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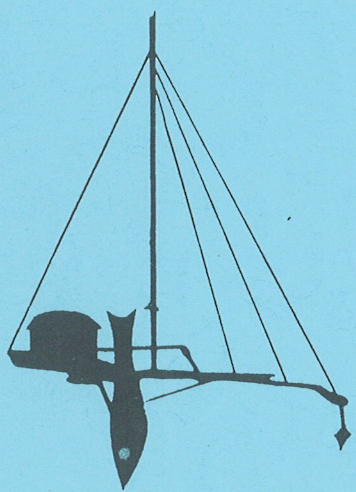
The climate and weather of the

NORTHERN COOK ISLANDS



New Zealand Meteorological Service
Wellington, New Zealand

THE CLIMATE AND WEATHER

OF

THE NORTHERN COOK ISLANDS

C. S. Thompson

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Note to 188 series

This publication is one in a series on the climate and weather of selected 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:

188(1)	Climate and Weather of Niue	(published)
188(2)	Climate and Weather of Southern Cook Islands	(published)
188(3)	Climate and Weather of Northern Cook Islands	(published)
188(4)	Climate and Weather of Tokelau	
188(5)	Climate and Weather of Tonga	
188(6)	Climate and Weather of Tuvalu	
188(7)	Cliamte and Weather of Western Kiribati	
188(8)	Climate and Weather of Western Samoa	

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

THE CLIMATE AND WEATHER OF THE NORTHERN COOK ISLANDS

Summary

The Northern Cook Islands lie within the extensive and persistent trade wind zone of the South Pacific. Wind speeds over the oceanic regions average 11 to 12 knots, but due to sheltering by the atolls' vegetation, mean speeds are reduced by up to 40 percent. Strong winds are rare as are tropical cyclones, but this area of the South Pacific can be a birth place of tropical storms especially when the phase of the Southern Oscillation is negative.

Temperatures are uniformly high all year round at about 28°C.

Rainfall variability is an important climatic feature of this island group. The predominantly convective nature of the rainfall means intensities and amounts are sporadic, which enhances the year to year variability of the rainfall. The Northern Cooks lie between the wet and dry zones of the South Pacific. Dry easterly spells of at least two months duration are common in the east of the group, but less so in the west due to the close proximity of the South Pacific Convergence Zone.

Because of high levels of solar radiation, there are high rates of evapotranspiration. Soil moisture deficits are likely most years, and the amount of deficit increases markedly across the Northern Cooks from the dry eastern region to the wetter western portion.

1. INTRODUCTION

The Cook Islands are a group of atolls and volcanic islands situated in the vast South Pacific Ocean between latitudes 8°S - 23°S and longitudes 156°W - 167°W (Fig. 1). The islands take up an area of only 241 km^2 in this zone which has a total surface area of 1.95 million km^2. There are two clusters of islands, the Northern Cook Islands and the Southern Cook Islands.

The Northern Cook Islands consist of six main low-lying coral atolls north of 14°S. The largest atoll is Rakahanga, with a land area of 1055 hectares (ha) surrounding a shallow, almost land-locked, lagoon. Penrhyn (or Tongareva), with a total land area of about 600 ha, encloses a lagoon with an area of about 280 km , making it one of the largest lagoons in the

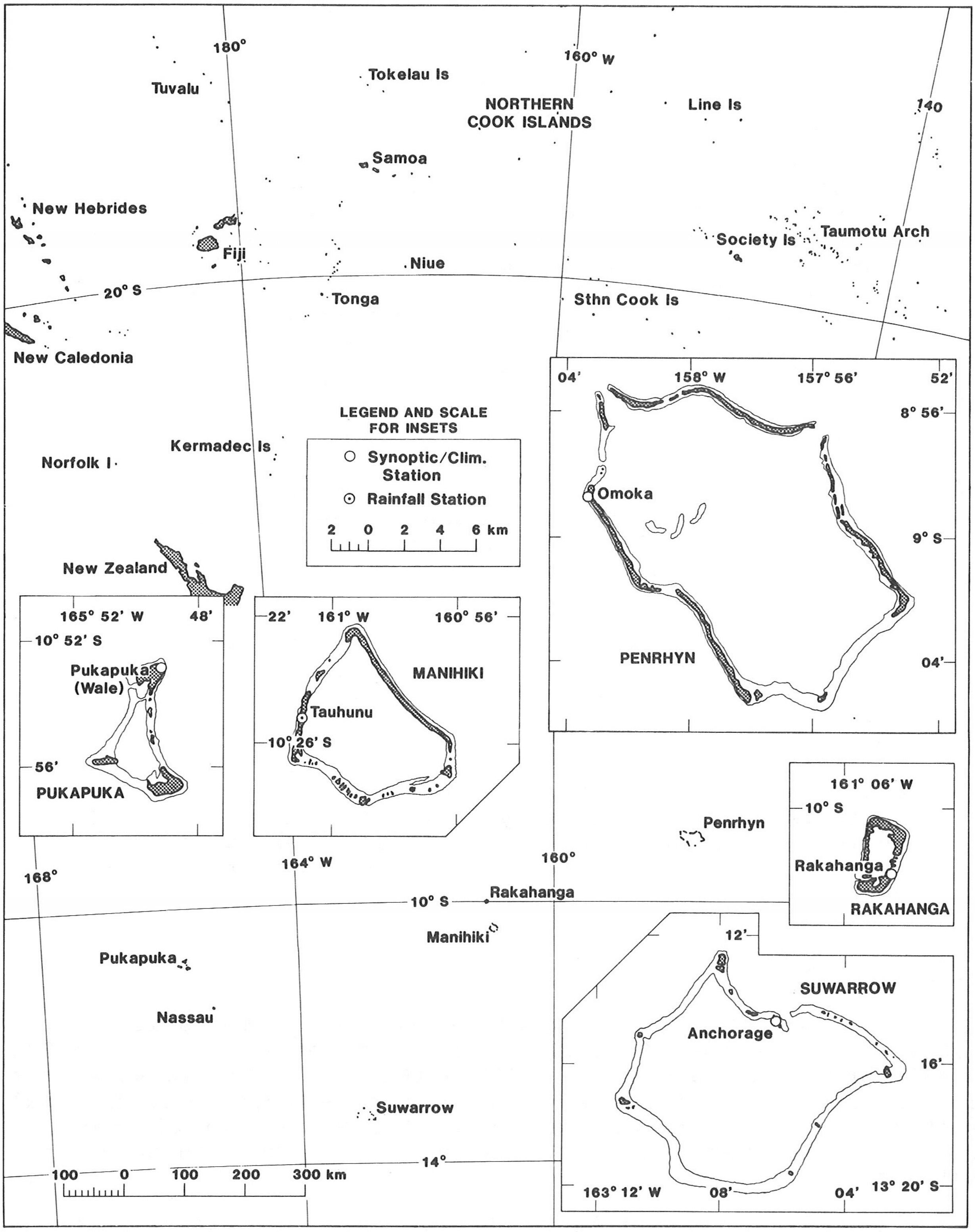

Fig. 1. Location map

South Pacific (Carter, 1984). Nassau is a 225 ha coral outcrop on the western margin of the Northern Cooks. Manihiki consists of many small coral islets with a total land area of 140 ha. Pukapuka (or Danger Island), the most populated island in the group, is also one of the smallest. These five atolls contain just 11 percent of the total Cook Islands population. Suwarrow (or Suvarov) is a coral atoll now uninhabited; it is a bird sanctuary.

The atolls' soils generally have a low fertility level permitting only a restricted range of crops such as coconuts, breadfruit and palm trees. The main cash crop of the Northern Cooks is copra, although there are extensive taro swamps on Wale Island, Pukapuka (Carter, 1984).

The data used in this publication, when not otherwise indicated, were obtained from the New Zealand Meteorological Service's archives. The earliest meteorological observing programme in the Northern Cooks began in 1929 on Pukapuka. Climatological observations are made daily at 8 a.m. local time which is 1800 UT (Universal Time). There are currently three climatological observing stations in the Northern Cook Islands. These stations record rainfall, temperature and barometric pressure. There has been a concentration on these locations in preparing the climatic tables for this publication. Table 1

Table 1. The meteorological record

Location	Data Period	Station Type*	Remarks
Penrhyn	Apr 1937-present	Climate/synoptic	
Penrhyn Air.	Dec 1978-present	Radar wind finding	
Rakahanga	Nov 1941-present	Climate/synoptic	Wind under-estimated
Manihiki	Aug 1937-present	Rain/synoptic	Poor exposure
Pukapuka	Aug 1929-present	Climate/synoptic	Poor exposure
Nassau	Nov 1941-Sep 1945 Mar 1966-Jun 1969	Rainfall	
Suwarrow	Nov 1940-Jul 1946	Rainfall	Fragmentary record
	Aug 1946-Jul 1951	Climate	

* Climate: Stations making full climatological observations daily.
Synoptic: Stations making observations of selected parameters, primarily for use in weather analysis and forecasting, several times daily.
Rainfall: Stations making daily rainfall observations.

presents information about the location and the type and length of the meteorological record. With the exception of Penrhyn, weather observations on atolls in this island group are made from sites that are poorly exposed.

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

(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 due to the eastward migration of anticyclones (Revell, 1981). Between the permanent anticyclone to the east and the migratory ones to the west is a region of convergence, the South Pacific Convergence Zone.

An important feature of the trade winds is the frequent presence of strong temperature inversions between 1200-2500 m. Over the Cook Islands the inversion height varies seasonally, being 1800-2500 m in the wet season, and 1200-1800 m during the dry season. Above the inversion, westerly winds predominate with dry subsiding air. Consequently the growth of convective clouds to high altitudes is inhibited as cloud tops rarely penetrate the inversion and showers become less likely. Surface wind strengths are normally moderate, although speeds may reach 25-30 knots* at times. Scattered showers on windward slopes of mountainous islands (e.g., Rarotonga) are likely. Clouds are often aligned in bands parallel to the wind direction.

(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 5° of the Equator, the doldrum belt is a zone of high rainfall and great seasonal

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

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 into the Coral Sea on the southern fringe of the doldrums. This trough is regionally known as the 'monsoon trough'. The resultant light winds reflect in part alternating periods of easterlies and westerlies. The 'monsoon westerlies' are occasionally squally. Although the monsoon westerlies frequently blow as far as the date line, they do on occasions reach the Cook Islands.

During the winter season, the doldrum zone lies principally in the Northern Hemisphere, and the Australian monsoon trough is absent.

The zone marking the convergence of the North Pacific trade winds with the South Pacific trades is known as the Intertropical Convergence Zone (ITCZ). It is an extensive area of cloud and showers due to the ascent of air, although the intensity fluctuates with 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 ITCZ is from 3°N-10°N in the eastern central Pacific, and from 5°N - 15°N near America.

(iv) <u>The South Pacific convergence zone</u>

The south pacific convergence zone (SPCZ) is an area of convergence between the low latitude easterly trade winds and the higher latitude south-easterly trades. It is an area of cyclonic wind shear, and is a semi-permanent cloud feature of the Southern Hemisphere. It is an important feature of the tropical South Pacific to which the long-term rainfall distribution, as displayed by Seelye (1950) and Hessell (1981), is ascribed.

The position and intensity of the SPCZ can vary considerably. On average this feature usually lies to the west and south of the Northern Cooks, Western Samoa, Tahiti, and Easter Island (Trenberth, 1976). 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).

During summer, the SPCZ lies from between the Solomon Islands and Vanuatu, in the west to the Tubuai (Austral) Islands near 23°S 150°W, in the east, but well south of the Northern Cook Islands (Fig. 2). The western edge of the zone becomes an extension of the monsoon trough of Northern Australia and the Solomon Islands. The westerlies associated with the doldrums on the northern side of the SPCZ frequently blow as far as the date line, and occasionally spread as far east as the Northern Cook Islands.

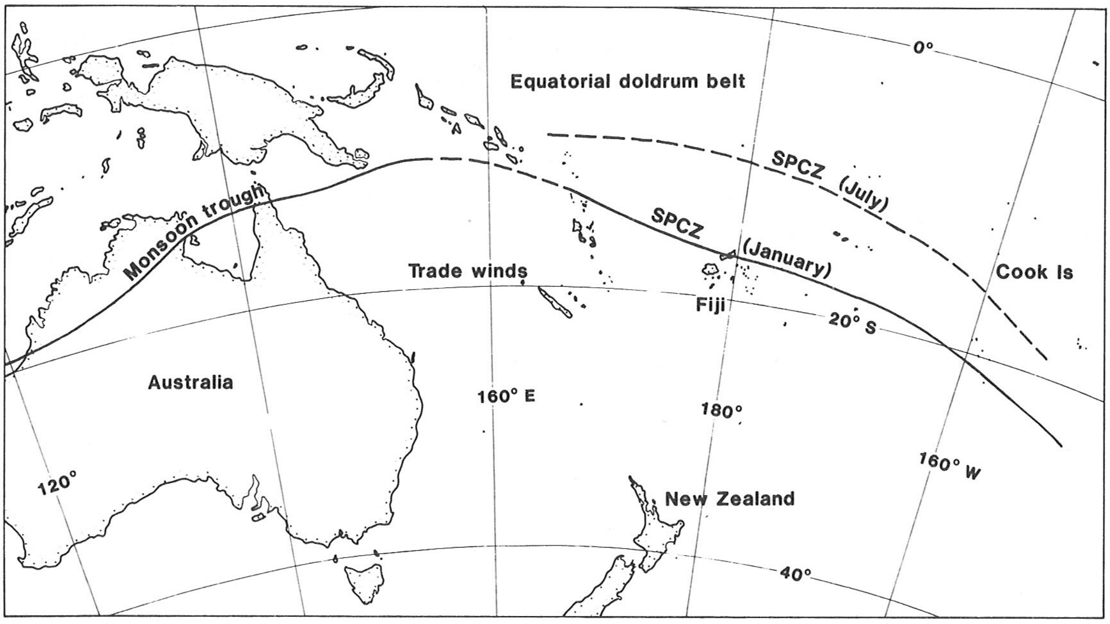

Fig. 2. Mean positions of South Pacific convergence zone in January and July. Adapted from Wyrtki and Meyers (1975) and Hessell (1981)

In winter, the SPCZ is occasionally very weak or inactive. Its mean position is from near Tuvalu to between the Southern Cook Islands and French Polynesia (Fig. 2). A broad belt of easterly or south-easterly trade winds lies over the tropical south-west Pacific.

Spatial variation in the location of the SPCZ has been noted (Trenberth, 1976) to be associated with the Southern Oscillation Index (SOI). This index represents an oscillation of pressure between the western and eastern regions of the South Pacific Ocean. Trenberth measured the SOI from the normalised differences in pressure between Papeete (Tahiti) and Darwin (Australia). The SOI is reasonably persistent from one month to the next, although the persistence is least in the period March to May when the phase of the SOI is likely to change (Gordon, 1984, pers. comm.). Serial correlation of monthly SOI values, as a measure of persistence is given in Table 2.

Table 2. Persistence (serial correlation) of monthly values of the Southern Oscillation Index

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0.62	0.59	0.49	0.54	0.35	0.58	0.75	0.77	0.83	0.76	0.66	0.62

When the SOI is positive the SPCZ lies to the south and west of its mean position (Trenberth, 1976). The Northern Cooks come under the influence of a stronger South Pacific anticyclone, with generally increased easterlies and drier conditions. Table 3 presents average wind frequencies during the four driest and wettest years at Penrhyn and Pukapuka. These have been compared with the long-term frequencies, and departures are also given. Dry years on both atolls are associated with positive phases of the southern oscillation. (The phase of the SOI is considered to be positive for a year if it was positive for at least six months of the year). On Penrhyn the frequency of easterly and north-easterly directions increased and the westerlies and north-westerlies decreased. On Pukapuka, which lies closer to the SPCZ than does Penrhyn, there is an increase in the frequency of northerly winds in the divergent zone of the trade winds (Hessell, 1981), while easterly winds increased only slightly.

Table 3. Wind frequencies (percent) during dry and wet years on Penrhyn and Pukapuka

	N	NE	E	SE	S	SW	W	NW	CALM	SOI
Dry Years.										
(a) Penrhyn (1938, 1962, 1974, 1976)										
Frequency	10.0	26.8	53.2	6.7	0.2	0.0	0.2	1.3	1.1	positive
Departure	-1.1	1.4	8.0	-3.2	-1.3	-0.5	-2.0	-0.6	-1.0	
(b) Pukapuka (1938, 1945, 1974, 1976)										
Frequency	11.5	11.4	56.4	3.2	0.8	0.3	0.2	1.9	12.1	positive
Departure	5.8	-7.0	3.9	-1.9	0.1	-0.3	-2.2	-1.8	1.3	
Wet Years										
(a) Penrhyn (1940, 1941, 1958, 1977)										
Frequency	11.3	13.1	38.3	15.9	3.7	0.7	5.8	3.9	7.2	negative
Departure	0.2	-12.3	-6.9	6.0	2.2	0.2	3.6	2.0	5.1	
(b) Pukapuka (1936, 1948, 1958, 1973)										
Frequency	6.4	10.6	45.0	11.7	1.4	0.9	3.3	5.9	14.8	negative
Departure	0.7	-7.8	-7.5	6.6	0.7	0.3	0.9	2.2	4.0	

In the wettest years, when the SOI is predominantly negative, Table 3 shows an increase in the frequency of the 'westerly' monsoon and very light wind conditions, together with a reduction in easterly and north-easterly winds. However, on Pukapuka in 1973 despite there being 3552 mm of rainfall, the SOI was mostly positive.

Figure 3. shows a satellite picture of an active SPCZ taken at a time when the SOI was in a negative phase. Consequently the SPCZ was lying north of its usual position. On the northern and eastern side of the SPCZ is the almost cloud-free zone associated with the ridge of high pressure which extends from the anticyclone of the eastern South Pacific. At 29°S 150°W are the remnants of tropical cyclone 'Esau' which passed near the southern fringes of the Southern Cooks on 4th March 1981.

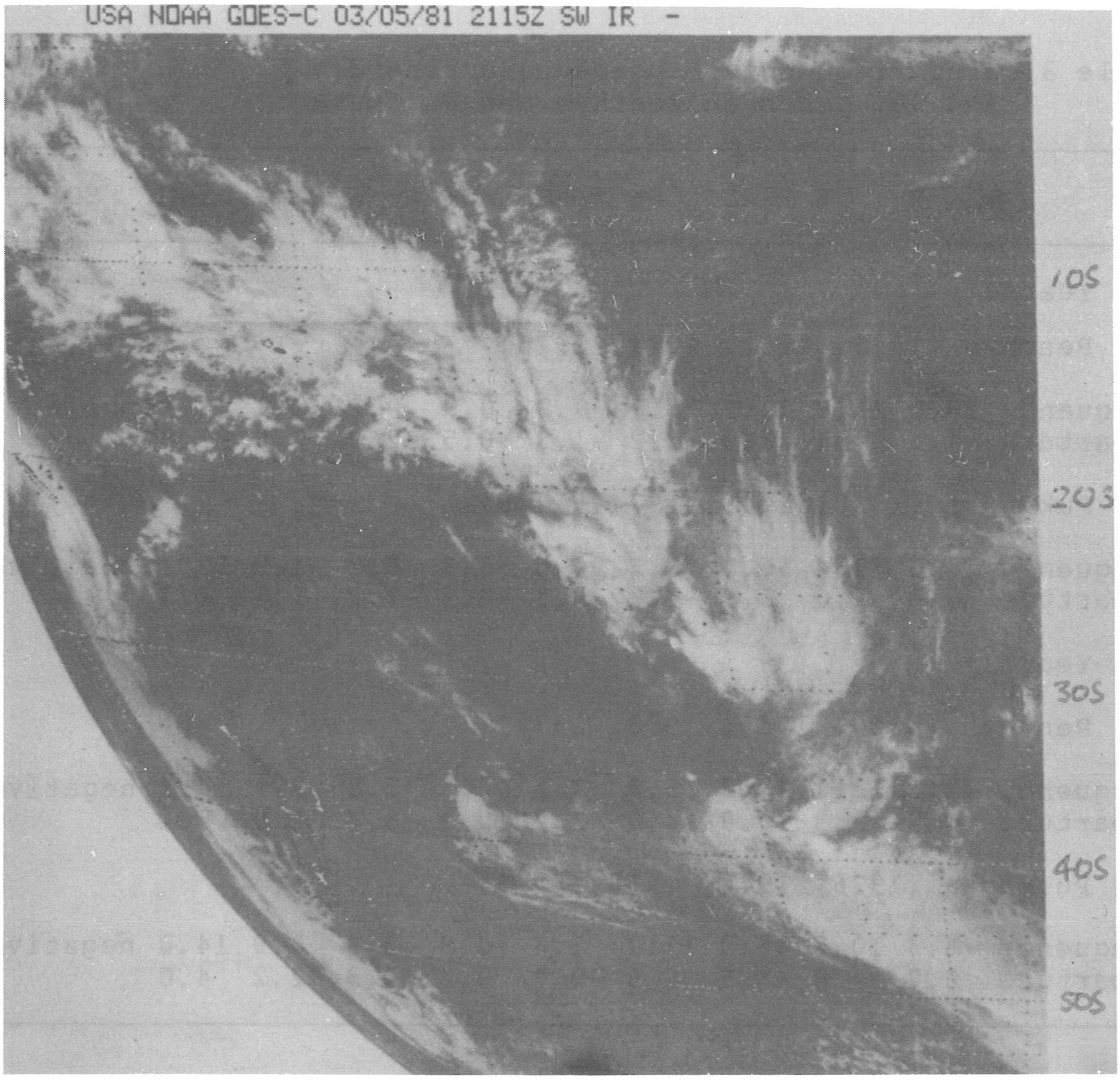

Fig. 3. South Pacific convergence zone as seen from a satellite photograph taken on 5th March 1981

3. TROPICAL CYCLONES

Tropical cyclones are usually classified in terms of the wind speeds associated with them (Table 4). Those disturbances having mean wind speeds in excess of 33 knots are called 'tropical cyclones', and in particular those with wind speeds over 63 knots are classified as 'hurricanes'. They are accompanied by great destructiveness. Disturbances in which the maximum speed does not exceed 33 knots are called 'tropical depressions'.

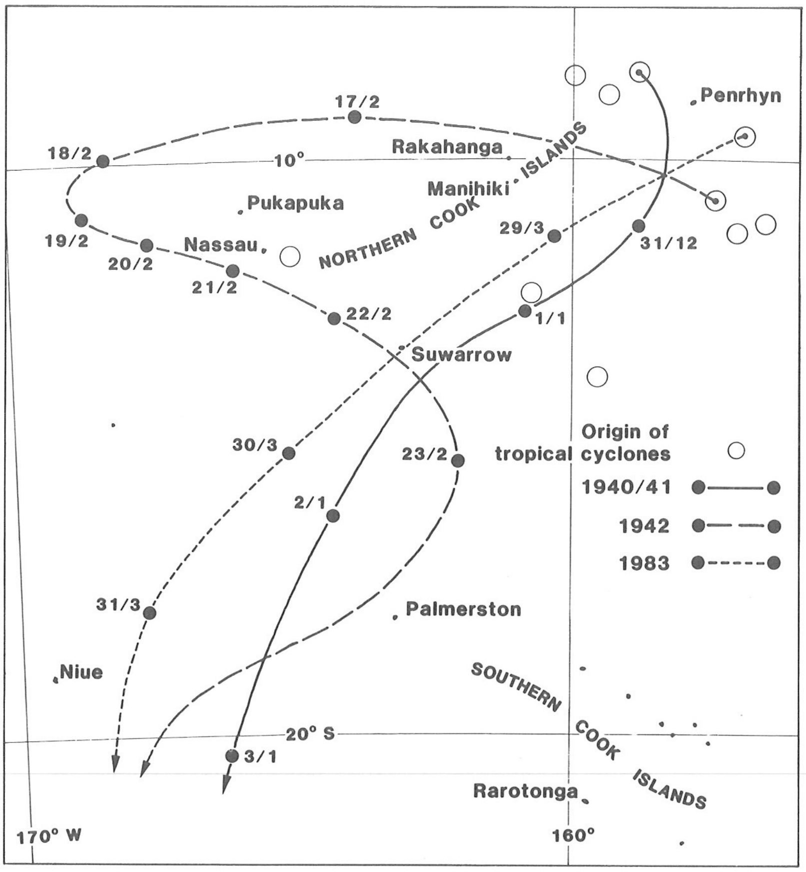

Fig. 4. Points of origin of tropical cyclones and tracks of cyclones causing damage in Northern Cook Islands 1940-1984

In the South-West Pacific region, tropical cyclones frequently develop in a trough of low pressure in a zone of cyclonic wind shear on the northern side of the SPCZ. Other factors favouring the formation of tropical cyclones are a supply of warm moist ascending air lying over a sea surface having a temperature of at least 26-27°C (Gabites, 1963). Tropical cyclones seldom form within 300 kilometres of the Equator where the Coriolis parameter is small, or in zones of strong vertical shear. Although tropical disturbances may occur all year round, tropical cyclones are confined largely to the warmer months, November to April. The Northern Cooks are seldom affected by tropical cyclones. Since 1940 there have been 11 reported cases of tropical cyclones developing in this area (Kerr, 1976; Revell, 1982), of which only three resulted in damage to some of the atolls. Figure 4 shows the tracks of the three cyclones which seriously affected the Northern Cooks, together with the birth place of other cyclones.

Table 4. Classification of tropical cyclonic circulations

Cyclone Intensity	Speed Range (knots)
Tropical depression	<33
Tropical cyclone	>33
gale	34 - 47
storm	48 - 63
hurricane	>63

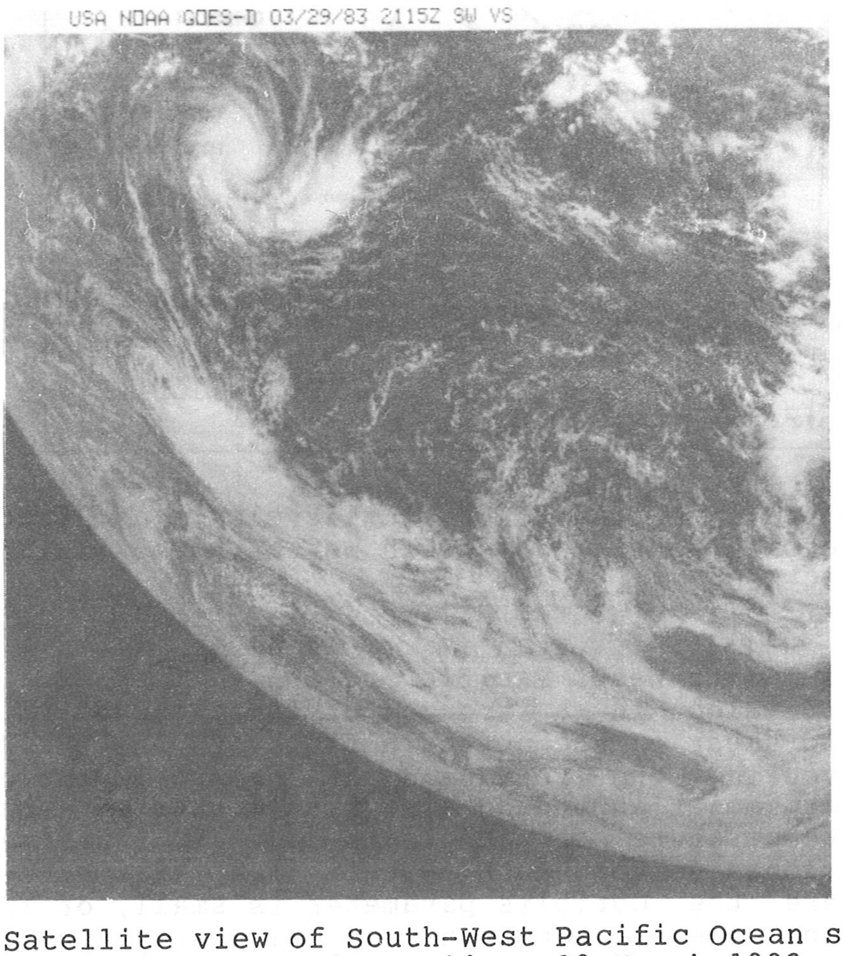

Fig. 5. Satellite view of South-West Pacific Ocean showing tropical cyclone 'Tomasi' on 29 March 1983

Table 5 lists the dates and points of origin of these cyclones. Nine of the cyclones occurred in three periods. All the periods were associated with significant negative phases of the southern oscillation, which persisted for periods of at least 12 months. Revell and Goulter (1984) related the median position of the origin of cyclones for a number of seasons with the SOI. In the low index phase, there was a tendency for the median to shift north and east with the SPCZ.

Figure 5 shows a satellite photograph of the South-West Pacific Ocean region including the characteristic shape of a tropical cyclone. At the time of the picture, this tropical cyclone, called 'Tomasi', was located at approximately 14°S 164°W. It was also displaying an eye characteristic of intense tropical cyclones. 'Tomasi' had passed within 60 kilometres of Suwarrow Atoll.

Table 5. Tropical cyclones in Northern Cooks region 1939/40 -1983/84

Origin (Deg) South	West	Date+ (UT)	Movement to 20°S	SOI phase	Remarks
8.5	159.1	30 Dec 40	SSE-SW	Negative	Lowest pressure at Penrhyn 971 hPa* at 4 p.m. on 29th. Wind est. force 12 on Suwarrow as cyclone passed just east at 10 p.m. on 31st.
8.5	160.0	13 Jan 41	SE	Negative	Winds did not exceed force 4
10.8	157.3	16 Feb 42	W-SE-SW	Negative	Wind est. on Nassau at NW force 12 on 20th. Damage on Pukapuka and Nassau. Suwarrow reported 8 m seas over Anchorage Islet.
14.2	157.9	17 Feb 58	N-SE	Negative	Gales at Penrhyn 19-22 Feb.
12.2	160.6	12 Mar 61	SE	Negative	SOI an isolated negative value in essentially a positive episode.
11.2	156.2	16 Apr 77	S-SE	Negative	'Robert'. Gale force winds in region.
11.1	157.0	6 Dec 77	E	Negative	'Tessa'. Winds below gale force.
14.0	159.6	16 Feb 78	SE	Negative	'Diana'.
8.5	159.2	10 Dec 82	SSE	Negative	'Liza'. Winds below gale force.
11.5	165.0	25 Feb 83	ESE	Negative	'Prema'. Minor cyclone reaching gale force in region for a time.
9.5	157.0	27 Mar 83	SW	Negative	'Tomasi'. Developed into a major hurricane. Passed within 60 km of Suwarrow.

+ Date refers to time when first observed.
* One hectopascal (hPa) is equivalent to one millibar (mbar).

4. CLIMATIC ELEMENTS

Wind

The Northern Cooks lie within the extensive trade wind* zone of the South Pacific Ocean. While winds from the easterly quadrant blow for about 75 percent of the time over the atolls (Fig. 6), there are however important seasonal differences (Table 6). Easterlies and south-easterlies have their highest frequencies during May to October when trade winds are most strongly developed. Between 70 and 80 percent of winds are recorded from the east or south-east on the northern atolls, but only 60 percent at Suwarrow. Trade winds may persist for weeks at a time, during which the weather is generally settled (Revell, 1981). From November to April when the SPCZ tends to lie at its most westward and southward position, the Northern Cooks lie in the region of 'divergent easterlies'. North-easterly and northerly winds are relatively frequent, and westerly and north-westerly 'monsoon' winds become more prominent. However, although the frequency of easterlies is almost halved, they are still predominant.

Table 6. Wind direction frequencies (percent)

	a. Penrhyn				b. Rakahanga		
Dir	Nov-Apr	May-Oct	Combined	Dir	Nov-Apr	May-Oct	Combined
N	17.2	5.0	11.1	N	11.9	3.0	7.5
NE	30.2	20.6	25.4	NE	11.4	5.3	8.4
E	34.9	55.7	45.2	E	46.1	75.9	60.9
SE	4.5	15.4	9.9	SE	2.2	6.7	4.4
S	1.8	1.1	1.5	S	1.0	0.2	0.6
SW	0.8	0.3	0.5	SW	0.8	0.0	0.4
W	4.3	0.1	2.2	W	3.1	0.1	1.6
NW	3.7	0.2	1.9	NW	6.9	0.5	3.7
Calm	2.6	1.6	2.1	Calm	16.6	8.4	12.5

	c. Pukapuka				d. Suwarrow		
Dir	Nov-Apr	May-Oct	Combined	Dir	Nov-Apr	May-Oct	Combined
N	16.5	3.5	10.0	N			6.4
NE	18.5	10.5	14.5	NE			14.3
E	35.5	62.7	49.1	E			33.6
SE	5.2	14.0	9.6	SE			25.1
S	1.8	1.7	1.8	S			6.3
SW	1.5	0.5	1.0	SW			0.9
W	4.2	0.5	2.3	W			2.5
NW	7.7	1.0	4.3	NW			4.0
Calm	9.3	5.7	7.5	Calm			6.9

* Data from ship reports indicate nearly 85 percent of winds blow from the easterly quadrant. See section on Marine Winds, page 41.

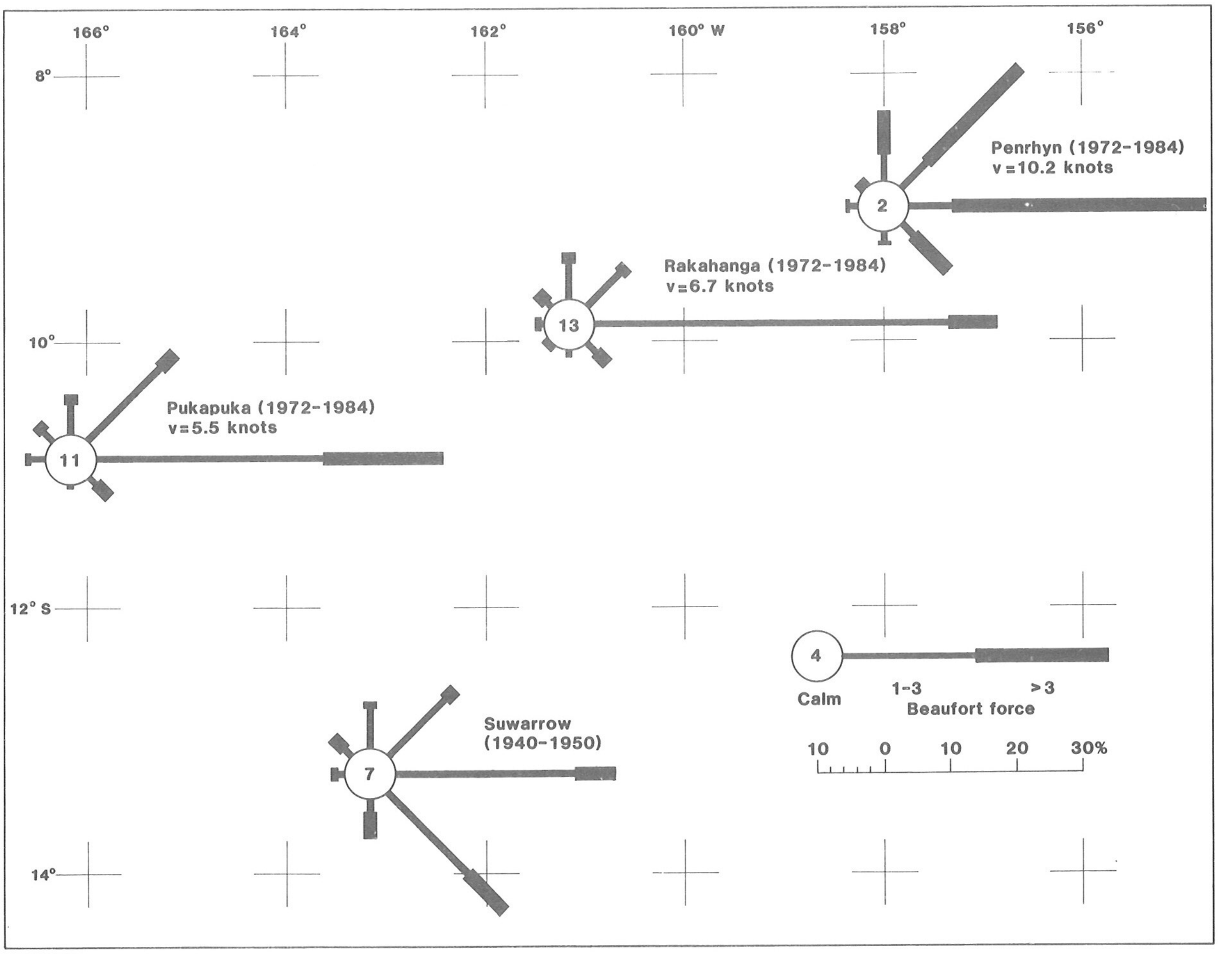

Fig. 6. Mean annual wind rose - Northern Cook Islands

Mean monthly wind speeds are given in Table 7. The mean values have been derived from Beaufort scale estimates made at

Table 7. Mean wind speeds (knots) at 8 a.m.

Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Penrhyn	11	11	10	9	10	11	12	12	11	10	9	9	10
Rakahanga	7	8	6	4	6	7	8	8	8	7	7	7	7
Manihiki	7	5	6	6	6	8	8	8	7	6	6	6	6
Pukapuka	5	5	5	4	5	6	7	7	7	5	4	5	6
Nassau	7	7	6	7	6	8	8	9	9	9	7	7	7
Suwarrow													7

the climatological observing time of 8 a.m. With the exception of Penrhyn, the mean speeds for the individual atolls appear to be underestimated due to the poor exposure of the observing sites, being surrounded by dwellings and tall trees. Mean speeds from May to October are about 10 to 20 percent stronger than at other times of the year. Fresh or strong winds are most frequent in July or August than in any other month (Table 8). Easterly or south-easterly is the most frequent direction for these winds, but winds from the northerly quadrant are also reported. There is considerable interannual variability in the frequency of winds of Beaufort force 5 and above, which appears to be associated with the strength of the South Pacific anticyclone.

Table 8. Frequency (percent) of winds of Beaufort force 4 and above

Location	Nov-Apr	May-Oct	Combined	Windiest month
Penrhyn	18.3	24.8	21.5	August 35.6
Manihiki	11.3	16.4	14.1	August 35.5
Pukapuka	3.6	5.2	4.4	July 7.3

Gale force winds (at least Beaufort Force 8) have been reported at Penrhyn on only nine occasions in 34 years. On Manihiki and Pukapuka, during a similar number of years, 42 and 18 gales respectively have been observed. Many of the gales on Manihiki were reported with squally, showery conditions associated with winds from between north-west and north-east.

From a short instrumental record (1981-1983) on Penrhyn, the diurnal variation of wind speed is presented in Fig. 7.

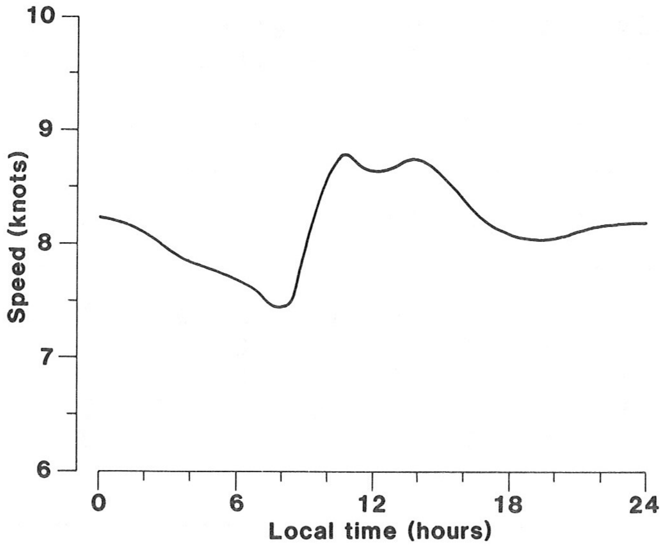

Fig. 7. Diurnal variation of wind speed, Penrhyn 1981-1983

The range of the variation is about 15 percent of the mean speed, and Fig. 7 shows most variation is between 8 a.m. and 11 a.m. The diurnal variation is similar to that on Aitutaki, Southern Cook Islands (Thompson, 1985), with a broad plateau of wind maximum during the afternoon and a minimum in the early morning. There appears to be some diurnal variation in wind direction on Penrhyn (Table 9). This table shows that 43 percent of night-time observations blow from 080 degrees to 100 degrees, but only 12 percent from 020 degrees to 040 degrees. However, in the afternoons, the relative frequency of north-easterlies increases to 20 percent while easterlies decrease to 38 percent. This effect is most pronounced during the summer and with wind speeds up to 20 knots.

Table 9. Relative wind frequencies (percent) on Penrhyn

Time of day Direction	Night (0000-0500)	Morning (0600-1100)	Afternoon (1200-1700)	Evening (1800-2300)
350-010	7.0	9.6	9.9	7.4
020-040	12.0	18.6	20.0	14.2
050-070	16.0	14.6	15.5	15.3
080-100	43.4	40.0	36.7	40.3
110-130	12.8	10.4	11.4	13.7
140-160	1.8	1.7	1.1	2.2
170-190	0.6	0.1	0.3	0.5
200-220	0.1	0.0	0.0	0.1
230-250	0.0	0.1	0.2	0.1
260-280	0.2	0.1	0.3	0.2
290-310	0.2	0.2	0.3	0.2
320-340	1.7	1.2	1.3	1.3
Calm	4.3	3.6	2.9	4.5

Wind power. Wind is a resource which can be used to generate electricity or for pumping water. Knowing the prevailing wind direction and mean speed are important considerations in estimating a location's potential as an energy resource. It is also useful to know what fraction of the time the wind blows between certain speeds, or at any given speed.

The Weibull distribution is commonly used in fitting observed wind speed distributions. From observations, the 'standard' wind speed, c (Weibull scale parameter), is that speed which is exceeded for 36.8 percent of the time (Swift-Hook, 1979). For a range of Weibull shape parameters, k, the mean speed, V_m, is closely related to the standard speed by:

$$c = 1.11 V_m$$

A value for k=2 has been adopted, since the accuracy of c is better than two percent for most values of k in the range 1.5 to 3 (Swift-Hook, 1979).

Assessment of the wind energy potential of a site can be found using a speed-duration diagram (Fig. 8). For a mean speed of 6 knots, the number of hours per year the wind is likely to blow between 6 and 30 knots is 4425 hours, while at 10 knots the corresponding value is 6850 hours.

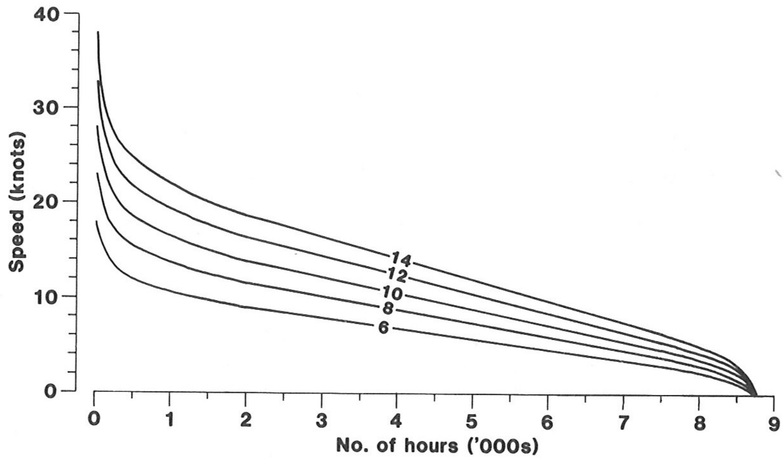

Fig. 8. Speed (kn)-duration (hr) diagram for various mean wind speeds. Derived from a Weibull distribution with a shape factor of two

Wind power is proportional to the cube of the wind speed. At a speed of one knot, the total cumulative wind power available in one hour is 8.82×10^{-5} kWh/m^2. The total energy available between 6 and 30 knots for various mean speeds is given in Table 10.

Table 10. Available wind power* (kWh/m^2) between 6 and 30 knots for specified mean wind speeds

	Mean speed (knots)				
	6	8	10	12	14
Time between 6 and 30 kts	4426	5970	6851	7343	7545
Wind power	283	707	1385	2276	3192

* Assumes a Weibull distribution with a shape factor of 2.

Estimates of wind power between 6 and 30 knots for the Northern Cook Islands observing locations are displayed in Table 11. An estimate of the mean wind was made assumimg that the 8 a.m. observations of wind were taken at the time when the winds were near the diurnal minimum (Fig. 7). It was also assumed that the mean speed was about 10 percent higher than the minimum speed (as was the case on Penrhyn). Table 11 indicates both the open ocean estimate and Penrhyn as having the greatest amount of wind energy potential, while on the other atolls the amount of wind energy available is reduced due to sheltering.

Table 11. Wind power estimates for Northern Cooks

Location	V_m	c	Wind Power kWh/m^2	Hours between 6 and 30 kts
Penrhyn	11.2	12.4	1903	7184
Rakahanga	7.4	8.2	554	5596
Manihiki	7.0	7.8	466	5307
Nassau	8.1	9.0	734	6027
Suwarrow	8.1	9.0	734	6027
Open Ocean	11.5	12.8	2041	7249

Rainfall

Rainfall in the tropics is a highly variable meteorological element, showing large interseasonal and interannual variation as well as considerable spatial variability. Much of the tropical rain results from convective processes. Lack of rain can cause drought, resulting in crops failing or in reduced yields, while intense heavy rains cause surface runoff and soil erosion.

Annual, seasonal and monthly rainfalls. The spatial distribution of annual rainfall over the Cook Islands and adjacent areas is given in Fig. 9. For the Northern Cook

Table 12. Rainfall normals 1951-1980

Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Penrhyn	209	190	179	149	147	162	114	124	129	129	148	204	1883
Rakahanga	342	246	194	162	145	141	119	146	144	178	225	294	2323
Manihiki	315	223	181	141	149	135	93	143	150	197	246	322	2295
Pukapuka	386	290	229	164	197	178	151	161	174	205	247	352	2739
Suwarrow	265	260	247	234	205	99	88	98	105	135	196	237	2169

Islands, the diagram shows that Penrhyn, on the edge of the South Pacific very dry Zone (Seelye, 1950; Hessell, 1981), receives least rainfall, 1883 mm a year. Rainfall amounts increase from Penrhyn to Pukapuka. Pukapuka, on the eastern edge of the South Pacific Wet Zone, also lies in the region of influence of the SPCZ. Monthly and annual rainfall normals for the standard 30-year period 1951-1980 are given in Table 12. Normal rainfall on Nassau was found to be the same as for Pukapuka.

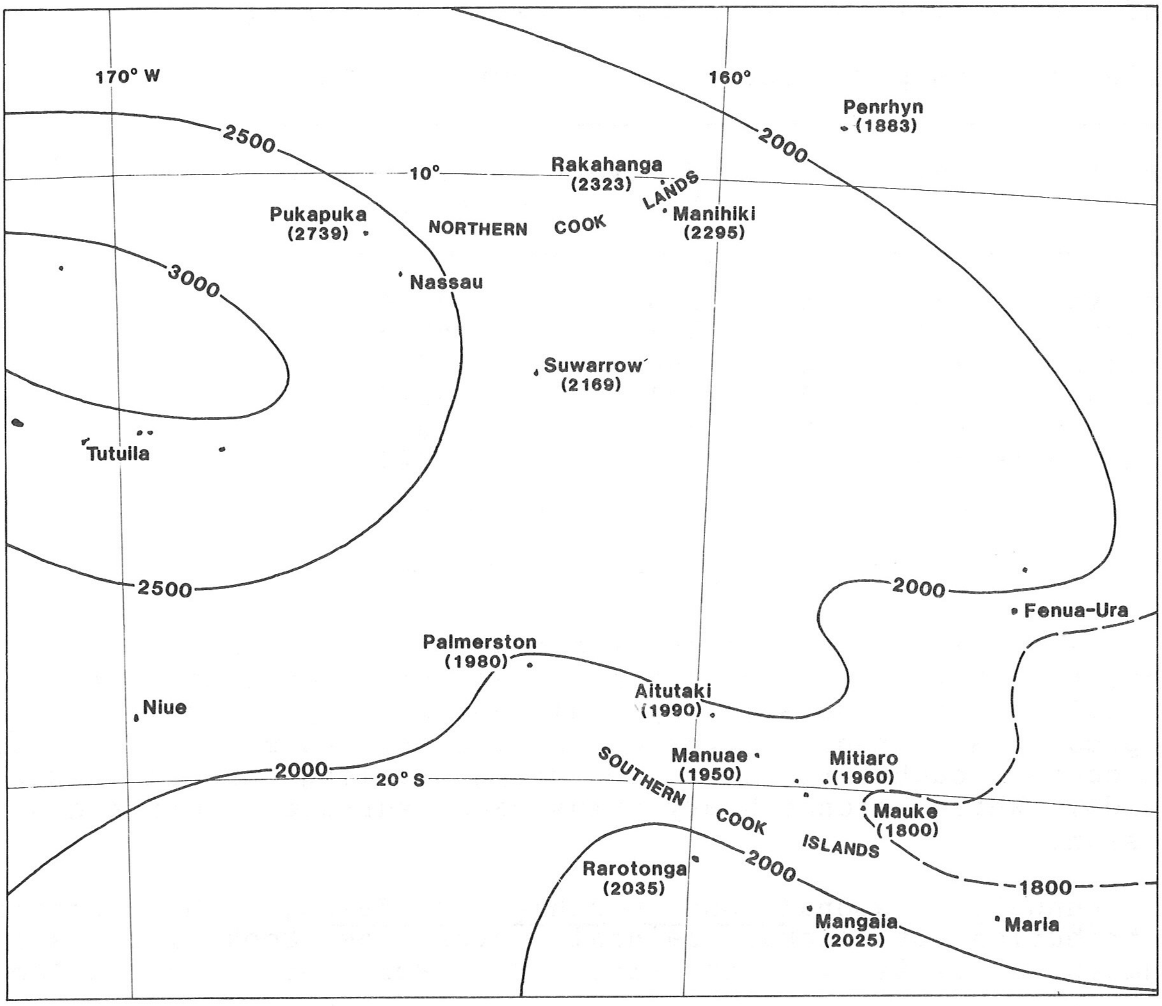

Fig. 9. Mean annual rainfall distribution for Cook Islands 1951-1980

There are two main 'rainfall' seasons in the Northern Cook Islands, a 'wet' season from November to April, and a 'dry' season from May to October. The seasonality of the rainfall regime is not as marked as in the Southern Cook Islands (Thompson, 1985). Sixty percent of the total rain falls during the wet season (Table 13). The dry season is most noticeable at Suwarrow in the south of the group.

Table 13. Seasonal distribution of rain

Location	Season Wet (mm)	Season Dry (mm)	Percentage of Annual Total Wet Season	Percentage of Annual Total Dry Season
Penrhyn	1018	805	58	42
Rakahanga	1450	873	62	38
Manihiki	1428	867	62	38
Pukapuka	1673	1066	61	39
Suwarrow	1439	730	66	34

Actual monthly rainfalls show great variation from year to year (Fig. 10 and Table 14). The coefficient of variation statistic in Table 14 has largest values and hence greatest

Table 14. Monthly rainfall extremes and coefficient of variation (CV) for Northern Cook Islands

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
(a) Penrhyn												
Highest	721	867	761	392	473	570	636	612	284	396	451	566
Lowest	28	28	42	36	24	13	11	21	4	24	32	11
CV *	84	89	66	58	73	72	85	82	63	63	70	84
(b) Rakahanga												
Highest	733	998	489	318	339	288	358	408	321	591	417	702
Lowest	70	48	45	37	20	5	12	21	3	25	60	62
CV	52	77	55	45	56	46	61	61	54	54	40	63
(c) Manihiki												
Highest	865	778	519	405	354	286	506	484	454	534	604	789
Lowest	55	41	52	40	53	34	22	34	17	48	61	64
CV	55	69	61	51	51	41	72	66	62	53	48	54
(d) Pukapuka												
Highest	1065	718	640	412	602	359	397	385	386	562	668	790
Lowest	116	81	26	40	41	59	21	23	10	43	80	124
CV	46	51	56	49	55	43	57	57	51	55	43	43

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

interannual variability at Penrhyn (in the dry zone), and least at Pukapuka (in the wet zone). Unlike the Southern Cook Islands, the coefficient of variation does not indicate that rainfall amounts in the dry season are more variable than in the wet season.

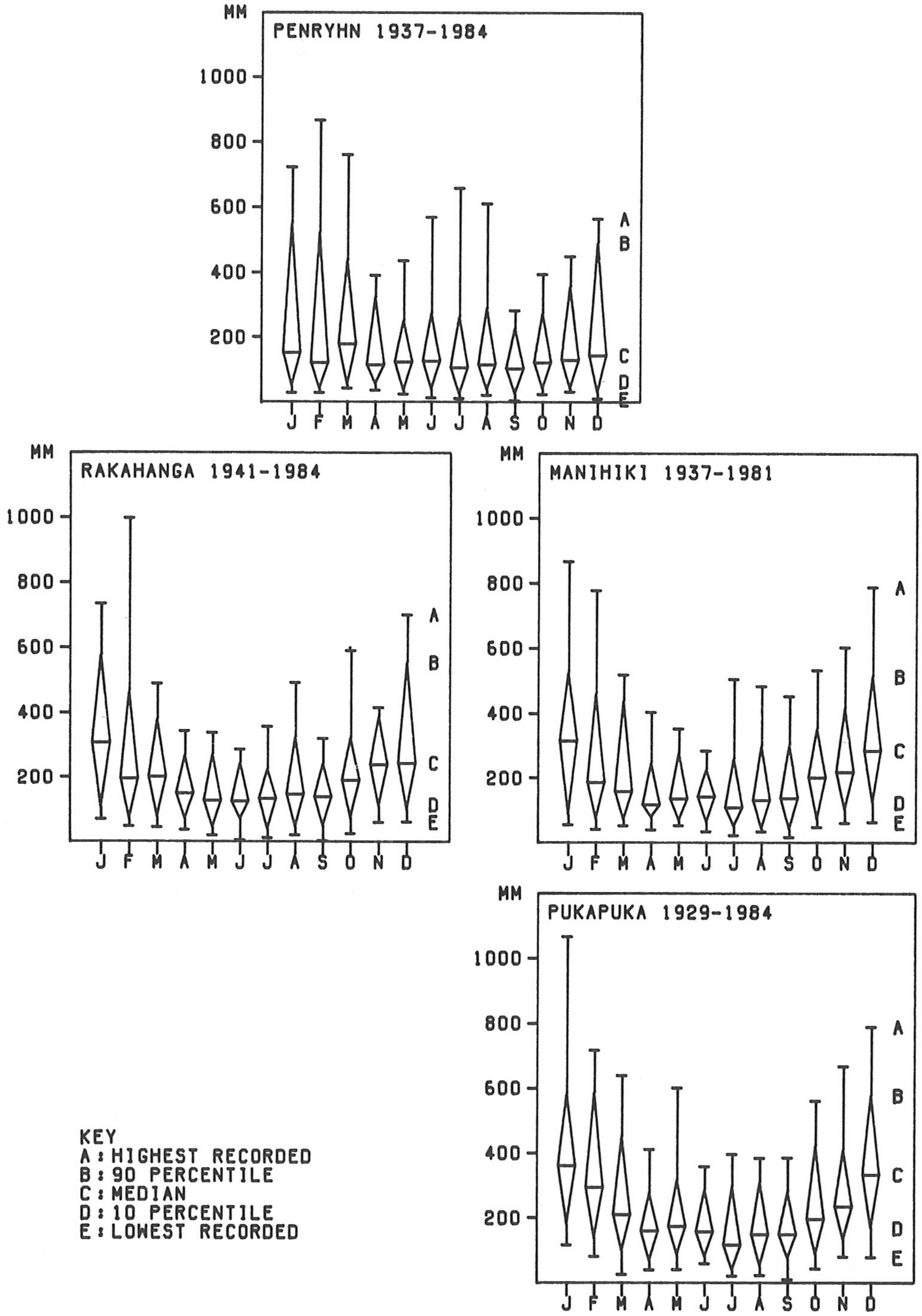

Fig. 10. Rainfall data - Northern Cook Islands

It is most useful to determine the frequency of particularly wet or dry months. A month is designated wet or dry if its rainfall is greater than 150 percent or less than 50 percent of the mean for the month concerned. Frequencies of wet and dry months during the main rainfall seasons are presented in Table 15. The frequencies of wet months at Penrhyn, Rakahanga and Pukapuka are 19 percent, 17 percent and 14 percent respectively, and of the dry months, 29 percent, 18 percent and 15 percent respectively. On Penrhyn, as at other atolls in the very dry zone, while the rainfall is low compared with the other islands in the Northern Cooks, a few exceptionally wet months account for much of the annual rainfall total. Dry months in the Northern Cooks outnumber wet months, except at Pukapuka when they are about equal.

Table 15. Percentage frequency of wet and dry months

	Wet Season (Nov-Apr) Frequency of months		Dry Season (May-Oct) Frequency of months	
Location	Wet	Dry	Wet	Dry
Penrhyn	18	21	26	32
Rakahanga	18	16	19	18
Manihiki	16	15	17	16
Pukapuka	13	15	16	16

Rainfall deciles can be used to assess the natural water resource availability at a location. Month-by-month variation of rainfall is given in Fig. 10. The 10 and 90 percentile values together with maximum and minimum values further indicate the large rainfall variability over the atolls. At Pukapuka 90 percent of all Januaries will have a rainfall less than 583 mm, but only in 10 percent will the rainfall be less than 181 mm.

Rainfall deciles for consecutive months can be used to assess the risk of an area to very dry conditions (drought). In Fig. 11 deciles are presented for 6 and 12 consecutive months. In 50 percent of the years, Rakahanga will receive in a 6-month period commencing in May less than 895 mm of rainfall. The lowest 6-monthly total recorded was 357 mm. In 10 percent of all 6-month periods beginning in May there will be at least 1383 mm.

Similarly, at Penrhyn for 12 consecutive months beginning in March, the lowest total recorded rainfall was 742 mm. In 90 percent of all 12-month periods beginning in September there will be at least 3351 mm.

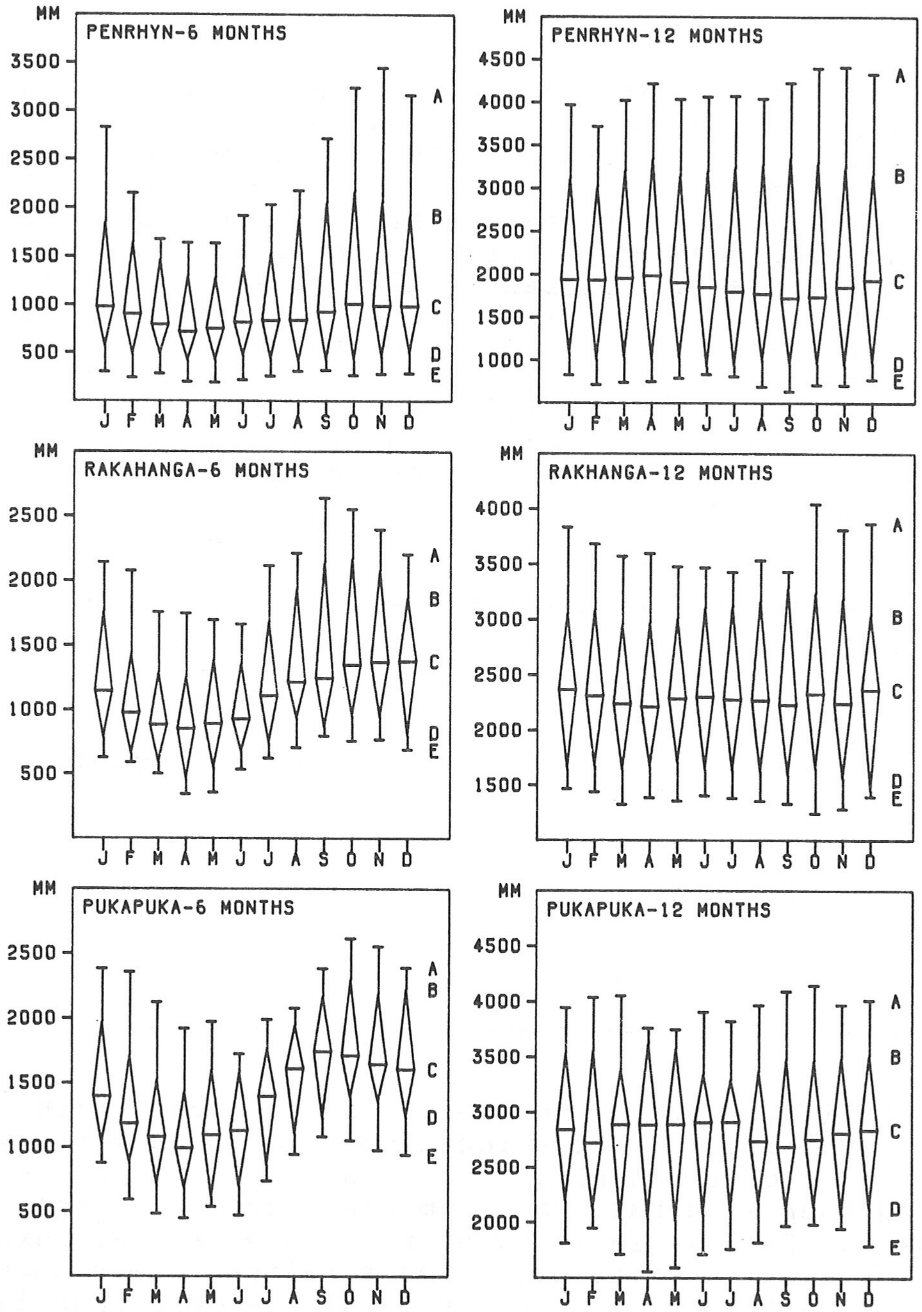

Fig. 11. Rainfall deciles for consecutive months for the Northern Cook Islands

The probability of receiving a specified amount of rainfall every year is important in estimating the water resource. Tropical rainfall is extremely variable from year to year, and poor rainfalls two or three years in a row can significantly reduce crop yields. Table 16 gives the probabilities of receiving at least 2000 mm and 2500 mm a year in at least four out of five successive years. This table also includes the probabilities that two successive years will receive less than 2000 mm and 2500 mm. A binomial frequency distribution has been used to compute the probabilities for the specified thresholds. At Pukapuka, in the wet zone, there is nearly a 50 percent probability of 2500 mm falling in four out of five years, and only a one percent chance at Penrhyn in the dry zone. The corresponding probabilities for two successive dry years are 0.1 and 0.6 respectively.

Table 16. Rainfall probability - Northern Cook Islands

Location	Percent probability of receiving at least 2500mm per year.	Percent probability of receiving at least 2500mm in 4 out of 5 successive yrs.	Percent probability of 2 successive years receiving less than 2500mm.
Penrhyn	22.5	1.1	60.1
Rakahanga	33.3	4.5	44.4
Manihiki	25.8	1.8	55.1
Pukapuka	68.3	49.4	10.0
Location	**Percent probability of receiving at least 2000mm per year.**	**Percent probability of receiving at least 2000mm in 4 out of 5 successive yrs.**	**Percent probability of 2 successive years receiving less than 2000mm.**
Penrhyn	45.0	13.1	30.3
Rakahanga	69.4	51.6	9.4
Manihiki	80.6	75.0	3.7
Pukapuka	95.1	97.8	0.2

<u>Raindays, rainfall persistence and diurnal variation.</u> The frequencies of days with rainfall above specified thresholds are given in Table 17. Table 17 shows that between 55 and 65 percent of days with more than 0.1 mm of rain occur during the wet season. Also, heavier falls of rain occur more frequently in the wet season than in the dry (Table 17d) contributing to the rainfall maximum of this period (Table 13).

Frequencies of days with rain vary markedly from season to season and from year to year. Table 18 gives the highest and lowest recorded number of rain days. Variability is most noticeable on Penrhyn and to a lesser extent on the other atolls. The coefficient of variation increases as the threshold value for raindays increases, reflecting the considerable interannual variation in the frequency and intensity of meso-scale and synoptic scale disturbances.

Table 17. Days with rain - Northern Cook Islands

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
(a) Above 0.1 mm threshold												
Penrhyn	19	18	21	18	17	16	14	17	16	17	16	18
Rakahanga	21	18	19	17	16	15	12	15	16	18	18	18
Manihiki	16	15	17	15	12	12	12	11	12	14	16	17
Pukapuka	22	20	21	16	17	16	15	16	17	19	19	20
Suwarrow	21	21	19	17	15	13	15	15	16	19	17	22
(b) Above 1 mm threshold												
Penrhyn	15	16	17	15	13	13	10	13	13	13	13	15
Rakahanga	18	16	17	14	13	12	11	13	14	15	16	16
Manihiki	15	14	16	14	10	10	10	10	11	13	14	17
Pukapuka	20	18	19	13	15	14	13	14	15	17	16	18
Suwarrow	17	19	15	15	13	11	9	10	13	15	14	20
(c) Above 5 mm threshold												
Penrhyn	9	9	10	8	7	6	5	8	7	6	7	9
Rakahanga	12	11	8	8	7	6	5	8	8	9	10	11
Manihiki	12	10	12	9	7	6	6	6	7	9	11	13
Pukapuka	14	12	11	7	8	8	7	8	9	10	10	12
Suwarrow	12	12	11	9	7	4	4	4	6	6	7	13
(d) Above 20 mm Threshold												
Penrhyn	4	4	4	2	2	2	1	2	1	2	2	4
Rakahanga	5	4	3	2	2	2	1	2	2	2	4	4
Manihiki	5	4	4	2	2	1	1	2	2	3	3	5
Pukapuka	5	5	4	3	2	2	2	3	3	3	4	5
Suwarrow	5	4	3	2	2	2	1	1	1	2	2	3

Table 18. Extremes in annual numbers of days with rain, and coefficient of variation (CV)

	Raindays											
	0.1 mm			1.0 mm			5.0 mm			20.0 mm		
	High	Low	CV	High	Low	CV	High	Low	CV	High	Low	CV
Penrhyn	261	154	17	215	119	20	137	49	35	49	6	56
Rakahanga	235	160	13	204	136	13	131	75	18	45	25	20
Manihiki	198	136	13	189	131	12	130	95	12	42	29	15
Pukapuka	272	167	11	224	144	11	146	86	17	56	27	24

The persistence of rainfall of various amounts over several consecutive days is given in Table 19 for Penrhyn, Rakahanga and Pukapuka. For example, at Rakahanga 42 percent of all days have no rainfall. For seven-day periods, there is a three percent chance there will be no rainfall, but there is a 26 percent probability that the total rainfall will be between 25.1 mm and 50 mm.

Table 19. Persistence of rainfall - Northern Cook Islands (i.e. percent of n-days with various amounts of rain)

n-days / Amount	Penrhyn 1	3	5	7	14	30	Rakahanga 1	3	5	7	14	30
Nil	47	19	8	4	1	0	42	14	6	3	1	0
0.1 - 5mm	28	27	19	13	3	0	29	24	14	8	1	0
5.1 -10mm	10	14	14	12	5	0	11	14	12	9	2	0
10.1-15mm	5	9	11	9	5	1	6	10	10	9	3	0
15.1-20mm	3	7	8	9	6	1	3	7	10	7	4	0
20.1-25mm	2	5	6	7	5	1	6	6	7	8	3	0
25.1-50mm	6	11	18	22	24	11	5	14	22	26	20	4
50.1-100mm	1	6	11	16	27	25	2	7	14	20	33	16
100.1-150mm	0	1	2	4	12	21	0	2	4	7	18	21
over 150mm	0	1	2	4	12	40	0	1	2	4	16	57
over 200mm					7	26					8	39
over 300mm					2	12					3	16
over 500mm					0	3					0	3

n-days / Amount	Pukapuka 1	3	5	7	14	30
Nil	38	11	4	1	0	0
0.1 - 5mm	29	21	11	6	1	0
5.1 -10mm	11	15	11	6	1	0
10.1-15mm	5	10	10	8	2	0
15.1-20mm	5	8	8	15	2	0
20.1-25mm	3	6	7	7	3	1
25.1-50mm	6	16	23	26	17	2
50.1-100mm	3	10	17	25	33	11
100.1-150mm	0	2	5	8	20	17
over 150mm	0	1	3	6	22	68
over 200mm					12	51
over 300mm					4	24
over 500mm					0	5

An analysis of synoptic weather reports from Penrhyn and Pukapuka, to determine the diurnal variation of rainfall, is presented in Fig. 12. Penrhyn and Pukapuka both show the main maximum between midnight and dawn, and a relative minimum from late morning to mid-afternoon. Pukapuka shows another maximum in the evening while Penrhyn has a minimum. Both atolls exhibit diurnal variation patterns which are equally typical of low-lying coral atolls of the Pacific Ocean (Lavoie, 1963; Finkelstein, 1967; Dorman and Bourke, 1981). Instability in the oceanic environment tends to be enhanced at night due to cloud top radiational cooling (Ruprecht and Gray, 1976).

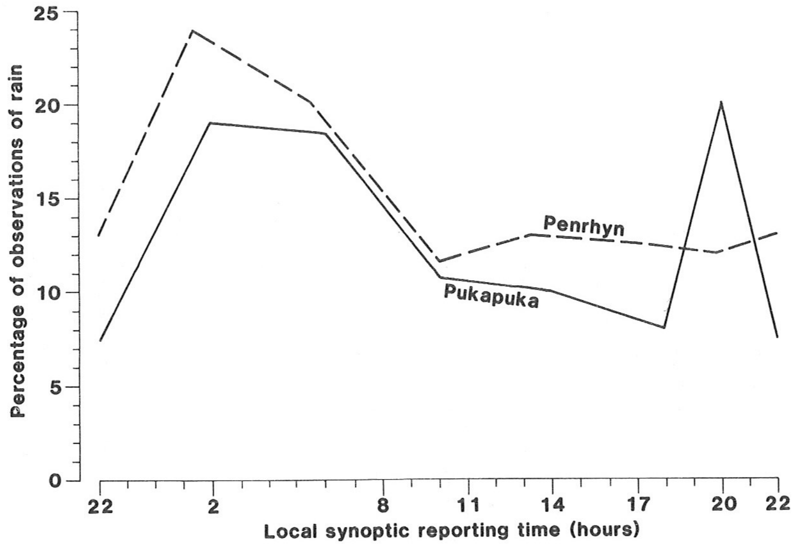

Fig. 12. Diurnal variation of rainfall on Penrhyn and Pukapuka

<u>Extreme short period rainfalls</u>. An assessment of the frequency of high intensity rainfalls for selected durations has been made as depth-duration-frequency tables (Table 20). This analysis has been derived from annual maximum rainfall measured at a fixed time, usually the climatological reporting time, over one, two and three-day periods. A least squares regression (Coulter and Hessell, 1980, WMO, 1983) was used to determine the amount of rain that could be expected to fall for a given return-period. The results have been adjusted to provide 24, 48 and 72-hour estimates of rainfall for various return-periods using factors given by Coulter and Hessell (1980), since rainfall measured at fixed time intervals rarely indicates the 'true' maximum amounts for indicated durations (WMO, 1983).

An example of the interpretation of Table 20 is as follows. At Rakahanga a fall of at least 284 mm in 48 hours can be expected to be measured on average once every 10 years. The table also indicates that exceptional falls of rain in excess 400 mm during a 72-hour period are likely to have return-periods of about 50 years.

Table 20. Depth(mm)-duration(hrs)-frequency(per yr) of Northern Cook Island rainfall

		Return Period				
		2yr	5yr	10yr	20yr	50yr
Penrhyn	24hr	115	166	199	231	272
	48hr	144	208	250	290	342
	72hr	166	242	294	343	406
Rakahanga	24hr	137	191	227	261	305
	48hr	170	239	284	328	384
	72hr	190	269	322	373	438
Manihiki	24hr	152	188	212	235	265
	48hr	183	253	298	342	398
	72hr	228	292	335	377	429
Pukapuka	24hr	136	184	215	245	283
	48hr	180	247	290	333	385
	72hr	214	298	353	406	474

Maximum recorded one, two and three-day falls of rain are shown in Table 21 together with an estimate of their return-period.

Table 21. Highest one, two, three-day rainfalls (mm)

No. of days	1	2	3	1	2	3
	Rainfall (mm)			Approx. return-period (yrs)		
Penrhyn	255	351	372	30	50	30
Rakahanga	243	338	379	15	20	20
Manihiki	192	275	352	5	7	15
Pukapuka	299	456	520	50	50	50

The rainfall amounts are extreme values which may occur at any time of the year, although there is a tendency for the largest amounts to fall during the wet season. Table 22 gives mean monthly values of maximum one, two and three-day rainfalls. The amount of rain falling on day two and day three is substantially less than the one-day total, because atmospheric moisture represents a resource for which conservational laws apply. For example, on Pukapuka the mean one-day rainfall in January is 84 mm, while for two and three-day falls the corresponding amounts are 116 mm and 138 mm respectively. This table also shows that in general two-day falls of rain in the wet season are about 35 percent greater than the one-day fall, and 25 percent greater during the dry season. Three-day rainfalls in the wet and dry seasons are about 60 percent and 40 percent greater respectively than the one-day totals.

Table 22. Mean maximum one, two, three-day rainfalls (mm)

Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
One-Day												
Penrhyn	51	61	48	35	40	39	39	41	32	44	45	53
Rakahanga	75	66	49	40	44	38	39	45	37	51	66	68
Manihiki	75	61	59	34	60	32	29	63	43	54	76	84
Pukapuka	84	79	55	41	59	48	44	41	46	56	60	77
Two-Day												
Penrhyn	74	83	62	45	51	48	50	52	43	56	58	69
Rakahanga	105	89	64	50	52	50	51	60	52	61	88	87
Manihiki	122	81	80	45	64	38	41	82	51	67	97	123
Pukapuka	116	109	71	56	73	62	55	56	62	74	82	105
Three-Day												
Penrhyn	91	100	74	51	58	55	55	58	48	61	68	81
Rakahanga	129	103	77	58	59	56	57	66	58	67	99	100
Manihiki	148	83	101	53	81	46	47	91	62	78	109	144
Pukapuka	138	132	84	66	82	70	64	64	71	84	95	125

Dry spells. Dry spells are a reflection of rainfall variability caused by some anomalous and persistent pattern in the general circulation of the atmosphere. A 'dry spell' may be defined as at least 15 consecutive days with less than 1.0 mm per day, and a 'very dry spell' (drought) as 15 or more days

Table 23. Dry and very dry statistics

Location	Number/ Decade	Mean and Max. Length (days)		Predominant Season
Dry				
Penrhyn	5.2	18	27	Dry
Rakahanga	2.7	24	38	Dry
Pukapuka	0.4	-	-	
Very Dry				
Penrhyn	1.7	20	27	Dry
Rakahanga	1.6	27	38	Dry
Pukapuka	0.2	-	-	

with no rain. Table 23 presents statistics of low rainfall conditions over the Northern Cooks. The majority of dry spells and droughts have been recorded during the dry season. On Penrhyn 71 percent of very dry spells and 67 percent of dry spells have been observed during the dry season of the year, while on Rakahanga, the corresponding values are 88 and 92 percent. On Pukapuka, there have been only two recorded instances of dry spells, in 55 years of record, and only one observed drought.

Persistence of abnormal monthly rainfalls. Abnormal monthly rainfall is defined as a departure of at least 50 percent from the average monthly amount. In the tropics persistence of such rainfall over several months is not uncommon (Seelye, 1950). This is most pronounced in the Southern Hemisphere in areas close to the Equator, and especially in the very dry zone of the South Pacific. Persistence of abnormal rainfall is given for Penrhyn, Rakahanga and Pukapuka in Table 24. Each abnormal period of rainfall is the maximum number of consecutive months of either high or low rainfall. In deriving Table 24 the persistence of the events is considered exclusive. For example, a three-month high rainfall period on Penrhyn occurs on average about 10 times each century. Such events are not also included as two two-month or three one-month events.

Table 24. Average number of runs per decade of stated maximum no. 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	6	7	1	2	3	4	5	6	9	11
(a) Penrhyn (1937-1984)	7.7	2.5	1.0	0.6	0.0	0.4	0.2	11.9	4.2	1.7	0.0	0.0	0.2	0.2	0.2
(b) Rakahanga (1941-1984)	11.4	3.2	0.2					11.8	2.7	0.9	0.2				
(c) Pukapuka (1935-1984)	11.0	3.0	0.6	0.0	0.2			10.4	2.8	0.2	0.2				

While it is common to have one month of abnormal rainfall nearly every year in the Northern Cook Islands, it is rare for abnormal periods of rainfall to persist for more than 3 or 4 months. On Penrhyn, there is likely to be a low rainfall period exceeding 9 months about once every 20 to 25 years. There have been two such periods since records were started in 1941. One period persisted for 11 months from October 1970 to August 1971 when 489 mm (the lowest on record) were measured. Nine consecutive months of abnormally low rainfall, in which 373 mm fell, occurred from April 1974 to December 1974. Both these events occurred when the SOI was high.

Table 25 illustrates the relationship between periods of at least three months of abnormal rains on Penrhyn, Rakahanga and Pukapuka and the SOI. In compiling this table the SOI was averaged over the same length as the rainfall period. There were 33 separate events in the period from 1938 to 1984 inclusive. Abnormal periods observed on two atolls at the same time have been counted as one event. There were five periods when widespread, abnormal rainfall was observed. Table 24 indicates that low rainfall periods are commonly associated with high SOI values, while the SOI tends to be negative in high rainfall periods.

Table 25. Abnormal rainfall periods of at least three months and the corresponding Southern Oscillation Index(SOI)

Mean SOI	Frequency percent of abnormal rainfall Low	High
SOI 0.5	50.0	0.0
0.5 SOI 0.0	27.8	33.3
-0.5 SOI 0.0	5.6	13.3
SOI -0.5	16.7	53.4
No. of cases	18	15

Sunshine and solar radiation

Sunshine. A direct effect of clouds in the tropics is to reduce the amount of sunshine reaching the earth's surface. Sunshine in the Northern Cooks has never been recorded with sunshine recorders, but information about the spatial and temporal variation of monthly sunshine totals can be obtained from observations of cloud amounts. A single morning cloud cover observation in the Southern Cooks has been found to give a good estimate of the mean day-time cloud cover (Thompson, 1985). Monthly sunshine totals were determined from the following empirical relation:

$$S = S_o (1 - aC^2)$$

where

S_o = total possible sunshine for the latitude of the location

a = an empirical latitude dependent constant from Thompson (1985)

C = cloud amount expressed as a fraction between 0 and 1.

Table 26 gives monthly averages of cloud cover observed at 8.00 a.m. in the morning, and Table 27 presents sunshine estimates derived from observations of cloud. These tables show Penrhyn as being the cloudiest atoll (although it has relatively low rainfall) with its sunshine totals representing about 45 to 55 percent of total possible. Sunshine estimates for the other atolls represent about 55 to 70 percent of the total possible. The cloudiest time of the year is from November to April when the sun is in the southern sky. May to August is generally the sunniest time of the year as well as being the driest.

Table 26. Mean monthly cloud amounts (oktas) at 8 a.m.

Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Penrhyn	5.5	5.5	5.3	5.1	5.0	4.9	4.8	4.7	4.9	5.0	5.4	5.5
Rakahanga	5.2	5.0	4.6	4.4	4.1	4.1	3.9	3.8	3.8	4.2	4.7	5.1
Manihiki	5.0	4.9	4.7	4.3	4.0	4.0	4.0	3.7	3.7	4.4	4.9	4.9
Pukapuka	5.0	5.1	4.5	4.2	4.0	3.9	3.9	3.8	3.8	4.0	4.8	5.0
Suwarrow	5.1	5.2	4.6	4.3	4.1	4.0	4.0	3.9	3.9	4.1	4.9	5.1

Table 27. Monthly sunshine (hours) estimates

Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Penrhyn	160	142	169	174	183	182	195	204	189	192	162	161
Rakahanga	183	176	216	216	236	226	244	254	251	243	210	192
Manihiki	199	193	210	221	241	230	239	259	257	233	198	208
Pukapuka	199	171	223	226	241	235	244	254	242	256	205	200
Nassau*	200	171	223	226	240	234	243	252	241	256	205	201
Suwarrow	196	166	218	221	233	228	237	248	246	252	201	197

* Sunshine estimated from Pukapuka cloud cover

Solar radiation. Solar radiation consists of two components, direct radiation and diffuse radiation from clouds. It varies greatly with latitude as well as with the amount of cloud cover. Solar radiation can be estimated from the Angstrom correlation relation (Angstrom, 1924) which uses, as an input parameter, the relative duration of sunshine. Monthly estimates of solar radiation are given in Table 28. Radiation remains relatively high all year round, the range of 3 to 4 MJ/m^2/day being about 20 percent of the annual mean value. Highest radiation totals occur at the transition of seasons from dry to wet, and also in the wet season. There is a high diffuse radiation component in the wet season, and estimates of diffuse radiation by empirical methods (Liu and Jordan, 1960) indicate that as much as 50 percent of the total solar radiation consists of diffuse radiation. These estimates are similar to those found for the Southern Cook Islands (Thompson, 1985).

Table 28. Monthly solar radiation (MJ/m^2/day)

Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Penrhyn	18.7	18.7	18.6	17.6	16.3	15.5	16.0	17.6	18.9	19.7	18.9	18.6
Rakahanga	19.8	20.1	20.4	19.1	17.8	16.8	17.2	19.3	21.3	21.8	21.0	20.0
Manihiki	20.4	20.6	20.1	19.3	18.0	16.9	17.3	19.4	21.4	21.2	20.6	20.6
Pukapuka	20.5	20.0	20.7	19.5	18.3	16.9	17.2	19.1	21.2	22.3	20.9	20.4
Suwarrow	20.4	19.8	20.2	18.8	17.0	16.0	16.5	18.4	20.7	22.0	20.9	20.4

Air temperatures

The temperature regime of the Northern Cook Islands as presented in Fig. 13 is typical of tropical maritime climates. Figure 13 displays two important features: a marked lack of seasonality in that temperatures are uniformly high, and comparatively large diurnal variations. The mean annual temperature of the Northern Cooks is about 28°C, and the departure from the mean is less than one half of a degree. Interannual variability in the temperatures is small, the coefficient of variation being just two to five percent.

The mean diurnal temperature variation can be assessed from Fig. 13 and is the difference between the mean daily maximum and minimum for the particular atoll. The extent of any diurnal variation is influenced by the degree of cloudiness, the amount of solar radiation received, and the strength of the surface wind. Penrhyn, with a diurnal variation of just four degrees, is a relatively cloudy and windy atoll. Other atolls of the Northern Cooks show a diurnal variation of about seven degrees, and are sunnier, wetter and considerably more sheltered than Penrhyn.

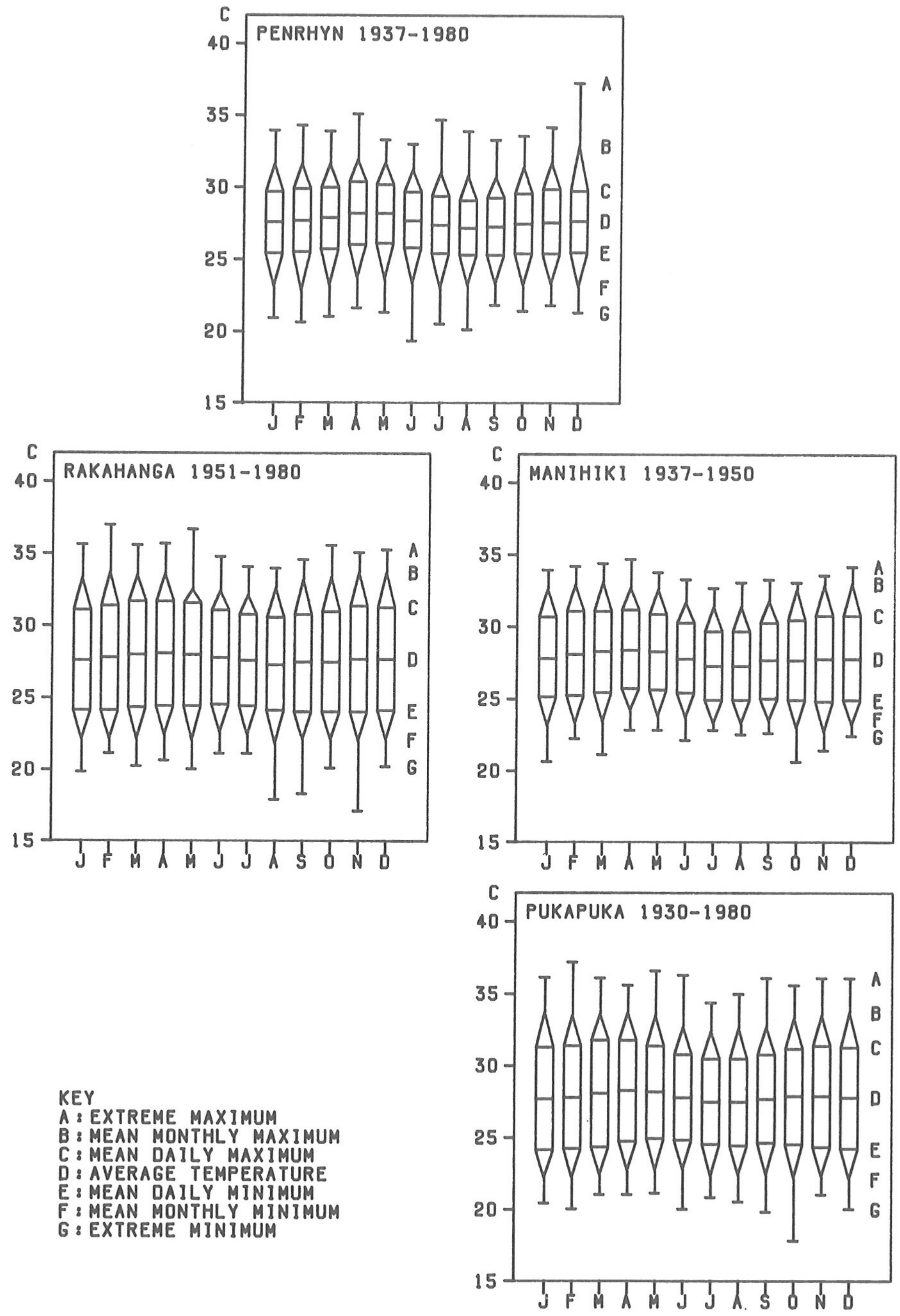

Fig. 13. Temperature data - Northern Cook Islands

Extreme temperatures are presented in Table 29. The highest temperature was 37.3°C, recorded on Penrhyn in December 1976. Maximum temperatures vary little from year to year, and the range in recorded maxima on Penrhyn and Pukapuka are 9.9 37.4° to 27.5°) and 7.2° (37.2° to 30.0°) respectively. Maximum temperatures in excess of 34° are seldom measured. They occur on about four to six days each year on Rakahanga, but only one day every four years at Penrhyn and one day every ten years at Pukapuka.

Table 29. Monthly extreme temperatures (°C)

Location	Jan	Feb	mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
a. Maximum												
Penrhyn	33.9	34.3	33.9	35.1	33.3	33.0	34.7	33.9	33.3	33.6	34.2	37.3
Rakahanga	35.6	37.0	35.6	35.7	36.7	34.8	34.1	34.0	34.6	35.6	35.1	35.3
Manihiki	33.9	34.2	34.4	34.7	33.8	32.3	32.7	33.1	33.3	33.1	33.6	34.6
Pukapuka	36.1	37.2	36.1	35.6	36.3	36.6	34.4	35.0	36.1	35.6	36.1	36.1
b. Minimum												
Penrhyn	20.9	20.6	21.0	21.6	21.3	19.3	20.5	20.1	21.8	21.4	21.8	21.3
Rakahanga	19.8	21.1	20.2	20.6	20.0	21.0	21.1	17.9	18.3	20.1	17.1	20.2
Manihiki	20.6	22.2	21.1	22.8	22.8	22.1	22.8	22.5	22.6	20.6	21.4	22.4
Pukapuka	20.4	20.0	21.0	21.0	21.1	20.0	20.8	20.5	19.8	17.8	21.0	20.0

The lowest temperature measured in the Northern Cooks* is 17.1°C. It was recorded on Rakahanga in November 1972. Temperatures below 20° are rare, and occur on one day about every five to ten years.

Hail and thunderstorms

An analysis of daily weather records for the Northern Cook Islands between 1937 and 1982 inclusive reveals that hail has been observed only on one occasion. This episode was reported on Penrhyn during the afternoon and evening of 19 January 1958. The hail storm occurred in a gale force westerly airflow on the northern side of an intensifying tropical cyclone lying about 250 km south of the atoll.

Table 30. Frequency of days of lightning

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Penrhyn	2.8	3.6	4.5	5.5	3.7	2.7	1.0	1.2	0.8	1.5	2.5	2.2
Rakahanga	3.4	6.2	6.6	4.9	6.4	1.9	0.5	0.9	1.4	2.8	4.5	3.5
Pukapuka	1.6	2.7	3.6	2.9	3.5	2.1	1.0	0.9	1.0	2.7	3.3	5.0

* Penrhyn has recorded a minimum of 15.6°C in February 1971. However it would seem that there was an error in the reporting of maximum and minimum temperatures during most of this month and this value has been discarded.

Thunderstorms in the tropics are a frequently observed phenomenon. They are more noticeable as lightning episodes rather than as thunder, lightning being observed twice as often as thunder. The frequency of lightning-days for the Northern Cooks is shown in Table 30. While lightning may occur in any month, about 65 percent of days of lightning are reported in the wet season.

Lightning displays a pronounced diurnal variation with an evening and night-time maximum. On Penrhyn, 50 percent of observed lightning occurred between 6.30 p.m. and 1.30 a.m., and a further 30 percent in the period from 1.30 a.m. to 10.30 a.m.

The probability of occurrence of thunder (and lightning) on any given day is small (Tomlinson, 1976). However, there is a greater probability that a day of lightning (or thunder) will occur given that there was lightning on the previous day. At Rakahanga the probability that any day is a day of lightning (P_0) is 0.083, but the probability that any day is a lightning-day given that the preceding one was (P_1) is 0.395. Persistence of a sequence of occurrences can be expressed by the persistence ratio, PR:

$$PR = 1-P_0/(1-P_1),$$

where PR = 1 in a random series.

Probabilities for other atolls are listed in Table 31.

The 10, 90 and 98 percentile values displayed in Table 31 are estimates of how frequently lightning days occur. These estimates have been derived from a modified Poisson distribution, in which allowance for persistence has been made (Brooks and Carruthers, 1953). For Rakahanga, the 98 percentile for annual frequencies is 82 days. This means that at least 82 days of lightning in a single year will occur on the average once in 50 years.

Table 31. Lightning-day statistics - Northern Cook Islands

Location	P_0	P_1	PR	Annual mean	10 percentile	90 percentile	98 percentile
Penrhyn	0.085	0.333	1.37	31.0	10	57	82
Rakahanga	0.083	0.395	1.52	42.9	24	65	82
Pukapuka	0.118	0.495	1.75	30.3	19	42	52

Moisture in the atmosphere

Atmospheric moisture content in the tropics is high. Its climatological importance is related not only to its capacity to control rain, but also to its strong influence on air temperatures through reflection and absorption of solar radiation (Nieuwolt, 1977). Atmospheric moisture in the tropical Pacific originates primarily from the ocean's surface through the process of evaporation. The water content is influenced by the sea surface temperatures, and the warm tropical airmasses have the capacity to take up more water vapour than do colder mid-latitude airmasses.

Table 32. Mean vapour pressure (hPa) at 8 a.m.

Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Penrhyn	29.6	30.3	30.8	31.2	31.0	30.2	29.3	29.1	29.6	29.6	29.5	29.4
Rakahanga	28.9	29.1	29.6	30.0	29.7	28.8	27.5	27.6	27.9	28.5	28.8	29.2
Manihiki	29.1	29.4	30.2	30.8	30.6	30.0	29.2	29.1	29.0	29.1	29.2	29.2
Pukapuka	30.1	30.3	30.8	31.0	30.7	30.2	29.3	29.2	29.4	30.2	30.5	30.5

The diurnal variation of vapour pressure during dry days on Penrhyn and Rakahanga is given in Fig. 14. Diurnal variation of vapour pressure generally shows a maximum during the mid-morning, and a minimum at night shortly before sunrise (Nieuwolt, 1977). Secondary minima and maxima occur during the afternoon and in the evening after sunset.

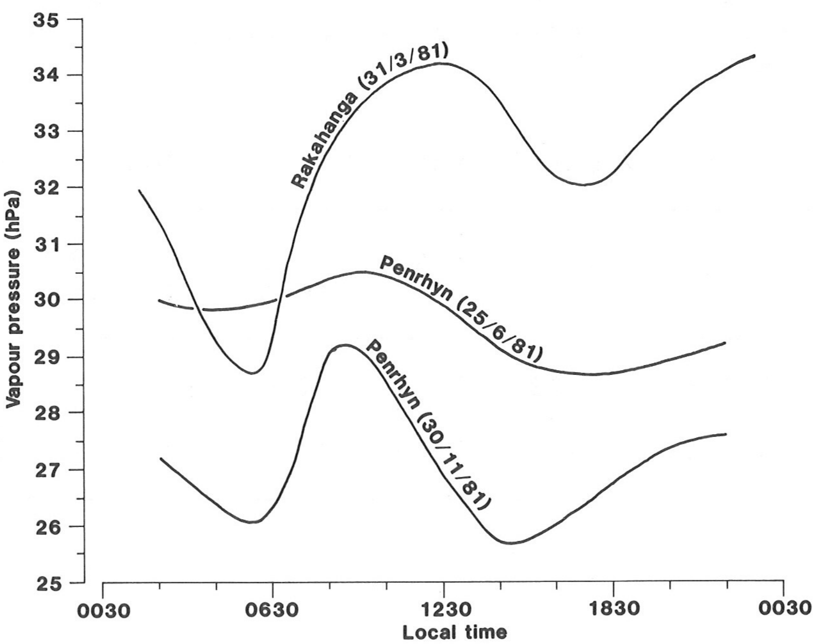

Fig. 14. Examples of diurnal variation of vapour pressure

Water vapour can be measured in several ways, the most commonly used being by vapour pressure and relative humidity. Table 32 gives mean vapour pressures for the Northern Cook Islands. Seasonal variation closely follows the seasonal variation in both air and sea temperatures. Highest values of vapour pressure occur in April when air and sea temperatures are generally greatest, while the lowest values occur in August or September. Like air temperatures, vapour pressure shows little variation from year to year. It is uniformly high having a coefficient of variation of just four to six percent.

Barometric pressure

The average 8 a.m. mean sea-level pressure values for the Northern Cook Islands are shown in Table 33. The table exhibits a seasonal variation in barometric pressure, with maxima recorded from August to October, and minima from December to February. Monthly sea-level pressure remains relatively constant from year to year. The coefficient of variation in all months is less than one percent, resulting from the absence generally of well-developed tropical cyclones and other tropical storms.

Table 33. Mean sea-level pressure (hPa)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
(a) Penrhyn (1937-1982).												
Mean*	9.5	9.7	10.0	10.3	10.6	10.8	11.1	11.4	11.7	11.4	10.1	9.4
Std. Dev.	1.2	1.0	0.9	1.1	0.8	0.7	1.0	0.9	1.1	1.0	1.0	1.2
(b) Rakahanga (1952-1982).												
Mean	9.4	9.7	10.2	10.5	10.9	11.3	11.5	11.8	11.9	11.6	10.4	9.7
Std. Dev.	1.0	0.9	0.8	0.5	0.5	0.5	0.6	0.7	0.8	0.7	0.7	0.9
(c) Pukapuka (1929-1982).												
Mean	8.0	8.4	8.9	9.3	9.9	10.3	10.6	10.8	11.0	10.6	9.1	8.1
Std. Dev.	1.5	1.4	1.2	1.0	0.8	0.8	1.1	1.0	0.9	0.8	1.1	1.3

* To get the actual sea-level pressure, 1000 hPa must be added to the mean values (i.e. 9.5 = 1009.5 hPa).

Mean sea-level pressures vary during the day, the semi-diurnal variation being a regular feature of barograph traces in the tropics throughout the year. Figure 15 presents traces for Pukapuka and Penrhyn, together with a comparison of the long-term semi-diurnal variation at Rarotonga, Southern Cook Islands. Two pressure maxima and minima can be noted. Maxima occur in the late morning (10 a.m - 12 noon) and evening (9 p.m. - 11 p.m.). The minima are about six hours out of phase with these times. The amplitude of the variation is relatively large, being about two to three hectopascals (hPa). Diurnal variations are not constant from day to day, but change with the amount of cloudiness (Riehl, 1954) and therefore local heating factors, and also with the time of year.

The lowest known pressure is 971 hPa recorded on Penrhyn in December 1940, and highest pressure is 1017 hPa also recorded on Penrhyn in September 1976.

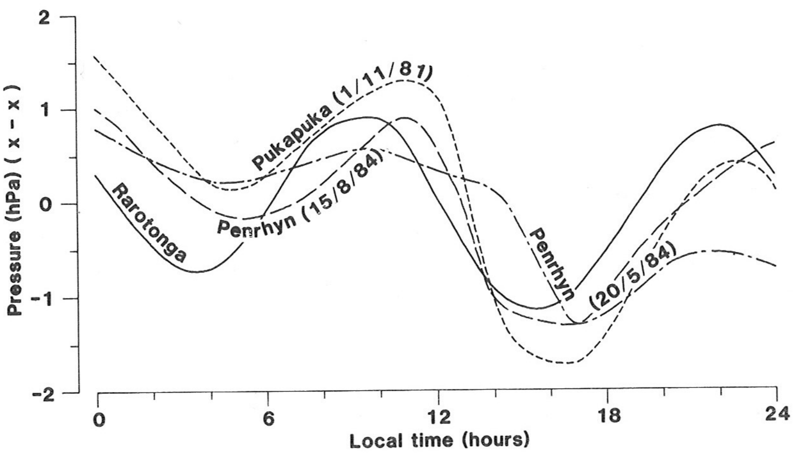

Fig. 15. Examples of diurnal variation of mean sea-level pressure on Pukapuka, Penrhyn and Rarotonga

Effective temperature

The temperature experienced by human beings depends on a number of factors, of which humidity, air temperature and air movement are important. In the tropics, there is frequently a combination of high humidities and high temperatures, and because evaporation of perspiration is limited, a feeling of oppressiveness is created.

A number of indices have been proposed to assess human comfort in warm conditions. One such concept is the 'Effective Temperature' (ET) index. Effective temperature is defined as the temperature of a still, saturated atmosphere which would induce the same sensation of comfort as that induced by the actual conditions of temperature, humidity and air movement. Human comfort varies considerably with climate, and Finkelstein (1971) adopted a critical effective temperature comfort range for the South Pacific of between 21°C and 24°C. Values of average monthly effective temperature for the Northern Cook Islands are given in Table 34. While ET values are relatively high all year round with little seasonal variation, the table also shows a low incidence of uncomfortably warm conditions especially on Penrhyn. This is mainly due to the persistent trade winds on the more exposed Penrhyn, but on the other atolls there is considerable sheltering.

Table 34. Average effective temperatures (°C)

Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Penrhyn	21	21	22	22	22	21	21	20	20	21	21	21
Rakahanga	22	22	22	24	22	22	21	21	21	22	22	22
Pukapuka	23	23	23	24	24	23	22	22	22	23	24	23

It should be noted that the index of effective temperature excludes consideration of solar radiation and precipitation. It cannot therefore be considered as completely definitive of physiological comfort which may also be dependent on clothing, fitness and experience of particular conditions.

Evapotranspiration and soil water balance

Atmospheric moisture originates from the earth's surface through the processes of 'evaporation' from land and sea surfaces, and by plant 'transpiration'. The combined effect of these two processes is 'evapotranspiration'. Evapotranspiration is a response mainly to two meteorological parameters: solar radiation and water supply from rainfall. In the tropical regions, evapotranspiration rates are high because of the high levels of available energy. Further, evapotranspiration has a relatively smaller interannual variation than rainfall.

When evapotranspiration is not limited by lack of rainfall, the loss of water to the atmosphere is at a maximum and is known as 'potential evapotranspiration' (PET). Potential evapotranspiration estimates calculated from the Penman formulation are given in Table 35. Highest rates of evapotranspiration are found on Penrhyn and least on Pukapuka. Seasonal variation is relatively small, varying from about 5.0-5.5 mm/day in January to 4.3-4.5 mm/day in July.

Table 35. Penman potential evapotranspiration (mm)

Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Penrhyn	167	148	163	148	144	133	141	153	157	170	161	166
Rakahanga	161	152	159	137	136	129	140	151	162	168	162	161
Manihiki	164	149	158	144	143	127	132	143	153	161	156	161
Pukapuka	158	140	155	138	138	124	133	146	158	166	149	154

Table 36. Water balance summary-Northern Cook Islands

Penrhyn (1938-1984)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
DE	44	29	20	18	26	26	30	38	37	32	40	41
RO	86	93	65	35	24	40	23	41	12	17	23	59
FDE	56	47	42	31	49	55	50	51	62	66	64	58
FRO	40	42	47	31	29	34	25	31	22	23	20	31

Rakahanga (1942-1984)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
DE	2	3	7	5	8	10	23	26	29	21	16	5
RO	157	107	61	27	25	29	28	33	24	35	57	109
FDE	10	7	24	14	21	26	45	45	40	50	45	15
FRO	76	62	60	55	45	43	45	33	36	38	62	76

Manihiki (1938-1981)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
DE	5	2	5	7	14	10	11	23	24	20	10	5
RO	162	93	60	19	29	20	24	32	26	46	67	123
FDE	15	15	17	32	35	29	33	41	48	45	18	11
FRO	74	65	49	35	35	35	33	34	32	36	58	83

Pukapuka (1929-1984)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
DE	0	0	0	2	1	3	12	18	18	11	4	0
RO	221	186	101	46	63	50	50	44	28	69	85	178
FDE	0	0	2	6	13	9	26	32	31	28	15	2
FRO	100	91	81	57	67	64	56	42	41	55	74	90

Note: Available water capacity of coralline sand soils 140 mm
DE Evapotranspiration deficit (mm)
RO Runoff (mm)
FDE Frequency percent of months with deficit
FRO Frequency percent of months with runoff

Comparing Table 35 with Table 12 (Rainfall Normals) shows that on Penrhyn, Manihiki and Rakahanga the amount of rainfall in some of the months, between July and November, is insufficient to meet total evapotranspiration requirements. The basis of the soil water balance results from this interaction between rainfall and evapotranspiration. When PET exceeds rainfall, water held in the soil is released until all the soil water is used. A deficit then exists. Soil water is replaced when rainfall exceeds PET, and if the soil becomes saturated, runoff occurs. Rainfall effectiveness can, however, be substantially reduced because high intensity rainfalls frequently exceed the infiltration rate of the soil.

Water balance summaries are presented in Table 36. Investigations into the water holding capacity of coralline sand soils in the Cook Islands have been carried out by the New Zealand Soil Bureau (D. M. Leslie, 1985, pers. comm.). Within the plant's rooting depth, these studies have indicated a typical available water capacity (or soil moisture capacity) of about 140 mm (F. J. Cook, 1985, pers. comm.). Moving westwards across the island group from the drier to wetter zone, Table 36 indicated that as the the amount of soil moisture deficit decreases, the amount of runoff increases. Soil moisture deficits and their frequencies of occurrence tend to be largest at the end of the dry season. Although surface runoff may occur at any time of the year, it is most likely from December to February, coinciding with the wettest time of the year.

5. MARINE CLIMATE SUMMARY OF THE NORTHERN COOKS

Ship weather reports during the period 1951 to 1980 in the area from 5°S to 15°S and from 155°W to 165°W were used to construct the tables and figure of this section. These data were obtained not only from New Zealand Meteorological Service archives, but also from data supplied by the Royal Netherlands Meteorological Institute (K.N.M.I.) and the Climatic Centre of the National Oceanographic and Atmospheric Administration (NOAA). A total of nearly 9500 ship observations were available.

Marine winds

Wind speed and frequency data of the oceanic region surrounding the Northern Cooks (Table 37) show that nearly 85 percent of the wind comes from the easterly quadrant. Mean wind speeds are highest during the dry season when the 'easterlies' are most pronounced. Wind speeds over 28 knots are occasionally reported (one percent of observations), the majority being associated with winds blowing from the east or south-east except in summer when most are associated with squally north or north-west winds.

Table 37. Seasonal wind data over the oceans surrounding the Northern Cook Islands

	Dec Jan Feb	March April May	June July Aug	Sept Oct Nov	Wet	Dry
Speed (km)	11.3	10.5	12.6	11.5	10.8	12.1
Dir. percent N	15.7	5.2	2.1	6.5	12.3	2.5
NE	32.5	19.3	11.5	18.3	26.7	14.0
E	31.0	50.4	58.3	49.5	37.9	56.6
SE	5.9	15.9	24.0	16.5	9.9	21.3
S	1.9	1.7	2.4	3.3	2.1	2.6
SW	1.2	0.7	0.3	1.1	1.1	0.6
W	3.1	1.6	0.4	1.0	2.5	0.6
NW	6.2	2.6	0.6	1.7	4.8	0.7
Calm	2.5	2.6	0.5	2.1	2.7	1.1
percent Speeds 27 kns	1.7	0.9	1.1	0.5	1.2	0.9

Sea and swell

Table 38 presents a seasonal frequency analysis of wind waves and sea swell. Wind waves and sea swells are measured and reported to the nearest 0.5 m. Over 90 percent of all waves, and up to 90 percent of reported swells have heights up to 2.5 metres. Predominant wave and swell directions are from easterly directions, but in summer north-easterly directions are relatively common.

Table 38. Wind wave and swell analysis for oceanic region surrounding the Northern Cook Islands

	Summer	Autumn	Spring	Winter
Frequency (percent of) Wind Waves				
Height Class(m)				
0 - 1.0	67.1	78.8	63.4	70.0
1.5 - 2.5	30.3	20.1	33.9	28.2
over 6.5	0.7	0.1	0.2	0.2
Frequency (percent) of Swell				
Height Class(m)				
0 - 1.0	23.2	36.5	13.5	23.9
1.5 - 2.5	63.1	56.3	66.7	62.0
over 6.5	1.0	0.2	0.5	0.5

Sea temperature

A warm 'Pacific South Equatorial Ocean Current' flows slowly past the atolls of the Northern Cook Islands from the east or north-east at speeds of up to one knot (Meteorological Office, 1967).

Monthly sea surface temperatures are given in Fig. 16. The mean annual temperature is 28.4°C, and the annual variation is just 1.5°C. Sea temperatures are highest in April and lowest in August. Interannual variation of sea surface temperatures is small, the coefficient of variation being about five percent of the mean temperature.

Comparing the mean air temperature (Fig. 13) with the sea temperature (Fig. 16) indicates that the annual march of the temperatures are in phase. Further, sea temperatures are nearly one degree warmer than the mean air temperature during the wet season but only 0.5 degree warmer in the dry season.

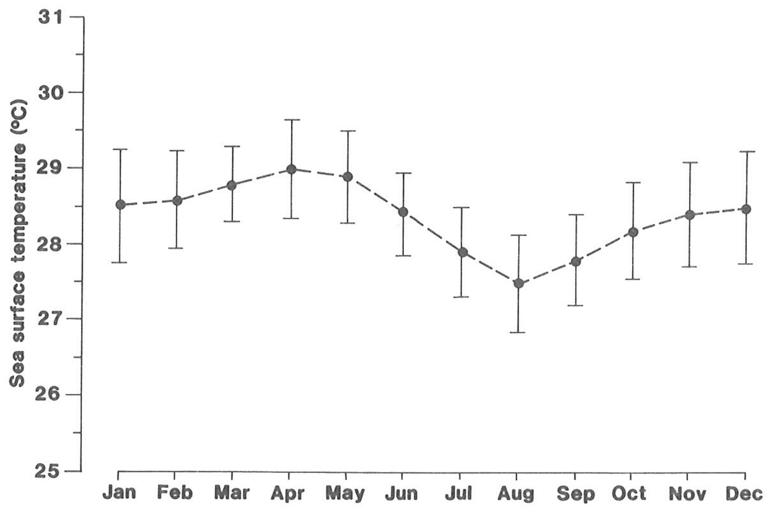

Fig. 16. Mean monthly sea surface temperature (°C) - Northern Cook Islands

6. ACKNOWLEDGMENTS

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