the northern Tuvalu atolls of Nanumea, Niutao and Nui (TVN), and the southern atolls of Vaitupu, Funafuti and Niulakita (TVS). A rainfall index was calculated using Wright's (1984) procedure, but with a datum period 1951-1970 over which to calculate the monthly means of transformed data. Three-month running means were applied to the rainfall and southern

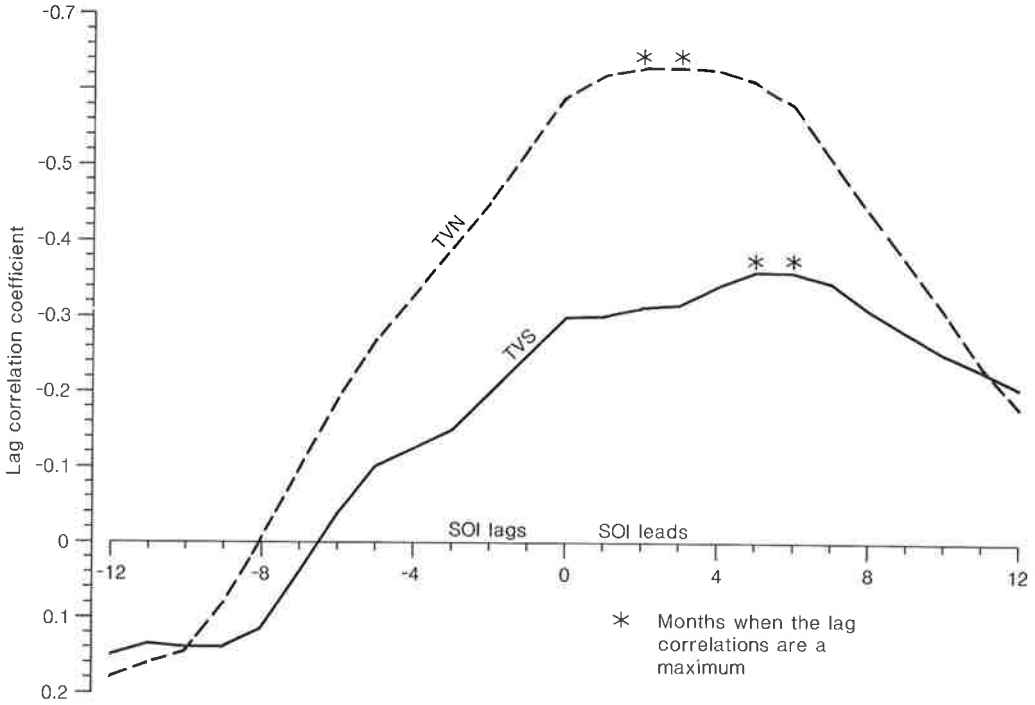

Fig. 9. Three-month running mean lag correlations between indices of the Southern Oscillation (SOI) and rainfall in northern Tuvalu (TVN) and southern Tuvalu (TVS)

Oscillation indices to remove much of the short period noise. Contemporary correlations between the SOI/TVN series and SOI/TVS series are -0.60 and -0.30 respectively. Both correlations are significant, which means that when the SOI has negative values, high rainfall is likely throughout Tuvalu.

Cross-correlations for lags up to 12 months are given in Fig 9. This figures shows clearly that the SOI leads the rainfall response at Tuvalu by several months. The peak correlations at 2-3 months in the SOI and TVN series, and 5-6 months in the SOI/TVS series are highly significant, even after the effects of persistence have been removed. Figure 9 also shows that in the southern Tuvalu time series the SOI influence on rainfall is not as strong as it is in northern Tuvalu.

A rainfall time series of the year-to-year departures from the 1951-1970 mean for Tuvalu is given in Fig. 10. Overall correlation between the annual rainfall and a mean SOI for the same year is -0.65. Departures from the long-term mean of more five percent indicate a clear relationship with the SOI. Of the 10 dry years, 9 occurred when the SOI was positive. Five of the six wet years had negative values of the SOI.

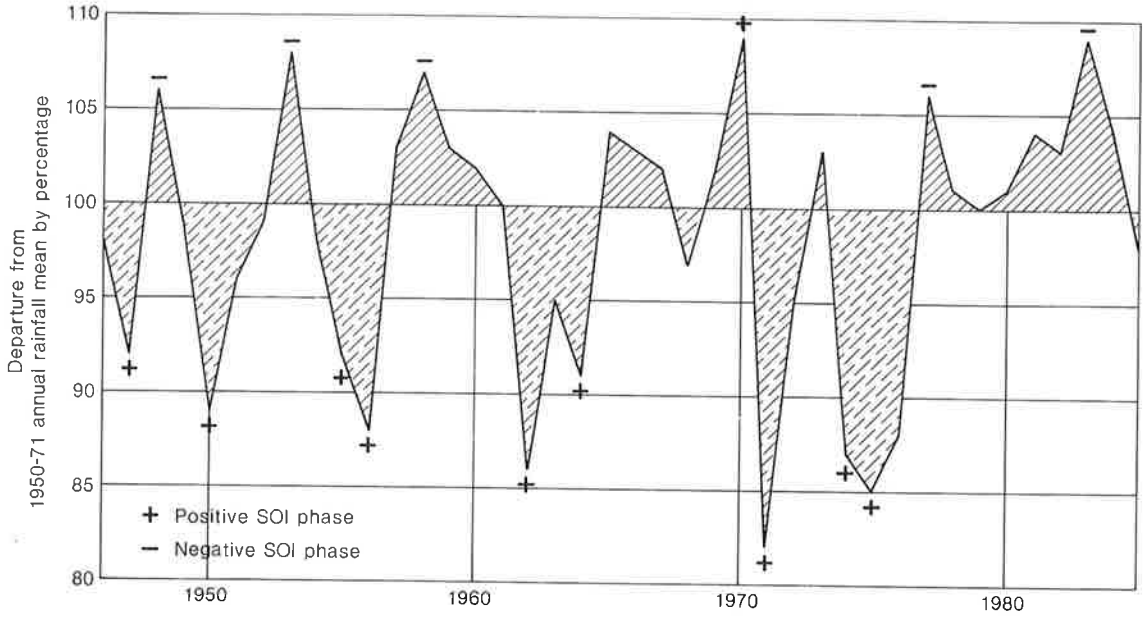

Fig. 10. Interannual variability of Tuvalu rainfall index

Persistence of abnormal rainfalls. Abnormal monthly rainfall is defined as a departure of at least 50 percent from the average monthly amount. Table 11 gives an indication of the frequency of abnormal rainfall in Tuvalu.

Table 11. Average number of runs per decade for the stated maximum number of consecutive months, each with abnormal rainfall

Max. no. consecutive months each with over 150 percent of average					Max. no. consecutive months each with less than 50 percent of average							
1	2	3	4	5	1	2	3	4	5	6	7	8
(a) Nanumea												
12.1	2.6	0.3	0.5	0.5	7.7	2.8	1.0	1.0	0.3	-	0.5	0.3
(b) Nui												
9.8	2.5	1.0			7.0	2.5	0.5	0.3	0.3			
(c) Funafuti												
10.9	1.6	0.2	-	0.2	9.8	0.7	0.4	0.2				
(d) Niulakita												
10.0	2.3	0.5			9.2	0.8	0.3					

Most years usually have some months of abnormal rainfall, but high or low rainfalls lasting more than two months are not very common. However at Nanumea and Nui it does appear that abnormally low rainfalls do persist longer than high rainfalls.

On Nanumea there has been one reported incidence of a very low rainfall lasting for an eight month period from March to November 1976. Only 37 percent of normal rainfall was recorded during this time, and occurred at a time when the Southern Oscillation had been positive during the preceding three years. Rainfall during the years 1974-1976 was substantially below normal.

A contingency table (Table 12) indicates the frequency of abnormal rainfall of at least two months in relation to the SOI. The results presented in the table were tested for a possible relationship between the phase of the SOI and high or low rainfall, using the chi-square test statistic under the assumption of no association between the two. The value of chi of 36 is very significant at a level beyond the 99.9 percent. The table indicates that periods of abnormally low rainfall are likely to be associated with a positive SOI and vice versa. The response of the rainfall to the SOI is similar to that described in the preceding section.

Table 12. Abnormal rainfall periods of at least two months and the southern oscillation index averaged over the corresponding period

Mean SOI	Frequency (percent) of abnormal rainfall High	Low
SOI $\geq$ 0.5	8.1	66.7
-0.5 < SOI < 0.5	42.9	20.8
SOI $\leq$ -0.5	49.0	12.5
No. of cases	49	48

Raindays, short-term persistence of rainfall, diurnal variation and rainfall duration. The frequency of days of rainfall above specified thresholds is given in Table 13. About half of all raindays with more than 0.1 mm occur during the wetter season, but there are more frequent, heavier falls of rain (Table 13(c)) which contributes to the rainfall maximum at this time of the year. About 65-70 percent of all days with rain of at least 50 mm per day occur during the wetter season.

The frequencies of raindays vary considerably from year-to-year (Table 14). Extreme values are presented together with a

Table 13. Days with rain - Tuvalu

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
(a) above 0.1 mm threshold													
Nanumea	20	16	18	19	18	17	18	17	16	14	15	19	207
Niutao	15	15	16	15	14	13	14	12	12	9	11	16	162
Nanumanga	15	15	19	16	15	16	18	16	12	11	14	17	184
Nui	21	19	22	20	19	19	20	21	18	17	18	21	235
Vaitupu	14	12	13	11	11	11	12	12	9	10	11	14	140
Nukufetau	16	13	15	12	13	13	13	13	12	12	13	14	159
Funafuti	22	21	24	21	21	21	22	23	19	22	22	22	260
Nukulaelae	16	14	15	11	12	11	11	12	12	16	14	14	158
Niulakita	22	21	24	20	21	18	21	19	20	23	22	21	252
(b) above 5 mm threshold													
Nanumea	14	11	13	11	10	9	11	11	7	7	8	12	124
Niutao	13	12	12	12	11	10	10	9	9	7	9	14	128
Nanumanga	11	13	15	12	10	11	12	12	8	8	9	13	134
Nui	14	12	13	10	11	10	11	11	10	9	12	13	136
Vaitupu	11	9	10	7	8	8	9	9	7	8	9	12	107
Nukufetau	13	10	11	9	9	10	9	10	10	8	10	12	121
Funafuti	13	13	14	9	10	11	11	11	9	11	12	13	137
Niulakita	13	14	13	10	11	9	10	10	10	12	13	11	136
(c) above 20 mm threshold													
Nanumea	7	5	6	4	3	3	4	3	3	3	3	6	53
Niutao	6	4	5	4	2	2	3	3	2	2	3	5	41
Nanumanga	4	7	9	6	2	3	4	6	3	2	4	8	58
Nui	7	6	6	3	3	3	3	3	3	3	5	6	51
Vaitupu	6	5	6	3	4	3	2	4	3	7	5	7	55
Nukufetau	5	4	5	3	3	3	3	4	3	3	5	6	47
Funafuti	7	5	6	3	4	3	3	4	3	4	4	7	53
Nukulaelae	7	5	7	3	3	4	5	4	3	5	5	6	57
Niulakita	6	5	5	3	4	3	3	3	3	5	6	6	49

measure of the dispersion. As the rainday threshold increases, so does the mean deviation coefficient. Variability is most most marked on atolls in the north of Tuvalu.

Rainfall persistence over several consecutive days (n-days) is presented in Table 15. This type of analysis is extremely useful in assessing the risk of short-term wet and dry spells at a particular location. For example, on Vaitupu, 62 percent of all days have no rain. For 7-day spells, there is a 7 percent probability of no rain, but a 22 percent chance that the total rainfall will be between 50 and 100 mm.

Table 14. Extremes in annual numbers of raindays, and mean deviation coefficient (MD)

	Rainday thresholds											
	0.1			5.0			20.0			50.0		
	High	Low	MD*	High	Low	MD	High	Low	MD	High	Low	MD
Nanumea	248	133	56	180	60	65	85	16	130	25	2	195
Niutao	195	82	70	175	62	88	74	11	153	19	2	159
Nanumanga	233	161	39	198	108	67	95	45	86	23	8	114
Nui	302	171	56	177	94	61	83	22	120	30	3	186
Vaitupu	189	106	59	146	56	84	79	28	93	31	9	116
Nukufetau	185	88	61	149	66	69	67	24	91	16	3	144
Funafuti	287	223	25	158	109	36	69	30	74	21	6	117
Nukulaelae	195	137	37	145	79	56	75	24	89	31	5	164
Niulakita	280	196	33	162	115	35	64	39	51	19	5	109

* MD is a ratio of the difference between the observed and mean values to the mean value expressed as a percentage.

Hourly observations of rainfall are only available for Funafuti. The diurnal variation of rainfall for the wetter

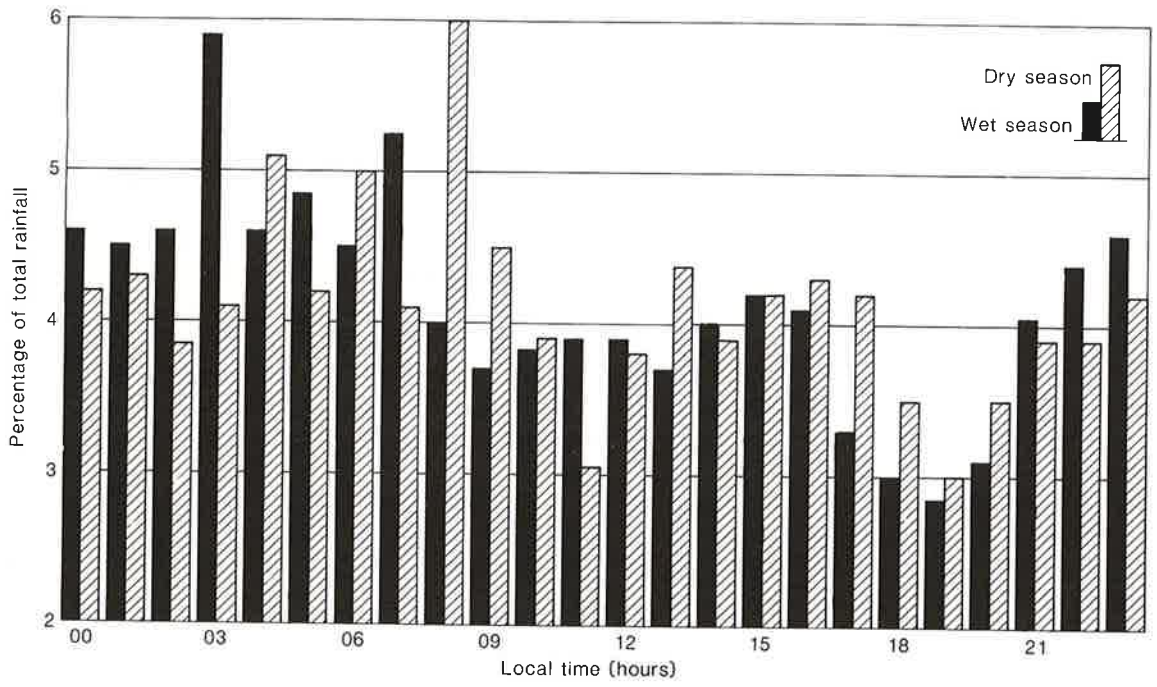

Fig. 11. Diurnal variation of rainfall at Funafati during the wetter and drier seasons

Table 15. Short-term rainfall persistence
(i.e. Percent of N-days with various amount of rain)

n-days	1	3	5	7	14	30	1	3	5	7	14	30
Amount rain	Nanumea						Vaitupo					
Nil	44	16	7	3	0	0	62	30	15	7	1	0
0.1 - 5mm	23	20	15	10	2	0	10	11	9	7	2	0
5.1 -10mm	10	12	10	9	3	0	7	10	9	8	3	0
10.1 -15mm	5	8	8	7	4	1	4	8	7	6	3	0
15.1 -25mm	7	6	13	11	7	1	5	10	12	11	6	1
25.1 -50mm	7	15	19	20	15	5	7	14	18	20	16	5
50.1 -100mm	2	11	17	22	23	15	4	12	17	22	27	12
100.1-150mm	0	3	6	10	17	14	0	3	7	10	17	13
over 150mm	0	1	5	9	28	63	0	2	5	8	27	68
over 200mm	0	0	2	4	18	53	0	0	2	4	16	54
over 300mm	0	0	0	1	6	33	0	0	0	1	5	29
over 500mm	0	0	0	0	1	9	0	0	0	0	1	7
Amount rain	Funafuti						Niulakita					
Nil	29	6	1	0	0	0	31	8	3	1	0	0
0.1 - 5mm	34	20	9	3	0	0	32	19	10	5	1	0
5.1 -10mm	7	13	9	5	0	0	12	12	7	4	1	0
10.1 -15mm	7	11	9	6	1	0	7	11	8	5	1	0
15.1 -25mm	4	15	16	13	3	0	7	14	14	11	3	0
25.1 -50mm	7	19	24	24	13	0	8	20	26	26	10	1
50.1 -100mm	2	13	22	29	30	7	3	12	22	29	32	4
100.1-150mm	0	3	6	11	22	12	1	3	6	11	23	11
over 150mm	0	1	4	7	31	80	0	1	4	8	30	84
over 200mm	0	0	1	3	16	63	0	0	2	4	15	67
over 300mm	0	0	0	1	4	35	0	0	0	1	6	35
over 500mm	0	0	0	0	0	6	0	0	0	0	0	7

drier seasons is shown in Fig. 11. Average hourly rainfall amounts have been expressed as a percentage of the 24-hourly total. While rain may fall at any time of the day, there is a tendency for rain to fall most frequently at night and least during the late afternoon. Nearly 55 percent of rain falls between 8 p.m. and 8 a.m. during the wetter time of the year, but 51 percent during the drier season.

The average duration of rainfall at Funafuti is 525 hours per year, or about six percent of the total time. It rains 50 percent more often during the wetter season (317 hours) than during the drier one (208 hours).

Extreme short-period rainfall. The duration of high intensity rainfall varies with the characteristic of the disturbance causing the rain. For up to one or two hours, thunderstorms produce heaviest falls. For longer durations, rainfall is usually produced from weather systems such as those associated with tropical cyclones or the SPCZ. The rainfall intensities in these systems decrease as the duration increases (Fig. 12).

The frequency of intense rainfalls for selected durations can be determined from depth-duration-frequency tables (Table 16). This table has been computed from annual maximum rainfall measured at 9 a.m. over one, two and three-day periods. These data are adjusted to provide estimates of 24, 48, and 72-hour rainfalls for various return periods. Table 16 indicates that at Funafuti for a 24 hour period, a rainfall of 268 mm can be expected or exceeded on average once every 20 years.

While high intensity rains may fall at any time of the year, there is a strong tendency for the extreme events to occur during the wetter season.

As mentioned above, rainfall intensities vary with time (Fig. 12). From this figure, short duration rainfalls (i.e. less than 24 hours) at Funafuti can be determined from this diagram. For example, a 12-hour rainfall with a return period of 10 years can expect at least 192 mm.

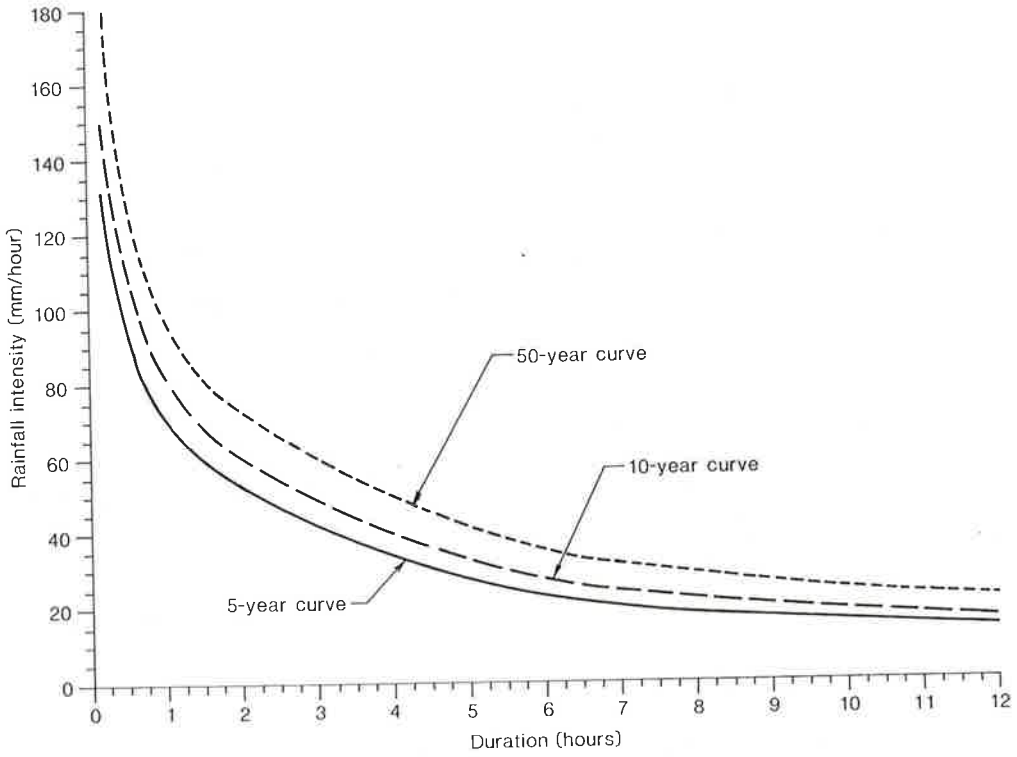

Fig. 12. Rainfall intensity-duration-frequency relationships for Funafuti, (1961-1978)

Table 16. Depth (mm)-duration (hrs)- frequency (per year) for Tuvalu

Location	Return Period	2yr	5yr	10yr	20yr	50yr
Nanumea	24hr	147	196	228	259	299
1971-1985	48hr	177	238	279	318	368
	72hr	198	253	290	325	370
Niutao	24hr	129	191	231	270	320
1971-1985	48hr	158	220	260	299	349
	72hr	191	274	329	382	450
Nui	24hr	144	192	224	255	295
1971-1985	48hr	183	246	289	329	389
	72hr	219	292	341	389	449
Vaitupu	24hr	139	186	218	248	286
1971-1985	48hr	174	239	282	324	378
	72hr	212	271	310	347	396
Nukufetau	24hr	134	188	224	258	303
1971-1985	48hr	161	210	244	276	317
	72hr	179	245	288	330	384
Funafuti	24hr	142	197	233	268	313
1961-1978	48hr	186	250	293	334	387
	72hr	209	277	322	365	421
Nukulaelae	24hr	132	175	204	231	266
1971-1985	48hr	169	226	264	300	346
	72hr	202	276	326	373	434
Niulakita	24hr	156	208	240	272	312
1971-1985	48hr	203	283	336	388	454
	72hr	231	307	358	407	469

Dry spells Fifteen consecutive days with less than 1 mm per day is classed as a dry spell. A short record, from 1971-1985 listing dry spells in Tuvalu, indicates that on average between one and ten dry spells can be experienced every decade. About two-thirds of all reported episodes in Tuvalu occurred during the drier season. Dry spells are more likely in the more northern atolls of Tuvalu.

Sunshine and solar radiation

Sunshine. Bright sunshine measurements were first started at Funafuti in 1932 and continued until 1941. In May 1977 measurements began again. The earlier record gave an annual

average of 2360 hours (N.Z.M.O., 1943), while the current record averages 2237 hour each year. On other islands of Tuvalu, sunshine has never been measured. As cloud cover directly affects the amount of sunshine reaching the surface of the earth, good estimates of spatial and temporal variation in sunshine can be obtained from observations of cloud cover.

Sadler, Oda and Kilonsky (1976) have assessed the cloudiness of the Pacific Ocean using satellite observations of cloud cover over the period 1965-1973. Monthly maps of cloud cover for 2.5° squares were prepared. Table 17 shows monthly cloud cover for island groupings in Tuvalu.

Table 17. Average cloud cover* (percent) over selected 2.5° latitude-longitude squares

Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Nanumea	59	57	54	51	48	49	46	47	49	48	50	54
Funafuti	61	61	56	54	51	51	47	51	51	54	54	59
Niulakita	61	58	54	53	54	52	51	52	52	57	54	60

* Source Sadler, Oda and Kilonsky (1976).

Comparing Sadler et al. estimates of cloud cover with known values for several South-west Pacific locations, it was found that their estimates were on average 10 percent too high. Thin cirriform cloud is frequently reported in the tropics, but does not appreciably reduce the bright sunshine amounts. Monthly sunshine values in Table 18 have been estimated from adjusted cloud cover data.

Table 18. Estimates of monthly sunshine (hours)

Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Nanumea *	185	139	199	217	222	213	225	216	205	233	178	182	2414
Nui **	186	139	199	216	221	212	224	215	205	234	180	183	2414
Funafuti	175	134	186	201	206	197	208	205	194	219	169	172	2266
Nukulaelae	176	134	186	201	205	196	207	205	194	219	170	173	2266
Niulakita	177	134	186	201	204	195	206	202	194	220	171	174	2264

* Sunshine estimates also apply to Nanumanga and Niutao.
** Sunshine estimates also apply to Vaitupu and Nukufetau.

Annual sunshine totals vary from about 2400 hours in the north to about 2250 hours in the south. The drier season is the sunnier time of the year with about 55-65 percent of the total possible sunshine being recorded.

Radiation. Global radiation comprises both direct and diffuse radiation. It varies greatly with latitude, as well as with the amount of cloud cover and sunshine. Global radiation has not been measured in Tuvalu, but Revfeim (1982) proposed a model for the for the estimation of both global and diffuse radiation using hourly sunshine values. Estimates of global radiation for Funafuti using this method are presented in Table 19(a). While there is a seasonal variation in the global radiation, the diffuse fraction is remarkably constant throughout the year, and amounts to about 60 percent of the total solar radiation.

Table 19. Global Radiation ($MJ/m^2/day$)

(a) Monthly radiation at Funafuti 1978-1984:- Revfeim method

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
17.9	19.6	18.8	19.0	17.1	16.7	15.8	17.6	19.2	20.5	19.5	19.6

(b) Monthly radiation estimates 1965-1973:- Angstrom method

Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Nanumea	19.3	18.6	19.8	19.5	18.0	17.0	17.5	18.4	19.6	20.9	19.2	19.0
Funafuti	19.4	18.6	19.3	18.7	17.0	16.0	16.4	17.6	19.0	20.6	19.3	19.1
Niulakita	19.6	18.6	19.2	18.4	16.7	15.7	16.1	17.4	19.0	20.6	19.5	19.4

Global radiation estimates in Tuvalu have also been computed from the Angstrom relation (Angstrom, 1924). It is given by;

$$Q/Q_o = a + b(n/N)$$

where

Q/Qo = ratio of global to extraterrestrial radiation
n/N = relative duration of bright sunshine
a = coefficient depending on prevailing cloud type
b = transmission characteristics of cloud free atmosphere

Coefficients a and b were assessed from Funafuti sunshine and from radiation determined by the Revfeim (1982) method. They were found to be a = 0.34 and b = 0.32, and the correlation coefficient was 0.97. The sum (a + b) is 0.66 indicates a moist turbid atmosphere (Mani and Rangarajan, 1983), typical of tropical

regions. These coefficients are similar to the ones found by Thompson (1986) using Fiji sunshine and radiation data. Estimates of global radiation using the Angstrom method for Nanumea, Funafuti and Niulakita are given in Table 19(b).

Air temperatures

Air temperatures on Tuvalu are uniformly high all year round. Figure 13 shows two features of tropical maritime climates; a lack of pronounced seasonal variation throughout the year, and a comparatively large daily variation of 5-6°C. The mean maximum and minimum temperatures are 31°C and 25°C

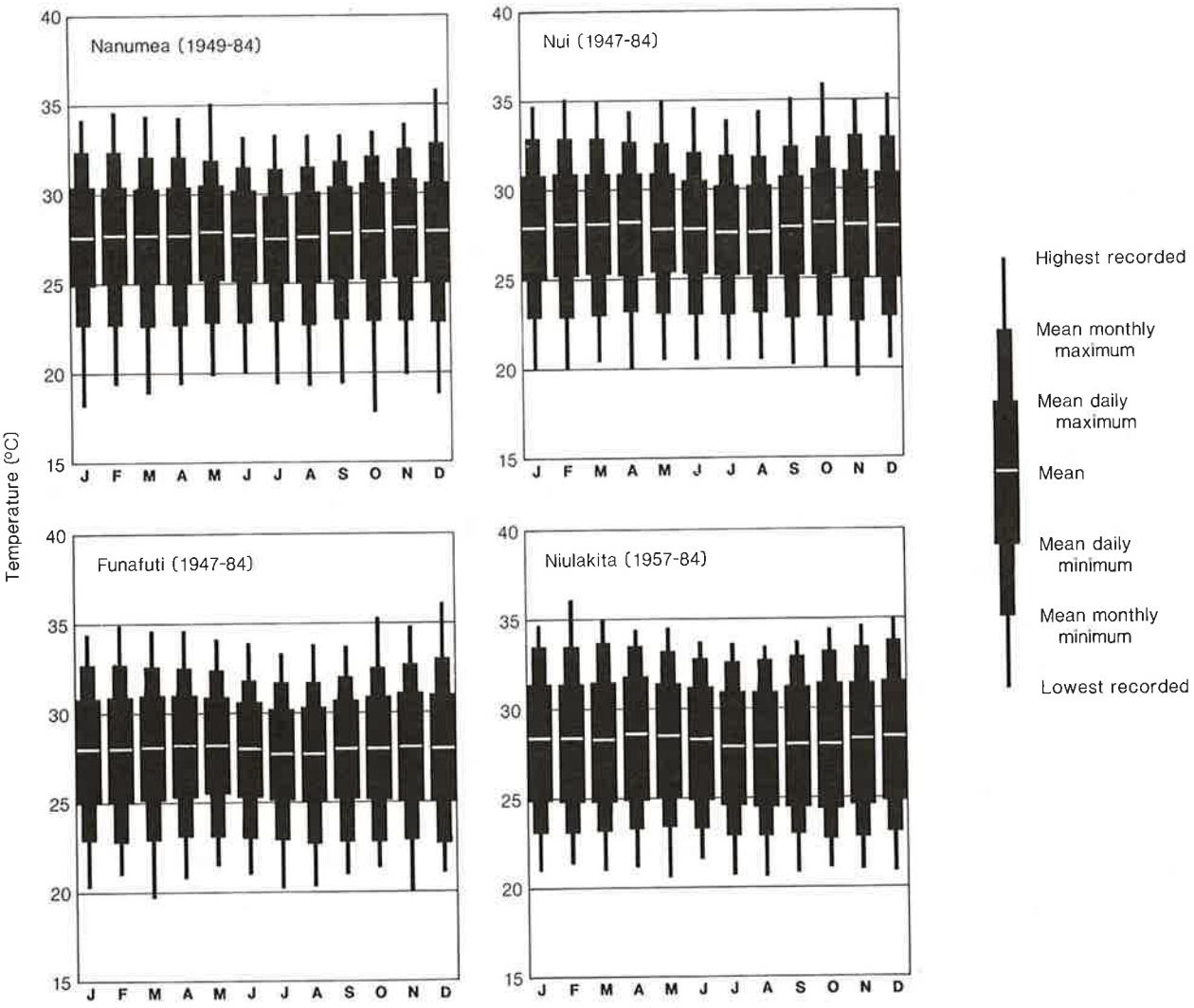

Fig. 13. Temperature variability on Tuvalu

respectively, and the departure from these means in any month is less than half a degree. Variability between years is also small, the coefficient of variation in both maxima and minima is just two to three percent.

Table 20 presents 10, 50 and 90 percentile values of the mean daily maximum, mean daily minimum and mean temperature for Funafuti. Since the islands and atolls of Tuvalu have a similar temperature regime this data can be generalised to apply to the whole island group. The mean temperature is the mid-point between the maximum and minimum temperatures (i.e. $[T_{max} + T_{min}]/2$). A maximum temperature in excess of 31°C in July can be expected in one year in ten (i.e. the 90 percentile).

Table 20. Percentiles of monthly temperature (°C) on Funafuti

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
(a) Mean daily maximum												
90 percent	32	31	32	32	31	31	31	31	31	31	32	32
50 percent	31	31	31	31	31	31	30	30	31	31	31	31
10 percent	30	30	30	31	30	30	30	30	30	30	30	30
(b) Mean temperature $[T_{max} + T_{min}]/2$												
90 percent	29	29	29	29	29	29	28	28	28	29	29	29
50 percent	28	28	28	28	28	28	28	28	28	28	28	28
10 percent	27	27	28	28	28	28	27	27	27	27	28	27
(c) Mean daily minimum												
90 percent	26	26	26	26	26	26	26	26	26	26	26	26
50 percent	25	25	25	25	25	25	25	25	25	25	25	25
10 percent	24	24	24	25	25	25	24	24	24	24	24	24

Highest and lowest temperatures recorded throughout Tuvalu are presented in Table 21. Temperatures in excess of 34°C occur about once every two years, and below 21°C about once every three or four years in the south, but only once every 10 to 15 years in the northern atolls.

Because temperatures are high all year round, people not accustomed to such conditions will experience some physiological discomfort. Effective temperature (ET) is an empirical index which assesses comfort, taking account of temperature, humidity and wind speed. This index cannot be considered as a complete definition of human comfort since radiation and rainfall are excluded.

Table 21. Highest and lowest recorded temperatures (°C) on Tuvalu

	Highest	Lowest
Nanumea	35.8	17.8*
Nui	35.9	19.5
Funafuti	36.1	19.7
Niulakita	36.1	20.6

* Minimum temperatures between August 1954 and April 1956 appear to be too low.

For the South-west Pacific the critical effective temperature at which discomfort is felt is about 21-24°C (Finkelstein, 1972). Effective temperatures on Tuvalu vary from 21-23°C throughout the year. Some discomfort will be experienced at any time of the year, especially in the afternoons, but with generally higher wind speeds during the drier time of the year ET values are slightly lower reducing the level of discomfort.

Thunderstorms

Thunderstorms in the tropics can provide a large proportion of an islands rainfall because heavy falls can result in very short durations. The frequency of thunderstorm-days for Tuvalu is given in Table 22. Days of thunder are fairly evenly spread throughout the year, but in the northern atolls there is a tendency for thunder to be slightly more prevalent during the drier season.

Thunderstorm episodes show a pronounced diurnal variation. Nearly 75 percent of observed thunder occurs in the evening and at night-time, with only 12 percent in the afternoon.

Table 22. Thunderstorm statistics - Tuvalu

Location	Mean no. per year	CV (percent)	Percentiles 10	90	98
Nanumea	18	39	10	27	35
Nui	26	77	5	52	80
Funafuti	31	39	16	47	60
Niulakita	24	49	10	39	53

The frequency of days with thunder varies considerably from year to year (Table 22). The 10, 90 and 98 percentile values in the table are estimates of how frequently a specific number of thunder-days occurs. For Niulakita, the 98 percentile (or average return period of 50 years) is 53 days of thunder a year. Fifty-seven thunder-days were observed in 1959.

Moisture in the atmosphere

Atmospheric moisture is derived primarily through evaporation from the ocean. About 50 percent of the total global radiation reaching the surface is used to evaporate sea water (Jacobs, 1951). Around Tuvalu the amount of heat energy available for evaporation is about 35-40 percent of the global radiation in the wetter season, and about 45-55 percent during the drier season. Evaporation rates for Tuvalu vary about 3-4 mm per day throughout the year.

Atmospheric moisture is commonly measured in terms of vapour pressure. Table 23 gives monthly values of vapour pressure for islands throughout Tuvalu. There is a small spatial and seasonal variation. Vapour pressure remains remarkably constant from year to year; the coefficient of variation is just one to three percent of the monthly value.

Table 23. Mean monthly vapour pressure (hPa) 1977-1984

Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Nanumea	30.9	30.5	30.7	30.9	30.9	30.7	30.3	29.9	30.0	30.0	30.4	30.6
Nui	30.5	30.5	30.7	30.8	31.1	30.7	30.3	30.1	30.0	30.2	30.2	30.6
Funafuti	31.4	31.5	31.5	31.9	32.2	31.7	31.5	31.5	31.3	31.4	31.2	31.0
Niulakita	31.2	31.2	31.2	31.1	31.2	30.8	30.3	30.0	30.1	30.7	30.9	31.1

Evapotranspiration and soil water balance

Table 24. Monthly Penman potential evapotranspiration (mm) for Tuvalu

Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Nanumea	149	139	155	139	132	125	129	141	148	158	150	151
Nui	159	147	158	141	132	124	132	143	148	161	151	158
Funafuti	153	139	157	139	133	126	132	142	150	157	147	153
Niulakita	157	142	157	138	135	129	136	147	153	161	148	159

Table 25. Water balance summaries for Tuvalu available water content for coral soils 140 mm

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
(a) Nanumea 1971-1985.												
WPD	0	0	12	1	0	17	17	13	23	35	35	9
ND	0	0	3	0	0	5	5	4	5	8	8	2
FDE	7	0	20	7	0	29	29	29	21	36	50	36
RO	243	162	222	96	78	101	112	131	73	58	41	194
NR	10	8	8	5	4	5	6	6	3	3	2	7
FRO	93	93	73	71	64	64	50	64	50	36	36	86
(b) Nui 1971-1985.												
WPD	0	0	0	0	3	5	10	9	9	9	6	0
ND	0	0	0	0	1	2	3	3	2	2	1	0
FDE	0	0	0	6	6	13	13	25	13	31	24	0
RO	227	222	226	76	79	86	107	131	62	59	143	229
NR	10	9	8	5	5	5	5	5	4	3	6	8
FRO	100	94	76	81	69	69	63	69	67	63	82	94
(c) Funafuti 1945-1985.												
WPD	0	0	0	0	1	1	0	0	3	5	2	0
ND	0	0	0	0	0	0	0	0	1	1	1	0
FDE	0	0	0	0	3	3	3	0	5	11	5	0
RO	247	214	167	114	114	102	110	141	77	103	147	253
NR	10	9	8	6	6	6	7	7	4	5	7	10
FRO	100	98	100	90	82	85	87	87	71	86	86	95
(d) Niulakita 1971-1985												
WPD	0	0	0	0	0	0	3	5	3	0	0	0
ND	0	0	0	0	0	0	1	1	1	0	0	0
FDE	0	0	0	0	0	0	7	7	7	0	0	0
RO	253	193	195	92	98	82	80	93	61	132	175	177
NR	10	9	8	5	5	5	5	4	4	6	8	7
FRO	100	93	100	93	93	73	87	73	73	80	93	93

WPD Water deficiency (mm) in the soil
ND Average number of days of deficit (days)
FDE Frequency (percent) of months with deficit
RO Removal of excess rainfall (mm)
NR Average number of days of excess rainfall (days)
FRO Frequency (percent) of months with excess rainfall

Evapotranspiration is the combined loss of water by evaporation from the soil and by transpiration from plants. In tropical regions where there is a large amount of energy available, evapotranspiration rates are high. When there is an adequate supply of water, evapotranspiration reaches a maximum and is usually called potential evapotranspiration (ET_{max}). Monthly estimates of ET_{max} for Tuvalu are given in Table 24, and have been computed from the Penman formulation given by Coulter (1973). There is little spatial variation of ET_{max} throughout Tuvalu, but there is some seasonal variation throughout the year. Potential evapotranspiration averages about 5 mm/day in January and 4 mm/day in June.

The interaction between evapotranspiration and rainfall form the basis of the soil water balance. When ET_{max} exceeds rainfall, soil moisture reserves are used. Conversely, a soil moisture deficit exists when all the soil water is utilised. Tuvalu, on average has sufficient rainfall all year round (Table 7) to meet evapotranspiration requirements. When rainfall exceeds ET_{max}, water is added to the soil until its maximum water content is reached. Any further rainfall causes runoff.

Coral atolls have highly permeable soils, and for this reason there is usually little runoff with the excess rainfall draining to the water table below. Water balance summaries for representative Tuvalu locations are given in Table 25. Soil moisture deficits are most likely to occur in the drier and sunnier northern atolls of Tuvalu than in the more southern ones. Table 25 also shows the excess of rainfall occurs all year round. Highest values and frequency of occurrence are from December to March.

At Nanumea there has been one recorded instance of at least 100 days of deficit in a single year. From June to December 1975, there were 102 days of soil water deficit, during which only 264 mm of rainfall (23 percent of average) was recorded. Elsewhere in Tuvalu there have been no other recorded instances of at least 100 days of deficit. On Funafuti there were 68 days between September and November 1950 during which only 251 mm of rain fell (29 percent of normal).

5. MARINE CLIMATE

The tables and figure used in this section were prepared from ships' observations of weather, sea-state and sea temperatures between 1951 to 1980 in an area from 2.5°-12.5°S, and from 172°E-180°. Data were obtained not only from the New Zealand Meteorological Service's archives, but also from data by the Royal Netherlands Meteorological Institute, and the Climatic Centre of the National Oceanographic and Atmospheric Administration. A total of 3500 observations were available.

Marine Winds

Wind speed and frequency data are presented in Table 26. On an annual basis just over 70 percent of winds blow from the easterly quarter, although the frequency reaches 86 percent in the period from June to August, but only 45 percent in the season six months later. Monsoon type winds between west and north in the November to February period are about as frequent as winds from the easterly quarter, and are seven times as likely to blow than during June to August.

The mean oceanic wind is 9.8 knots. Wind speeds tend to be strongest during the driest part of the year when the trade wind easterlies are most persistent. Strongest winds during the wetter season are mostly associated with the monsoon winds.

Table 26. Seasonal wind data over oceans surrounding Tuvalu (1951-1980)

	Sep Oct Nov	Dec Jan Feb	Mar Apr May	Jun Jul Aug	Nov-Apr	May-Oct	Annual
Speed (knots)	9.3	9.8	9.6	10.5	9.7	9.9	9.8
Dir N	6.0	14.2	8.3	3.4	12.2	3.5	7.8
(percent) NE	20.1	21.5	21.1	15.0	22.4	16.3	19.0
E	33.3	17.9	32.8	45.2	22.4	42.9	34.0
SE	22.6	5.5	16.7	25.4	9.6	25.9	18.9
S	3.9	3.8	3.0	3.9	3.4	3.9	3.7
SW	2.7	4.0	1.5	1.0	3.8	0.9	2.1
W	3.2	14.1	3.1	1.3	9.4	1.1	4.7
NW	4.9	15.0	8.2	1.6	12.7	1.9	6.5
Calm	3.3	3.9	5.3	3.1	4.3	3.5	3.8
percent speeds over 21 knots	3.4	2.2	4.3	3.6	3.4	3.4	3.4

Sea temperatures

Monthly sea surface temperatures are given in Fig. 14. The mean annual temperature is 28.9°C, and the range is less than 0.5°C. Variability between years is small, with the variation being just four percent about the mean. Sea surface temperatures are on average one to two degrees warmer than the over-lying mean air temperatures.

Sea and swell

Seasonal frequencies of wind waves and sea swell are given in Table 27. Waves and swell are measured and coded to the nearest

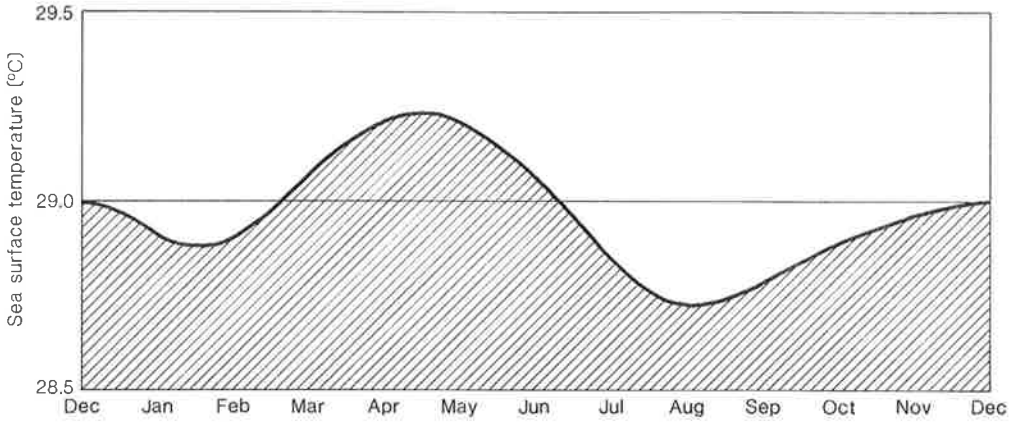

Fig. 14. Sea surface temperature (°C), Tuvalu region (Area 2.5°-12.5°S, 172°E-180°)

half metre. Nearly all the reported waves and swell are under three metres. The most frequent wave and swell direction is from the east, but swell from the north-east tend to predominate between December and February.

Table 27. Wind wave and sea swell analysis for oceanic region surrounding Tuvalu

	Sep Oct Nov	Dec Jan Feb	Mar Apr May	Jun Jul Aug	Annual
(a) Frequency (percent) of wind waves					
Class height (m)					
0 - 1.0	85	83	87	74	81
1.5 - 2.5	14	17	12	23	16
3.0 - 6.0	2	0	1	4	2
over 6.5	-	-	-	-	-
Modal direction	E	E	E	E	E
frequency (percent)	35	20	34	52	36
(b) Frequency (percent) of swell					
Class height (m)					
0 - 1.0	37	36	38	23	33
1.5 - 2.5	57	58	56	67	60
3.0 - 6.0	6	6	6	10	7
over 6.5	-	-	-	-	-
Modal direction	E	NE	E	E	E
frequency (percent)	36	24	26	38	30

References

Angstrom, A. K., 1924. Solar and atmospheric radiation. Q. J. Royal Met. Soc., 20: 121-126.

Coulter, J. D., 1973. Prediction of evapotranspiration from climatological observations. D.S.I.R. Inf. Ser., 96.

Hessell, J. W. D., 1981. 'Climatology of the Southwest Pacific Islands. 2. Climatological statistics', in W. R. Dale (ed.), Pacific Islands water resources, D.S.I.R. South Pacific Tech. Inv. 2.

Hill, H.W., 1963. 'The weather in the lower latitudes of the Southwest Pacific associated with the passage of disturbances in the middle latitude westerlies', in Symposium on tropical meteorology, Rotorua, New Zealand.

Finkelstein, J., 1972. Climate and comfort in the tropical South Pacific Islands. N.Z. Geographer, 27: 56-64.

Jacobs, W. C., 1951. 'Large scale aspects of energy transformation over the oceans', in Compendium of Meteorology.

Jackson, I. J., 1977. Climate, water and agriculture in the tropics, Longman, London.

Kerr, I. S., 1976. Tropical storms and hurricanes in the Southwest Pacific, N.Z. Met. Serv. Misc. Publ. no. 148.

Mani, A., and S. Rangarajan, 1983. Techniques for the precise estimation of hourly values of global, diffuse and direct radiation, Solar Energy, 31: 577-595.

Meisner, B.N., 1983. Time extrapolation rainfall normals for central Equatorial Pacific islands, J. Climate. Appl. Meteorol., 22: 440-446.

New Zealand Meteorological Office, 1943. Climatological notes South Pacific region. 14. The climate of the Ellice Islands.

Revell, C. G., 1981. 'Climatology of the Southwest Pacific Islands. 1. Circulation systems', in W.R. Dale (ed.), Pacific Islands water resources, D.S.I.R. South Pacific Tech. Inv. 2.

Revell, C. G., and S. W. Goulter, 1985. Tropical cyclones in the South Pacific and the Southern Oscillation, Mon. Wea. Rev., in press.

Revfeim, K. J. A., 1982. Estimating solar radiation income from 'bright' sunshine records, Q.J. Royal Met. Soc., 107: 427-435

Riehl, H., T. C. Yeh, J. S. Malkus, and N. E. La Seur, 1951. The northeast trades of the Pacific Ocean. Q.J. Royal Met. Soc., 77: 598-626.

Sadler, J. C., L. Oda, and B. J. Kilonsky, 1976. Pacific Ocean cloudiness from satellite observations. Dept. Meteorology, Uni. Hawaii, UHMET 76-1.

Swift-Hook, D. T., 1979. Describing wind data, Wind Engineering, 3: 167-186.

Thompson, C. S., 1986. The climate and weather of the Southern Cook Islands. N.Z. Met. Serv. Misc. Pub. no. 188(1).

Trenberth, K. E., 1976. Spatial and temporal variation of the Southern Oscillation, Q.J. Royal Met. Soc., 102: 639-653.

Wright, P.B., 1984. Relationships between indices of the Southern Oscillation, Mon. Wea. Rev., 112: 1913-1919.

Wyrtki, K., and G. Meyers, 1975. The trade wind field over the Pacific Ocean; the mean field and the mean annual variation. Hawaii Inst. Geoph. Rep. 75-1.