WAVE CLIMATE OF VANUATU

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November 1994

SOPAC Technical Report 202

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1. Introduction

The South Pacific Applied Geoscience Commission (SOPAC) acting through its Secretariat in Suva, Fiji, embarked on a wave data collection program in 1987 with the aim to map the ocean wave climate off the shores of several South Pacific island nations. The principal application of the wave data was seen to be the mapping of the wave energy resource of the islands needed to study the feasibility of developing wave power as a future energy source.

In the present report data from the wave measurement programme, recorded by a Waverider buoy, moored off the south eastern coast of Efate Island are combined with satellite altimetric data and island wind measurements in building up a picture of the climatology of ocean waves in the Vanuatu group. Wave data from special events such as Tropical Cyclones and energetic swells are highlighted. Influence of the El-Niño Southern Oscillation phenomenon on the wave climate is also discussed.

Companion reports describing the ocean wave climate of Western Samoa, Fiji, Tuvalu, the Cook Islands and Tonga are also available. Further, a report has been produced discussing region-wide differences in the wave climate, entitled The Wave Climate of the South West Pacific (Barstow and Haug, 1994a) also giving further details on the various data sources used, in particular, the GEOSAT satellite altimeter data. It is recommended that readers should acquaint themselves with this report first before reading the present one.

This report was produced by the SOPAC Secretariat with assistance from the Oceanographic Company of Norway AS (OCEANOR) and the Norwegian Hydrotechnical Laboratory (NHL). The work was financed by the Norwegian Agency for International Development, NORAD.

2. Some Basics

The ocean waves we are concerned with here are those waves generated by wind as opposed to tsunamis (or tidal waves) which are generated by subterranean seismic activity or landslide and the tides caused by the gravitational attraction of the moon and sun on the earth. In the South Pacific ocean wind waves are always present, it never being perfectly calm, and the energy involved is obvious to anyone at the coast as wave after wave dissipates on the reef or beach. Ocean waves have a typical range of wave periods from 2 secs. (short wind waves) to 25 secs. (long swell).

The generation of Ocean waves in response to wind depends both on the wind speed, the fetch or distance over which the wind blows and the duration of the wind in a given direction. A shift in wind direction leads to new waves growing in the new direction. There is, however, a limit to the growth of wind waves for a given wind speed. If the wind blows long enough over a long enough fetch the waves reach the so-called fully developed state.

Storm waves once created are known to attenuate very slowly and can travel many days across the ocean before dissipating on some distance shore. Ocean waves are known as swell away from their generation area.

The classic studies of ocean swell propagation were carried out in the Pacific during the early **1960s** (e.g., Snodgrass et al, **1966)** confirming the prediction of the linear wave theory that ocean waves travel across the ocean with a speed which increases with increasing wave period or wavelength. In a storm area waves of a range of wave periods are generated. When this spectrum of waves leaves the storm area, the longer waves travel faster, so that an observer at a distant point will detect the longer period swell waves first.

In reality, at a given location on the shore of a Pacific island, waves may be present arising from several different wind systems such as the local trade winds, storms in the southern ocean or northern Pacific, and occasionally from tropical cyclones. The exposure of the actual location is also very important, so that a location on the northern coast of an island will only experience swell from the northern hemisphere due to the island sheltering the location from southerly swell. It is, therefore, important to understand the variability of oceanic winds on different time scales in both the local area and source areas for swell in order to understand the variability of the wave climate. This is discussed in the next section.

3. Oceanic Winds

3.1 General Description

A good overview of the wind climate of the South Pacific is to be found in Van Loon (1984). Another useful reference is Harrison and Luther (1990) who presented climatological monthly mean winds from 33 island stations in the Pacific. The data were quality controlled by comparing neighbouring stations and long term averages from ship observations near to the islands. Generally, agreement is very good with differences generally no more than about 1 m/s in speed and 10 degs. in direction. We are grateful to Harrison for providing us with his long term climatological means. The statistics are reproduced here based on 10 years of data from Vila on Efate Island (Fig. 1)

No source of digitised wind data for Vanuatu could be located apart from a couple of years from the 1950s held by the Australian Meteorological Bureau.

In the Vanuatu group south easterly winds dominate throughout the year. The wind tends to be somewhat stronger during June to November. The wind is more variable in summer due to cyclone activity and the influence of the monsoon low which leads to a greater percentage of northerly winds at that time of year. There is, however, a fairly small wind variability in this area over the year compared to other parts of the South Pacific.

Harrison and Luther (1990) have compared the wind statistics at Vila with ship observations in the neighbouring seas. It is concluded that the winds are not representative for open ocean conditions as they are influenced to a fairly large extent by the island which is mountainous. Despite the wind speed being too low the main features seem to be present in the statistics (Fig. 1).

The Southern Oscillation Index (SOI) describes the well known pressure oscillation between the western part of the South Pacific, represented by Tahiti and the eastern part (Darwin in Australia), and is intimately related to the El-Niño phenomenon. When air pressure is relatively high at Darwin the SOI is negative. A time series of the SOI is shown from 1970 to the end of 1992 in Fig. 2. The major 1983 event is clearly seen as well as more moderate events in 1987 and a rare two year event in 1991-1992. These negative SOI episodes occur about every 4-5 years on average.

Island name: VILA N Latitude: -17.70 E Longitude: 168.30

Monthly climatology and standard deviation in M/S
Generated from daily average observations from 02 Sep, 1947 to 01 Dec, 1957

Month	U	Stddev	V	Stddev	Speed	Stddev
Jan	-1.17	2.65	0.52	2.10	2.84	2.24
Feb	-1.15	2.15	0.43	1.98	2.34	2.12
Mar	-1.28	2.71	0.37	2.29	2.97	2.34
Apr	-1.51	1.83	0.66	1.30	2.39	1.42
May	-1.58	2.11	0.74	1.46	2.61	1.66
Jun	-2.08	2.06	1.04	1.41	2.83	1.90
Jul	-2.36	1.96	1.13	1.31	3.02	1.82
Aug	-2.00	2.01	0.94	1.35	2.77	1.76
Sep	-2.62	2.37	1.35	1.50	3.50	2.06
Oct	-2.71	1.81	1.20	1.31	3.27	1.75
Nov	-2.39	2.12	1.12	1.31	3.15	1.79
Dec	-1.77	2.44	0.85	1.68	2.85	2.12

Fig. 1 ***Climatological statistics for winds at Vila(courtesy of Ed Harrison,Pacific Marine Environmental Laboratory in Seattle). U is the zonal (E-W) component velocity and V the meridional (N-S) component velocity.***

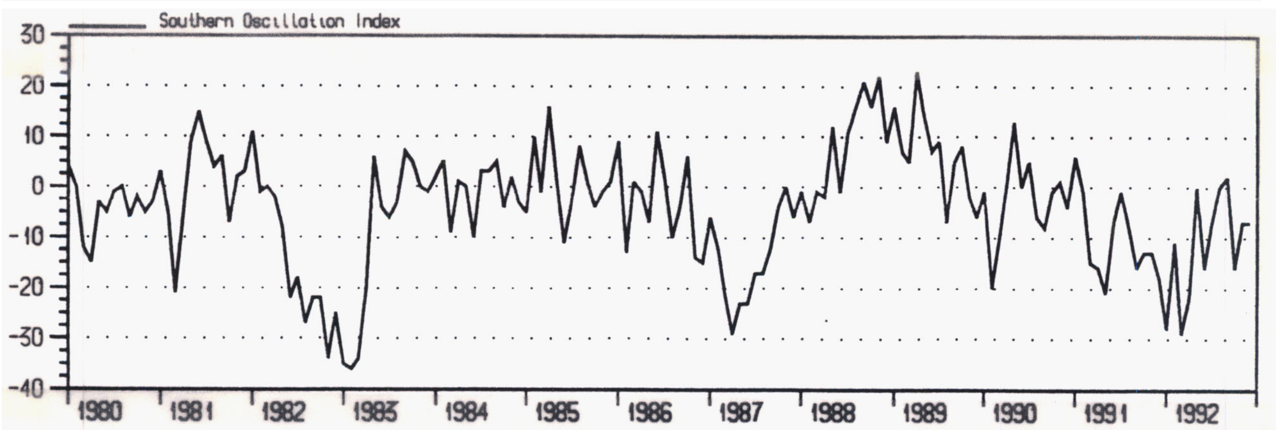

Fig.2 Time series of the Southern Oscillation Index from 1980 to 1992

It is unclear what effect the El-Niiio - Southern Oscillation phenomenon has on the winds at Vanuatu. We have used wind measurements from the GEOSAT altimeter (see Barstow and Haug, 1994a for more details) to compare the winds in the Vanuatu area between the 1987 El-Niño year and the following cold episode (positive SOI) in 1988. Mean wind speeds were up to 50% higher during April-May 1987, when the SOI was very negative, than the following year at the same time. This was due to strong easterlies north of a stable high over New Zealand for most of the period in 1987. This same feature led to long periods with westerlies and south westerlies east of New Zealand and higher than normal wave heights at Rarotonga in the Cook Islands (see Barstow and Haug, 1994b).

With respect to the representativity of the wave measurement period at Efate with respect to long term conditions it should be pointed out that for most of the time the SOI has been negative due to a rare double year El-Niiio during this period (Fig. 2), so that if the SOI has an influence on the winds in Vanuatu the representativity of the wind seas may be called into question.

Compared to other regions in the South Pacific, Vanuatu is more exposed to tropical cyclones. Van Loon (1984) indicates that about 2 cyclones occur on average every year. They are most common in December to March tending to develop north of the group, moving initially south westwards and subsequently south eastwards, typically south of 15°S.

4. Ocean Waves

4.1 Buoy Measurements

Wave measurements were carried out off the south eastern corner of Efate Island (Fig. 3) in position 17°52.5'S, 168°33'E between November 1990 and February 1993 with a Waverider buoy. The buoy was moored in position 1 (Fig. 3) in a water depth of 285 m. Full details of the measurements and the data analysis together with comprehensive statistics can be found in the data reports (Olsen et al., 1991; Barstow and Olsen, 1992; Olsen and Selanger, 1993). Time series plots of a selection of wave parameters are presented in Appendix A.

A Directional Waverider buoy was moored next to the Waverider from 17th November 1992 until 13th February 1993. The buoy collected directional wave data by way of the ARGOS satellite system. These data are not presented elsewhere. Time series plots of various wave parameters for this buoy are presented in Appendix B.

Time series of selected wave parameters for the duration of the measurement period are to be found in Appendix A. A brief definition of the various wave parameters are given below:

S(f): Wave spectrum (m^2s). Based on a 17 min. registration of the wave elevation relative to mean water level. The wave spectrum is computed using the Fast Fourier Transform over the frequency range f = 0.025 to 0.5 Hz (wave period, T = 19.

Hm0: Significant wave height (m). This is numerically close to the classical definition of significant wave height which is the height of the $^1/_3$ highest waves during the 17 min. measurement period. Hm0 is computed from the wave spectrum as follows:

$$Hm0 = 4\left(\int S(f)df\right)^{1/2}$$

Tp: Peak wave period (s). This is the wave period at which the wave spectrum attains its maximum value.

Tm-10: Energy period (s). There are many definitions of wave period. Tm-10 tends to be somewhat higher than Tm02. It is computed as follows:

$$Tm-10 = m_{-1} / m_0$$

where

$$m_n = \int S(f)f^n df$$

Tm-10 is used in the computation of wave power.

Tm02: Mean wave period (s).

$$Tm02 = \sqrt{m_0 / m_2}$$

J_T: Wave power (kW/m)

$$J_T = 0.49\ Hm0^2\ Tm{-10}$$

Hmax: Maximum wave height (m). Maximum wave height is the height of the highest single wave during a wave record. It is typically 1.4 - 1.6 times the significant wave height for 17 min wave records.

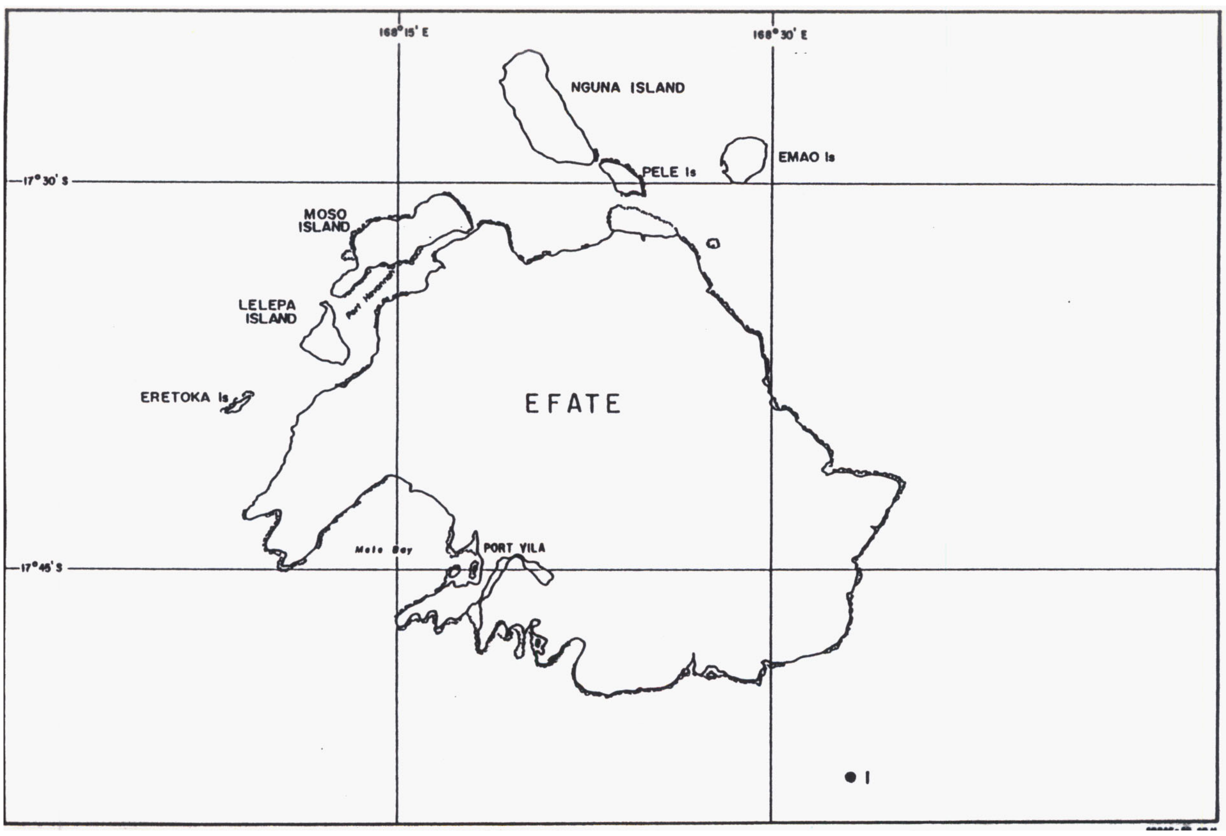

Fig.3 Location of the wave buoy (position 1) south-east of Efate, Vanuatu

4.2 Ocean Wave Statistics

The monthly variation of various wave parameters measured by the Waverider at Efate are shown in Fig. 4. Note that there was relatively low data recovery in certain months with less than one month of data available for January to May and August. Otherwise, apart from December for which 3 years of data are available, only 2 years are available. This means that the monthly variation of wave parameters cannot necessarily be considered to be representative for the long term particularly when we consider that the weather patterns have been unusual during the measurement period (Section 3.1). We see that mean wave heights were highest in March and May (both months with only one year of data). These were also months with a strong steady high over New Zealand for much of the time with stronger than normal easterlies. We will see later that similar conditions occurred in May 1987 and was most likely associated with El-Niño in these two years.

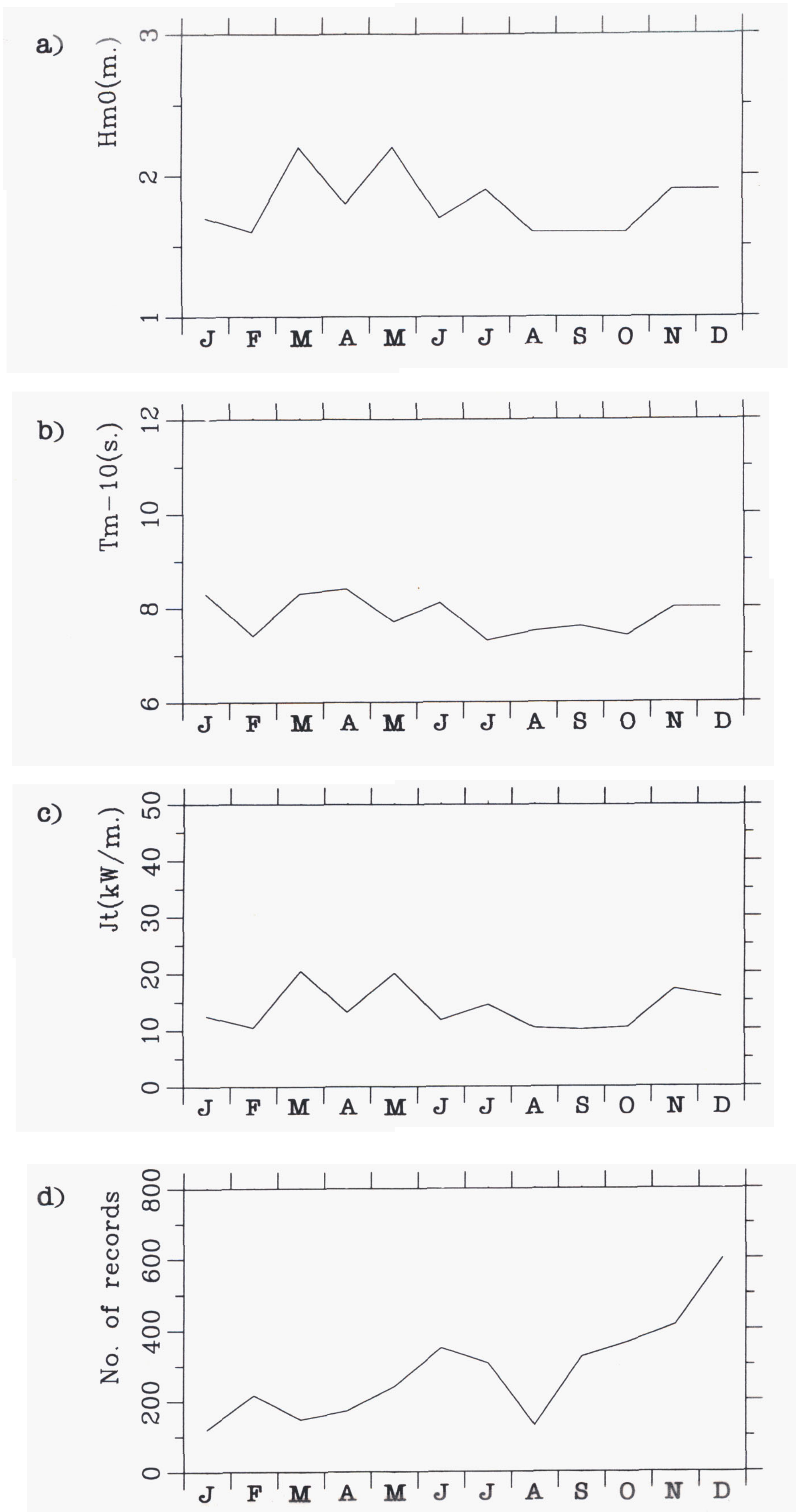

Fig. 4 *Annual variation of a) Significant wave height, Hm0, b) Energy period, Tm-10, c) Wave Power, J_T and d) Number of wave records for the Waverider measurements at Efate Island*

Wave height data from the GEOSAT satellite altimeter (see Barstow and Haug, 1994a for more details on these satellite measurements of waves and winds) have been analysed for the period November 1986 to September 1989. Average wave heights in the sea area to the east of Efate are given in the table below for 2 month periods.

Table 1 ***Mean significant wave height east of Efate Island on a bi-monthly basis derived from the GEOSAT data from 1986-89.***

Months	Mean Hm0(m)
Jan/Feb	2.17
Mar/Apr	2.33
May/Jun	2.31
Jul/Aug	2.36
Sep/Oct	2.00
Nov/Dec	2.00

This gives a somewhat different seasonal distribution of wave heights off eastern Vanuatu than the buoy, but as it is based on a longer period (typically 3 years) it is probably more representative of long term conditions with highest wave heights in winter. As the satellite data is mostly open ocean data, which are less affected by island wave shadows than the buoy data the wave heights are a little higher.

In Fig. 5, a time series of monthly mean buoy and satellite significant wave heights is shown for the respective measurement periods. We can also clearly see the higher values here from the satellite. The month to month variability is quite large at times, in part due to Tropical Cyclone events in certain months elevating the average value.

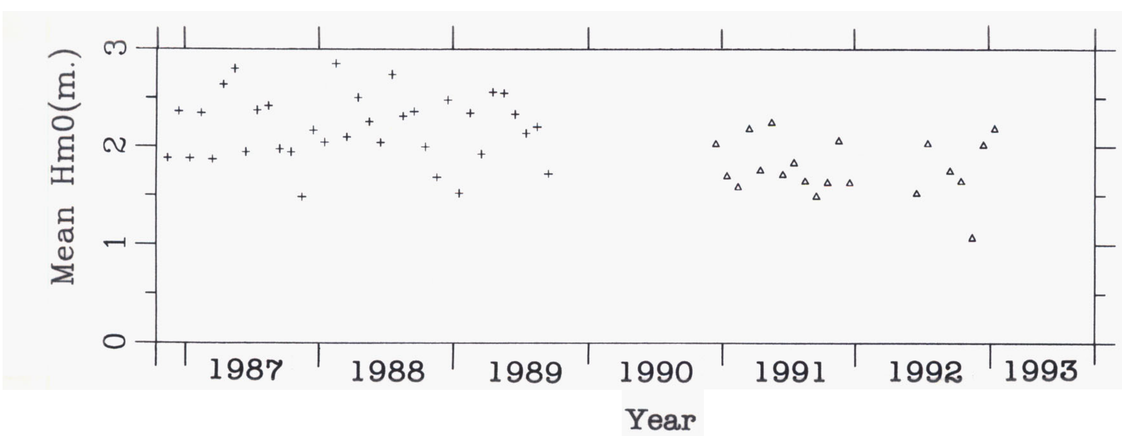

Fig. 5 ***A composite of monthly mean significant wave height for a) GEOSAT Altimeter data averaged over the sea area to the east of Efate*** (+) ***and b) Waverider data (∆).***

In the section earlier on oceanic winds around the Vanuatu group it was described how the south easterly winds in the April-May 1987 period of the El-Niño in that year were up to 50% higher than in the same two months in the following year when the SOI was high. This naturally also had a significant affect on the waves. In Barstow and Haug (1994) a contour plot of percentage change in wave height between these same two months in 1987 and 1988 over the South West Pacific is shown. Wave height is indeed higher in 1987 peaking at a 30% increase downwind of the peak change in wind speeds. Overall, however, wave heights are not significantly higher during the negative SOI event between November 1986 and September 1987 compared to the positive episode in the same months a year later. The highest monthly mean measured by GEOSAT was in February 1988. This was mainly due to Cyclone Bola which produced huge waves around Vanuatu late in the month. This event will be discussed further in the next section.

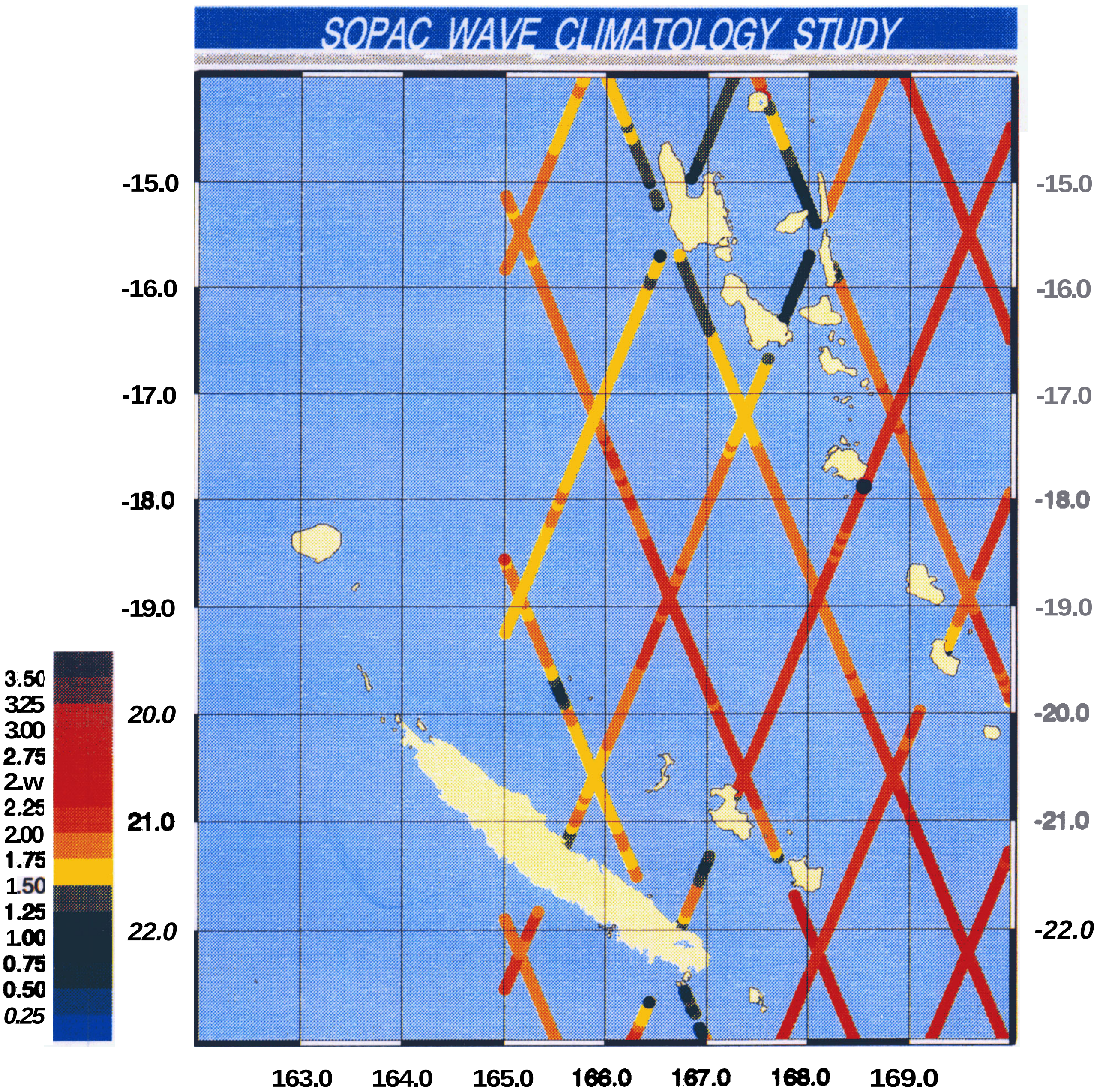

Fig. 6 ***Mean significant wave height along GEOSAT tracks during 1986-1989 around the Vanuatugroup and New Caledonia. Ascending tracks are those where the satellite moves along a track towards the north and from east to west. The Waverlder location is Indicated by a black circle.***

Next, we look at the variation of significant wave height over the entire Vanuatu group by analysing the GEOSAT satellite's data along its ground tracks. Fig. 6 shows colour coded average wave heights over the 3 year satellite mission period along the tracks (the satellite follows an exact repeat orbit returning to the same track every 17 days).

Significant wave heights average typically around or a little below 2.0 m along the eastern boundary of the Vanuatu group decreasing slowly towards the north. To the west of the island chain wave heights tend to be lower, particularly on the leeward side of the bigger islands.

A time series of monthly mean significant wave heights to the west of Efate from the altimeter is shown in Fig. 7. Again there is much month to month variability but again a tendency for higher waves in winter. The waves to the west of Efate will be predominantly wind waves from the south east, some southerly swell through the "window" between New Caledonia and the southern islands in the Vanuatu group, and also some swell from the north east passing in between some of the islands.

Highest wave heights in the Vanuatu group occur during tropical cyclones. Two cyclones caused high wave conditions during the buoy measurement period. First, significant wave height reached 5 m during Tropical Cyclone Tia on 20th November 1991 and, on New Year's Day 1993, wave heights reached **5** m as Tropical Cyclone Kina moved past. Significant wave heights may exceed 10 m, however, on occasion and the highest measurement known from the South Pacific was during Tropical Cyclone Bola when over 14 m significant wave height was recorded by the GEOSAT satellite altimeter (see also next section).

As for the wave height, the seasonal variation in wave period (Fig. 4.b) is erratic and probably not representative for the long term. The energy wave period, T_{m-10}, is, however, fairly low compared to other stations in the South Pacific averaging around 7-8 secs. for the year. This reflects the dominance of the wind sea component in this area. This may also be seen in the frequency distribution of the peak wave period (Fig. 8). A peak period of 8 secs. is most common. However, there is a not insignificant secondary peak at about 12 secs. and quite long period swells do occur on occasion.

The data suggest an annual average wave power of around 15 kW/m, which is probably slightly lower during the summer and also slightly lower in the north of the group. This does not, however, imply that the coast adjacent to the buoy location will experience 15 kW/m. This depends strongly on the wave direction. Waves with a northerly component, registered by the buoy including northerly swell during the northern hemisphere winter, will mostly be experienced on northerly facing coasts. As northerly winds are also more common at the same time of year this will tend to make the annual cycle somewhat stronger at the coast than indicated earlier for offshore areas.

The directional wave measurements offshore Efate were made from mid-November 1992 to mid-February 1993. The frequency distribution of the wave direction at the spectral peak during this period is shown in Fig. 9a.

5. Special Events

In this section, wave data are presented for a number of special events. We first consider wave data from tropical cyclones in Vanuatu. During the Waverider measurement period three cyclones were experienced which led to high wave conditions offshore Efate. These are described in the following. Some of the information used here is from the Fiji Meteorological Service's Tropical Cyclone Report series.

5.1 Cyclone Tia, November 1991

Cyclone Tia which moved on a southward track to the east of the Vanuatu group during 18th -21st November 1991 was not particularly intense. Its ground track and area affected by hurricane force winds can be seen in Fig. 11. The buoy moored offshore Efate was well outside the region of gale force winds. The time series plot (Fig. 12) shows that, nevertheless, significant wave height reached **5** m early on the 19th at about the time of the storm's nearest approach. Wave heights remained fairly high over the next two days as the storm slowed down and its track recurred northwards. A new wave height maximum occurred early on the 20th as a fairly energetic 10 sec. swell arrives.

5.2 Cyclone Kina, December-January 1992/1993

During Cyclone Kina both the Directional and non-directional Waveriders were located offshore Efate close to one another. Fig. 13 shows time series of wave height, period and direction parameters from the two buoys during the passage of the storm. The two buoys can be seen, reassuringly, to give more or less identical wave heights, peaking at close to 6 m on the 31st and 1st. Wave heights exceed 4 m for over 4 days due to the slow movement of the storm. The weather chart for 1st January is shown in Fig. 14. Wave direction at the spectral peak was surprisingly almost constant throughout the 14 day period shown in Fig. 13. However, the high frequency direction, which is close to the wind direction does rotate as the cyclone passes changing to almost southerly at the time of nearest approach, when wave heights were also highest, subsequently gradually reverting again to easterly over the following days, as the cyclone moved away to the south east.

5.3 Cyclone Sina, November 1990

This cyclone passed the Fiji group on a southerly track on 27th November causing a lot of damage and flooding there. High sea states were recorded as far away as Efate with 4 m significant wave height being recorded soon after the first buoy deployment there.

The most common wave direction during the measurement period was easterly. Wave energy cannot come from the north to west quadrant due to the presence of Efate Island. The high frequency wave direction (Fig. 9.b) is generally close to the local wind direction. The wind wave direction distribution is broader due to the greater variability of winds. Peak wave direction from the north east is significantly more common than wind seas from the same direction. This is due to long distance northern hemisphere swell. Similarly, swell from the higher latitudes in the southern hemisphere may occur on the south coast of Efate by way of the window between New Caledonia and Vanuatu. This may be seen in Fig. 10 where we have plotted the frequency distribution of wave directions for two low frequency bands: 0.06 Hz (17 secs.) and 0.07 Hz (14 secs.). The frequency distribution is totally different to those in Fig. 9 with easterly being a minimum for swell energy. Due to the time of year which is the northern hemisphere winter, when storm activity is common in the higher latitudes north of the equator, the dominant swell directions are north easterly. The secondary peak at about 160 degs. corresponds to swell arriving through the Mew Caledonia/Vanuatu window with a source probably somewhere to the east of New Zealand. 180 deg. waves are also fairly frequent, this corresponding to Tasman Sea swell. In Fig. 10a, a minimum in the distribution at 150 degs. corresponds to the shadow of the Vanuatu islands to the south west from which sector swell cannot arrive. Another minor peak at about 140 degs. is due to swell from storm activity further east of New Zealand arriving to the east of the line of the Vanuatu group.

During the winter (May-August) when northern hemisphere swell is uncommon the swell direction is likely to be much more dominated by southerly swells which are also strongest at that time of year year.

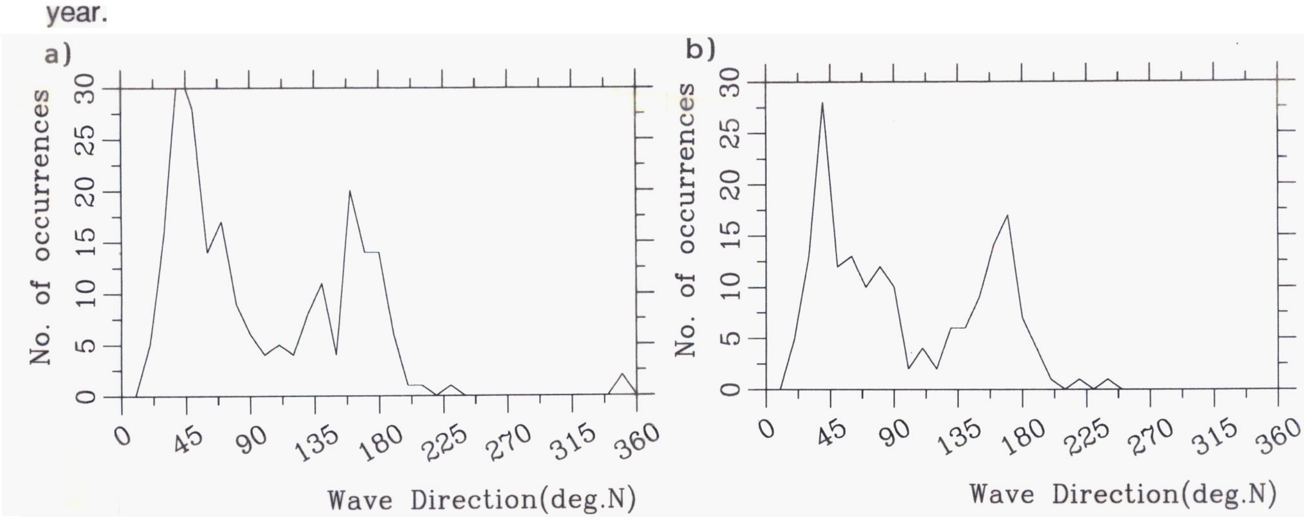

Fig 10.** **Frequency distribution of wave direction in a) 0.06 Hz and b) 0.07 Hz frequency bands from the 3 month Directional Waverider measurement campaign at Efate November 1992 to February 1993.

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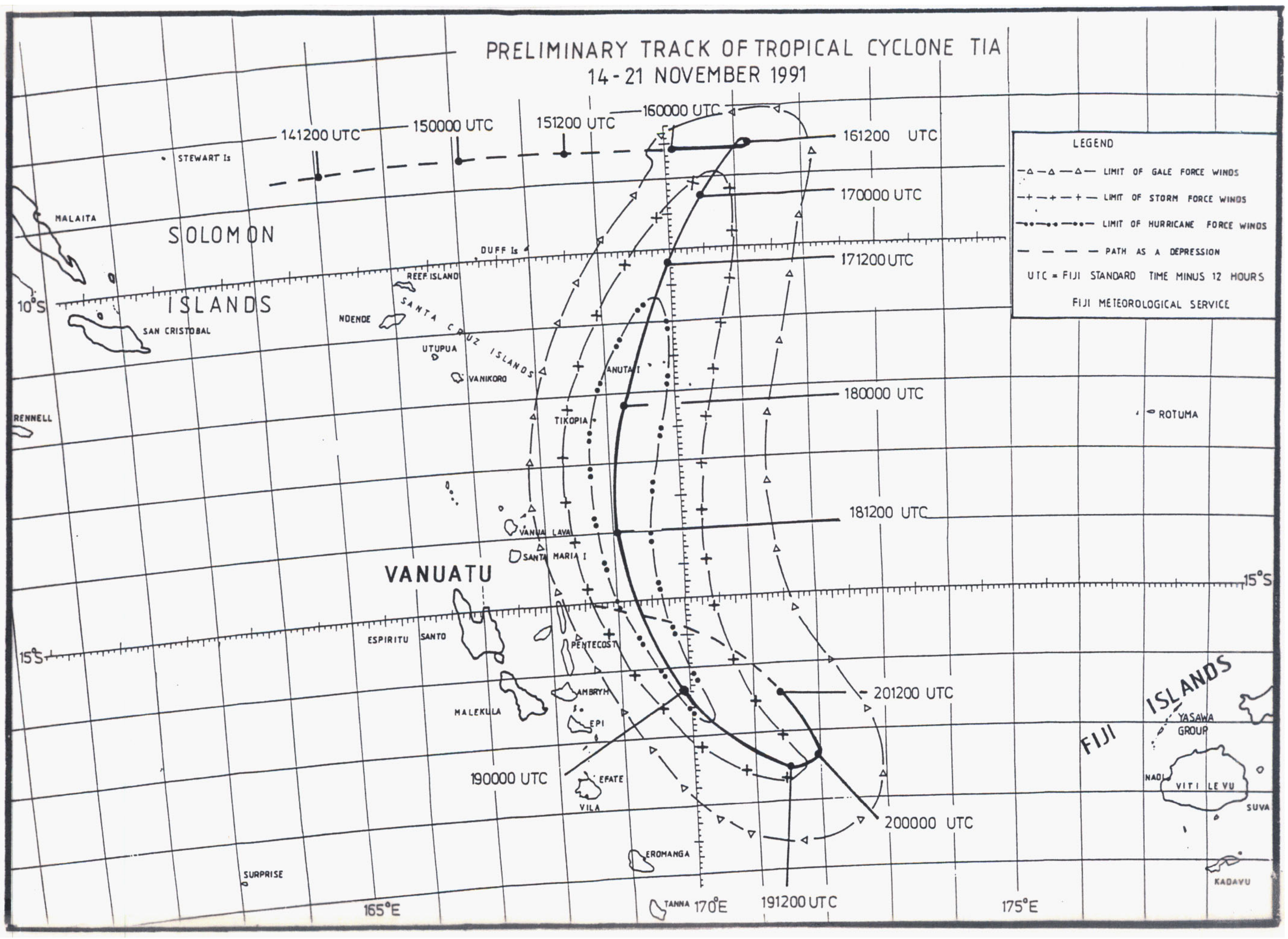

Fig.11 Track of Tropical cyclone Tia

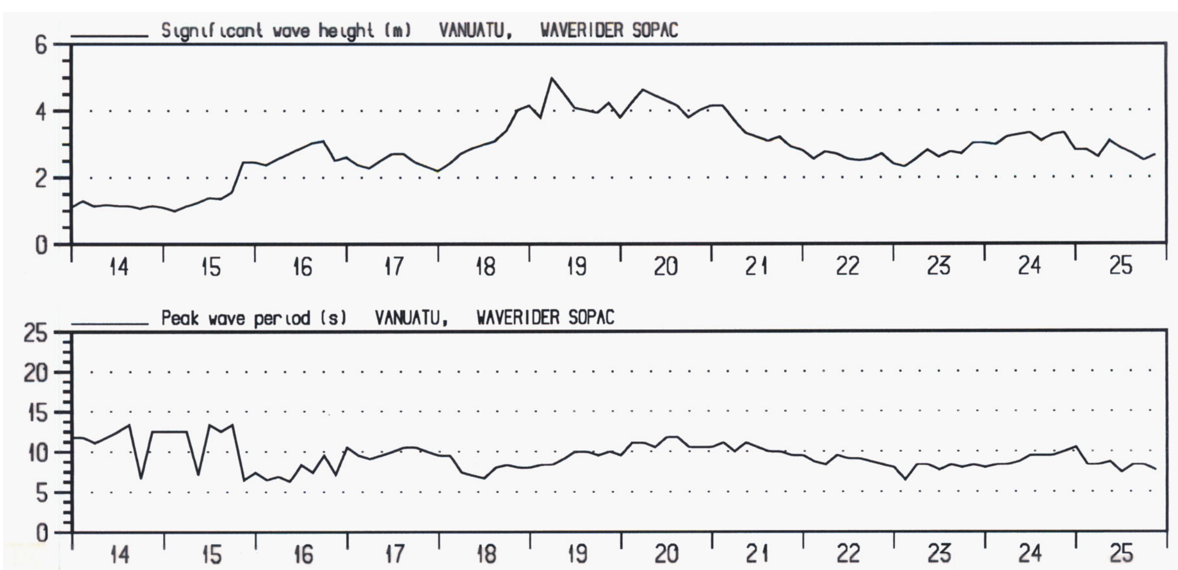

Fig.12 Time series of significant wave height and peak wave period from the waverider buoy off Efate, 14th-25th November 1991

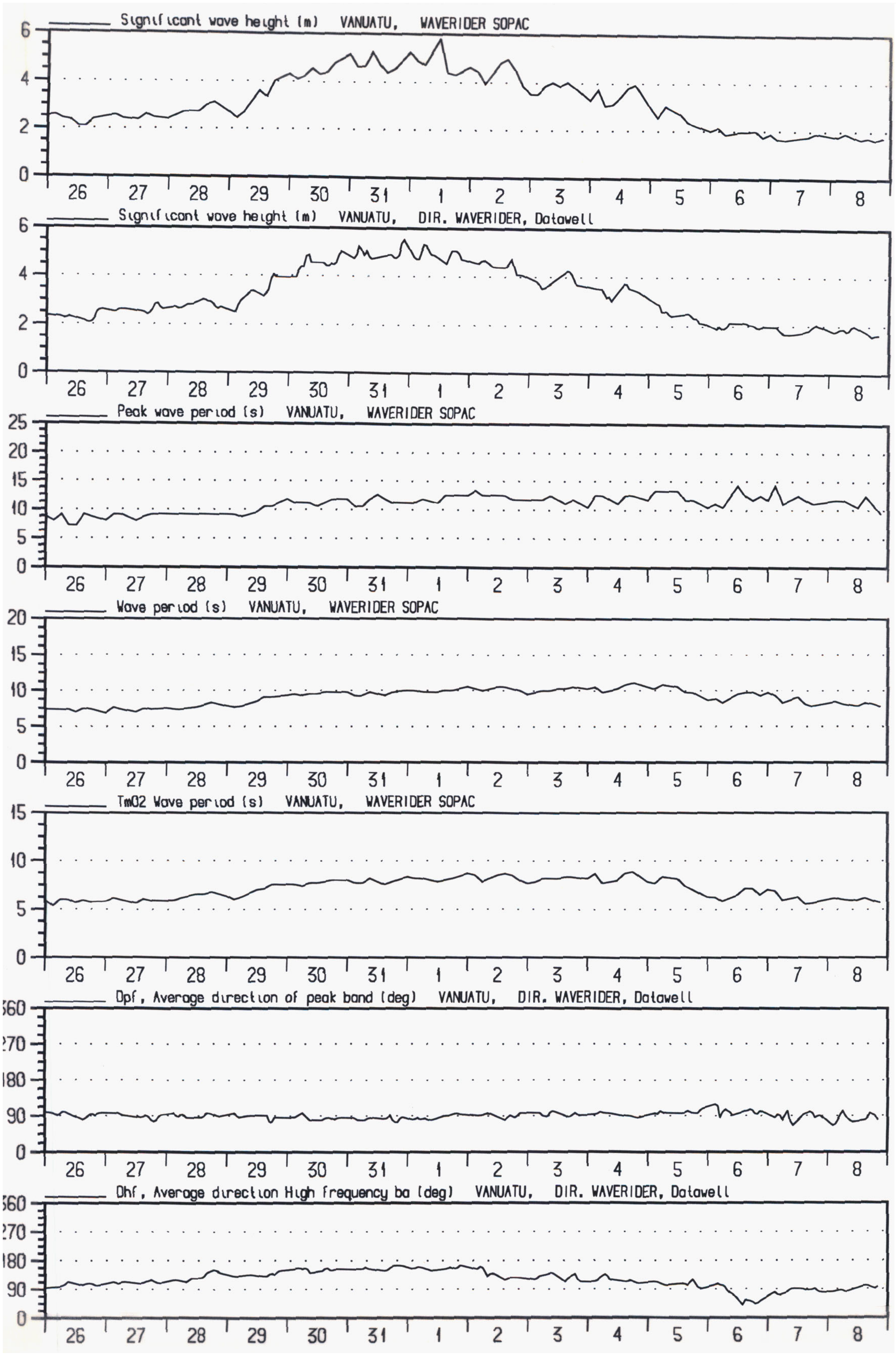

Fig. 13 ***Time series of significant wave height from the Waverider and the Directional Waverider, peak wave period, energy wave period, mean wave period, wave direction at the spectral peak and high frequency (wind wave) direction offshore Efate during the passage of Tropical Cyclone Kina; 26th December to 8th January 1992/93.***

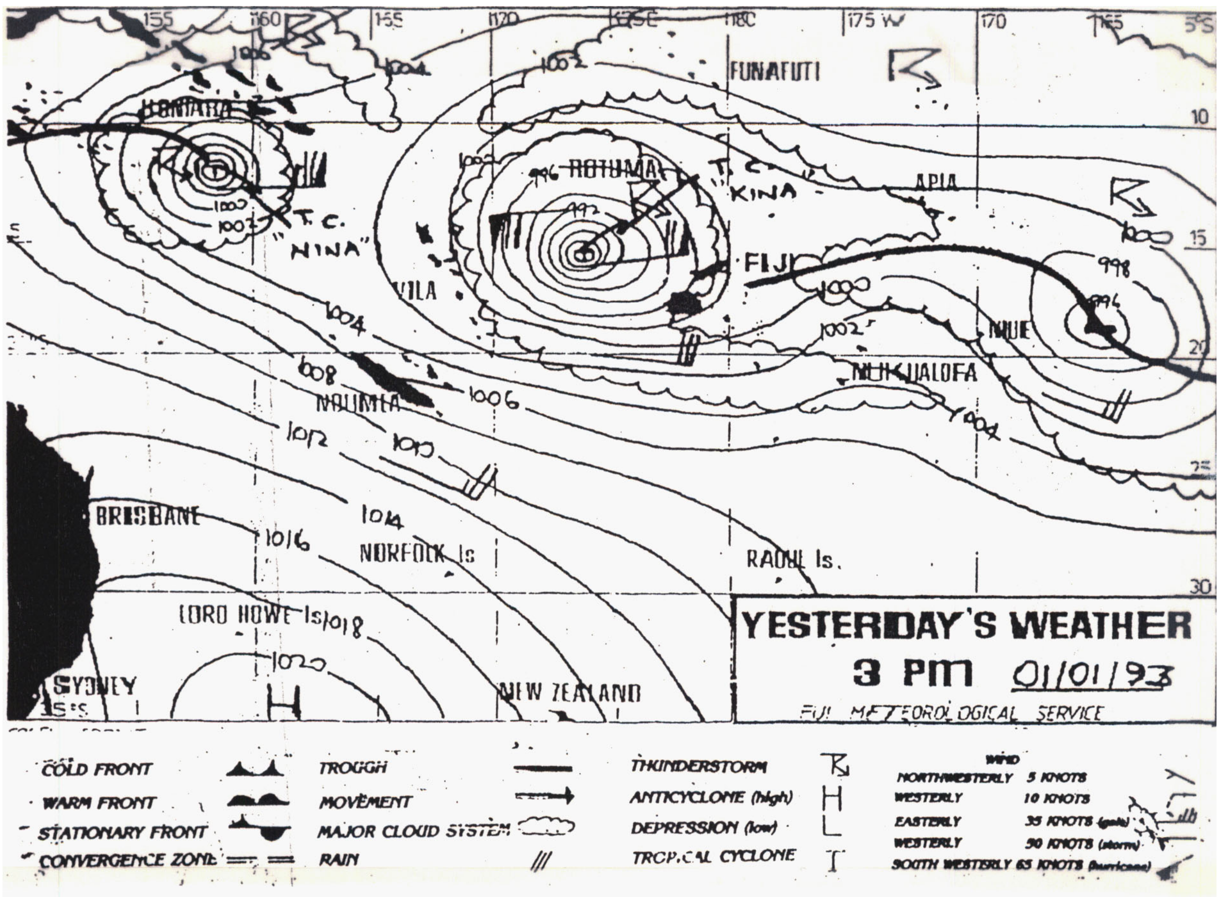

Fig 14 .Surface weather chart for 0300 UTC on 1st January 1993

5.4 Other cyclones

Wave data from a number of tropical cyclones are also available from the GEOSAT satellite data base for the South Pacific. The storms which most affected wave conditions in the Vanuatu group are described in the following. The data is presented for each storm on maps of the area with colour coded satellite tracks. The time of the satellite pass is given, and colours represent different significant wave height bands according to the key. The track of the cyclone is also given with the position of the storm centre at 00 UTC each day. The blue shaded area is the approximate area which experienced hurricane force winds.

5.4.1 Tropical Cyclone Patsy

Patsy moved first south westwards curving towards the south east as it moved through the sea area to the west of the Vanuatu group on 15th to 16th December 1986. It did not attain hurricane intensity. Nevertheless, seas were very heavy with significant wave heights, exceeding 6 m, recorded to the south of the storm centre on 16th December at 0300 UTC (Fig. 15).

5.4.2 Tropical Cyclone Uma

Very severe damage was reported in the Vanuatu group as Uma passed along a track parallel with the axis of the group towards the south east, passing Efate only 30 miles to the west. Efate was the island experiencing most damage. The satellite passed on a north westerly track to the west of the cyclone, mostly within the area of gale force winds on 7th February at 2000 UTC when the cyclone was located at the southern tip of the Vanuatu group. Wave heights were close to 7 m over a wide area although the track did not pass closer than 200 km from the storm centre (Fig. 16).

5.4.3 Tropical Cyclone Anne

This cyclone also reached hurricane force on 10th January 1988 a little to the north of Vanuatu. It moved on a south westward then south eastward track as it moved through the Coral Sea. Only northern Vanuatu was severely affected. It reached its peak intensity early on the llth, when located west of Santo. At 2000 UTC on the 11th, a GEOSAT ground track passed only about 50 km from the eye at about 19°S. Significant wave heights over 11 m were registered close to the point of nearest approach (Fig. 17).

5.4.4 Tropical Cyclone Bola

Bola caused considerable damage in Vanuatu. It had both an unusually long lifespan (8 days as a Tropical Cyclone) and gales associated with it covered an unusually large area, particularly to its east. It moved first westwards from its birthplace south of Tuvalu reaching Vanuatu on 28th February 1988, then circumscribed two double loops near Efate before moving on south eastwards. Its winds reached hurricane strength on the 28th. It is estimated to have reached its peak intensity on 1st March. It eventually became a strong depression with storm intensity for at least 6 days, afterwards causing severe flooding in New Zealand.

The large extent of gales, its long lifetime and hurricane force winds resulted in very high wave heights, particularly from a satellite pass to the south of the storm on 6th March along which significant wave heights exceeded 10 m along a distance of 240 km, reaching a maximum of over 14 m. This was the highest wave height registration from the South West Pacific.

As Bola retreated south into its depression stage high waves built up in the strong westerly winds to the north of the storm. Thus on the 8th March wave heights exceeding 6 m were still being recorded by the satellite in this area (Fig. 18).

5.4.5 Tropical Cyclone Dovi

Dovi moved more or less on a straight south east track about 150 km east of the Vanuatu group, although it performed a double loop close to Efate between 10th and 12th April 1988. The cyclone was of moderate strength. A GEOSAT track passed close to the centre with 6-7 m seas recorded on 9th April at 1300 UTC (Fig. 19).

5.4.6 Tropical Cyclone Harry

Harry was one of the major cyclones of the 1988/89 season. Damage was light, however, in Vanuatu. One track to the west of Efate during 10th February 1989 recorded significant wave heights greater than 6 m (Fig. 20).

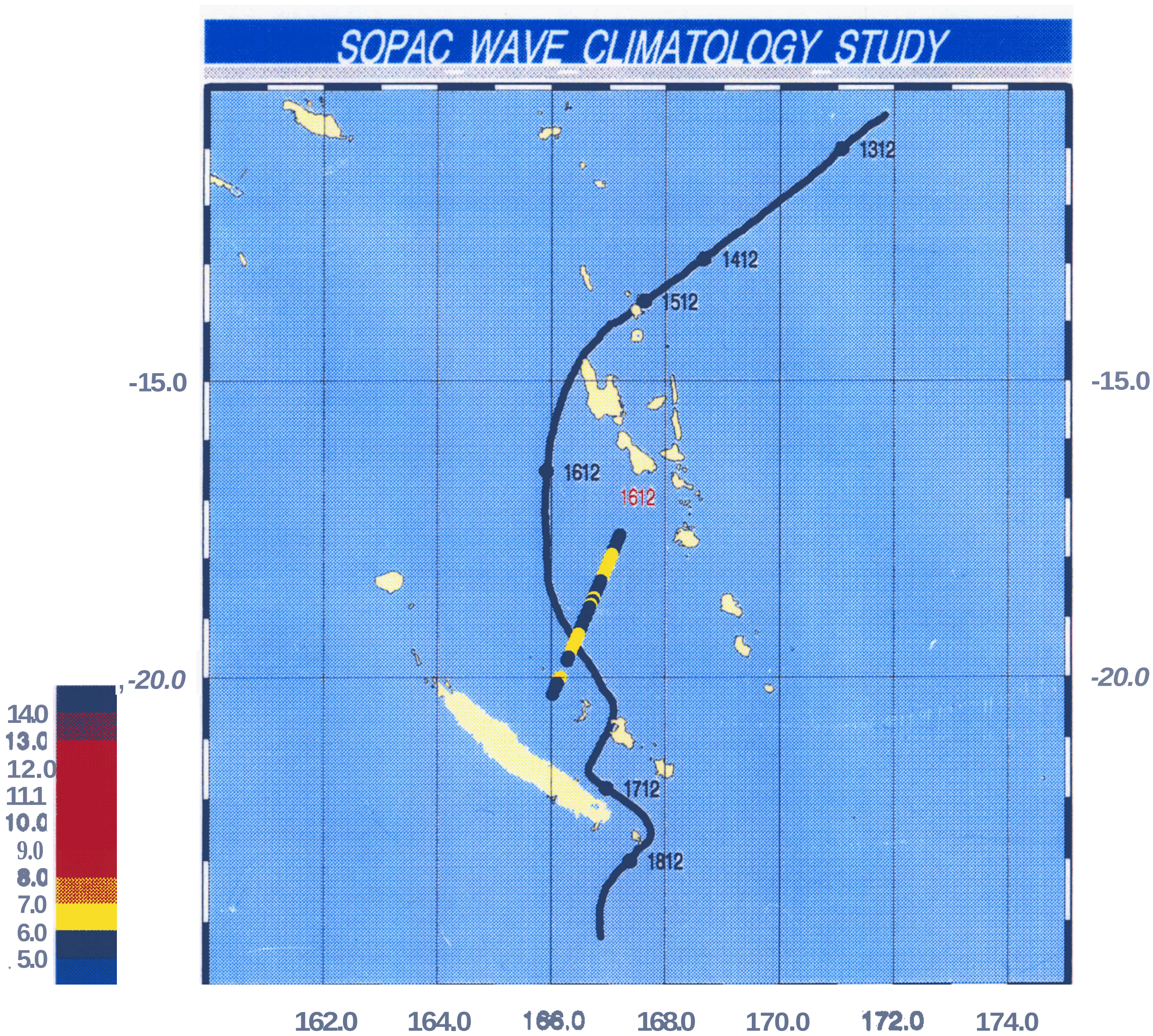

Fig. 15 Satellite significant wave height measurements exceeding 5 m close to the track of Tropical Cyclone Patsy. The location of the storm centre at 0000 UTC on each day from 13/12-86 to 18/12-86 is indicated. The day of each satellite pass is also shown.

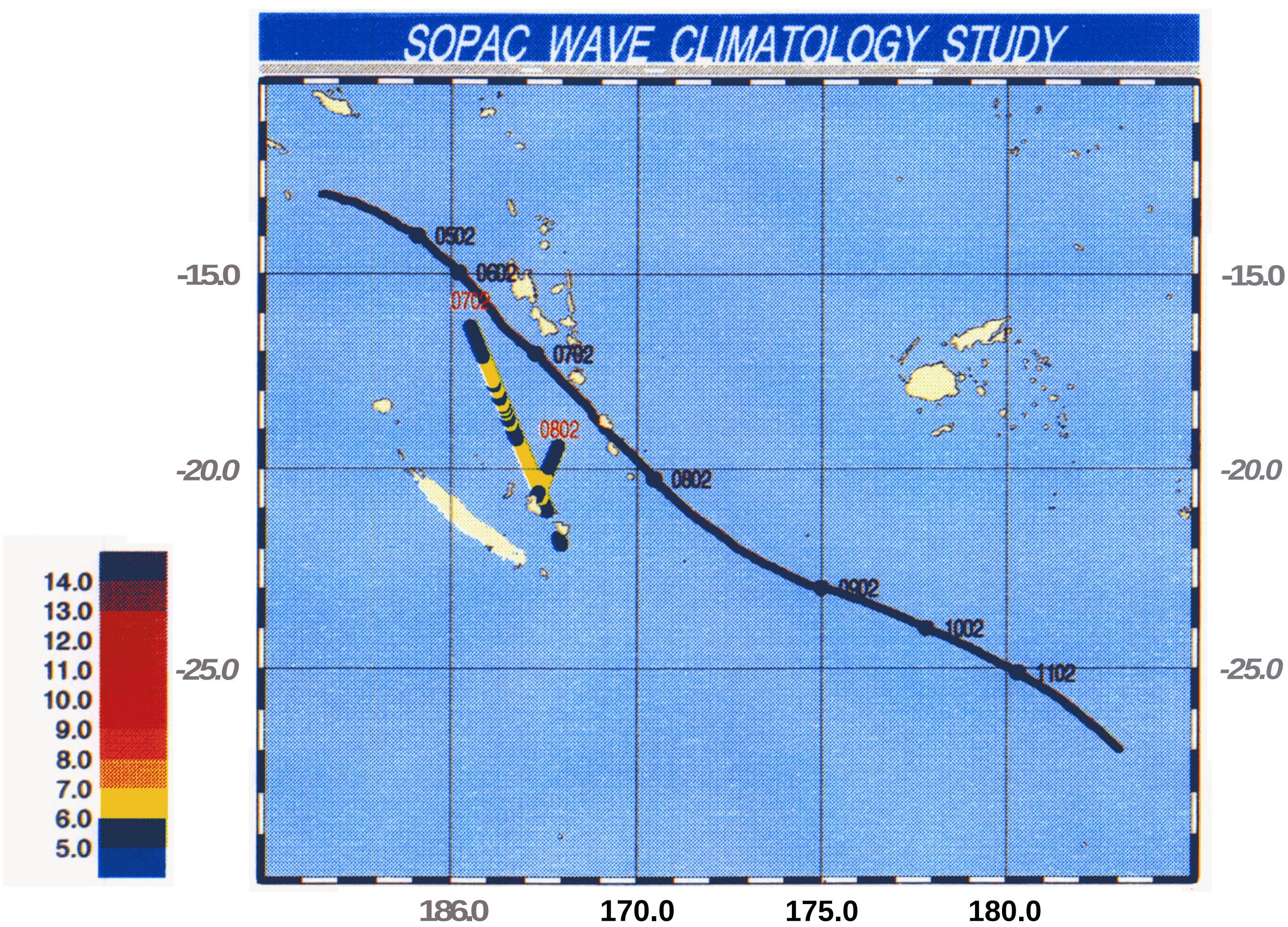

Fig. 16 *Satellite significant wave height measurements exceeding 5 m close to the track of Tropical Cyclone Uma from 5/2-87 to 11/2-87 is Indicated. The day of each satellite pass is also shown.*

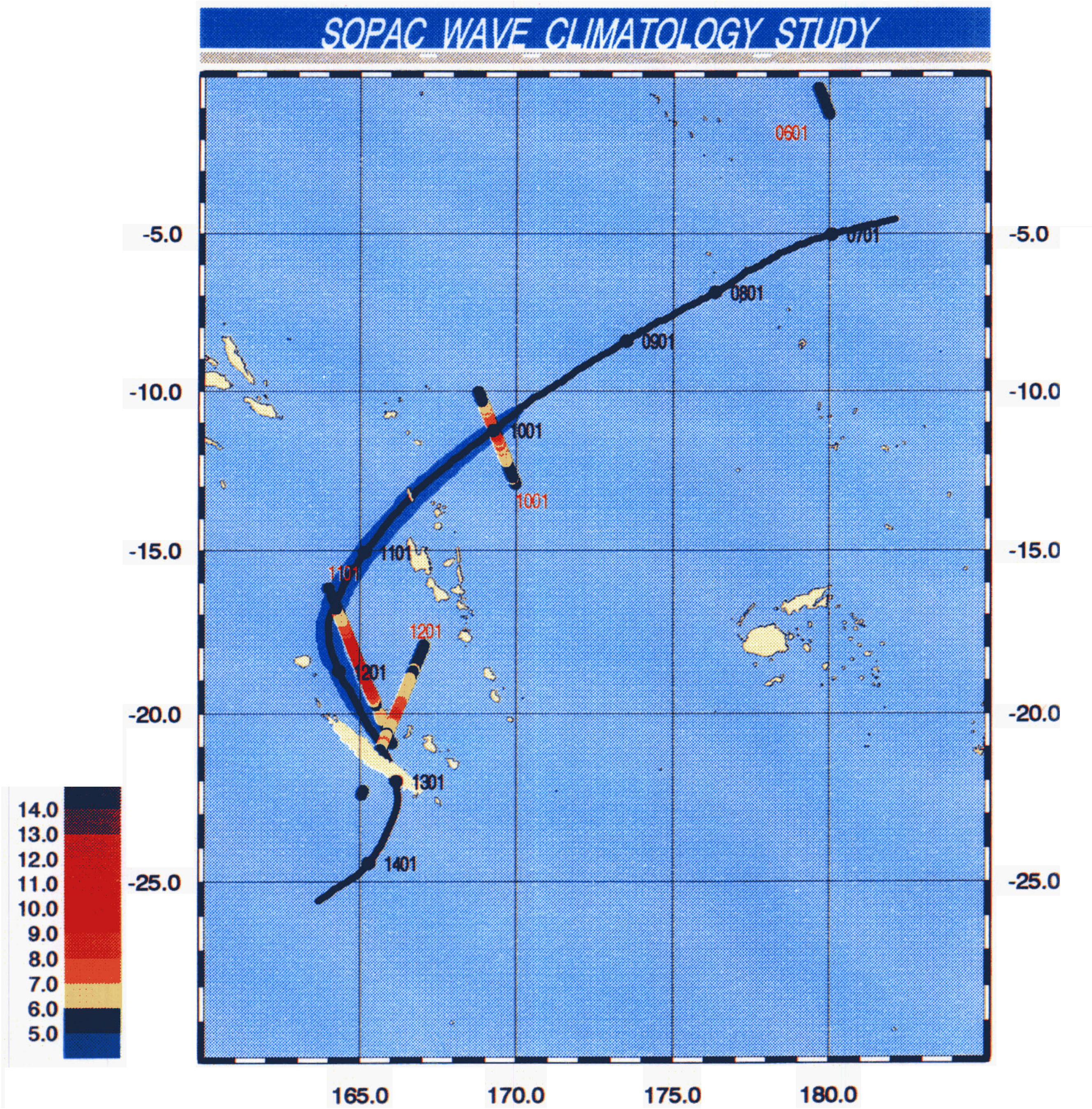

Fig. 17 Satellite significant wave height measurements exceeding 5 m close to the track of Tropical Cyclone Anne from 7/1-88 to 14/1-88 is indicated. The day of each satellite pass Is also shown. The blue shaded area indicates the region which experienced hurricane force winds.

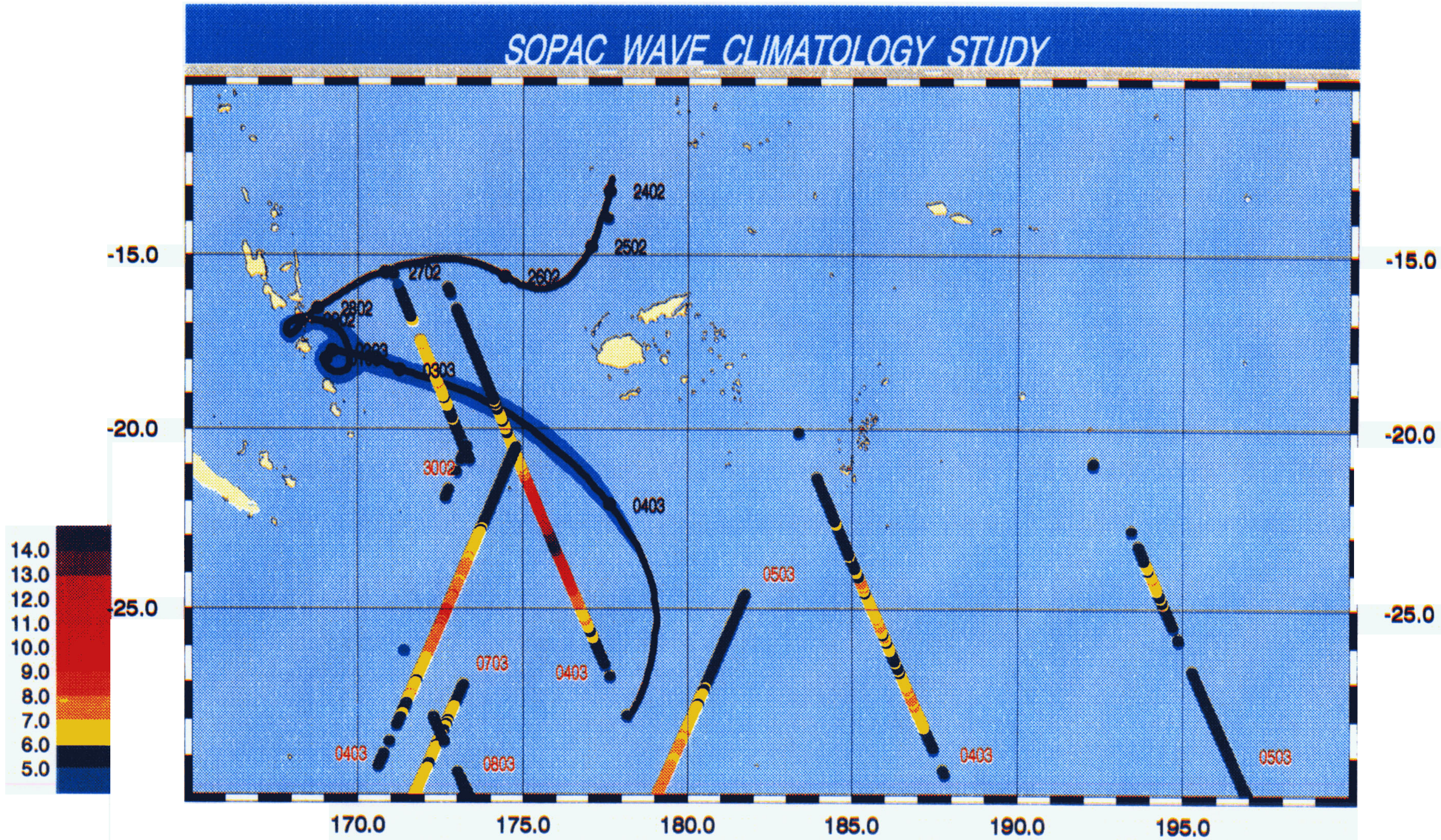

Fig. 18 ***Satellite significant wave height measurements exceeding 5 m close to the track of Tropical Cyclone Bola from 24/2-88 to 4/3-88 is indicated. The day of each satellite pass is also shown. The blue shaded area indicates the region which experienced hurricane force winds.***

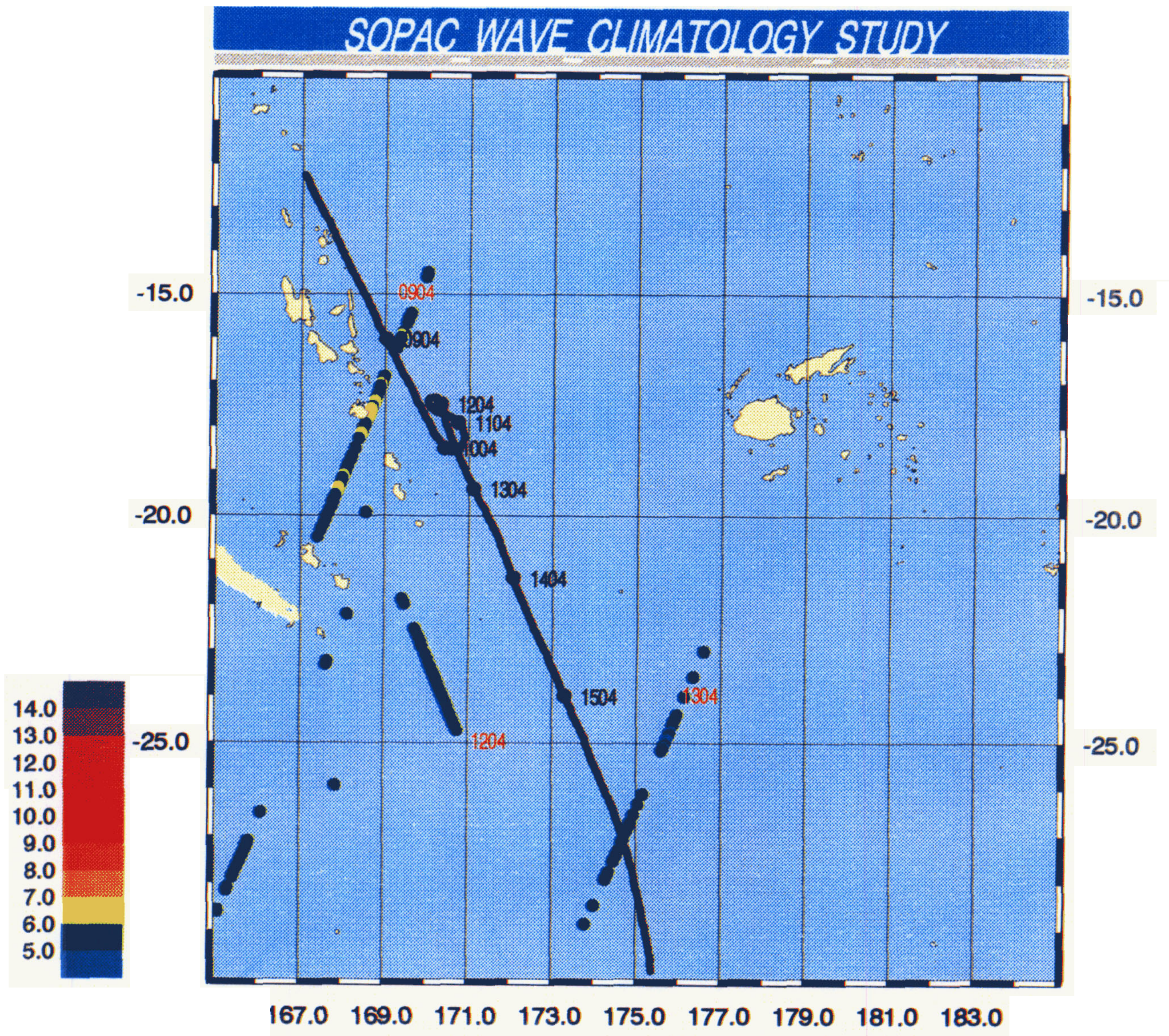

Fig. 19 Satellite significant wave height measurements exceeding 5 m close to the track of Tropical Cyclone Dovi. The location of the storm centre at 0000 UTC on each day from 9/4-88 to 15/4-88 is indicated. The day of each satellite pass is also shown.

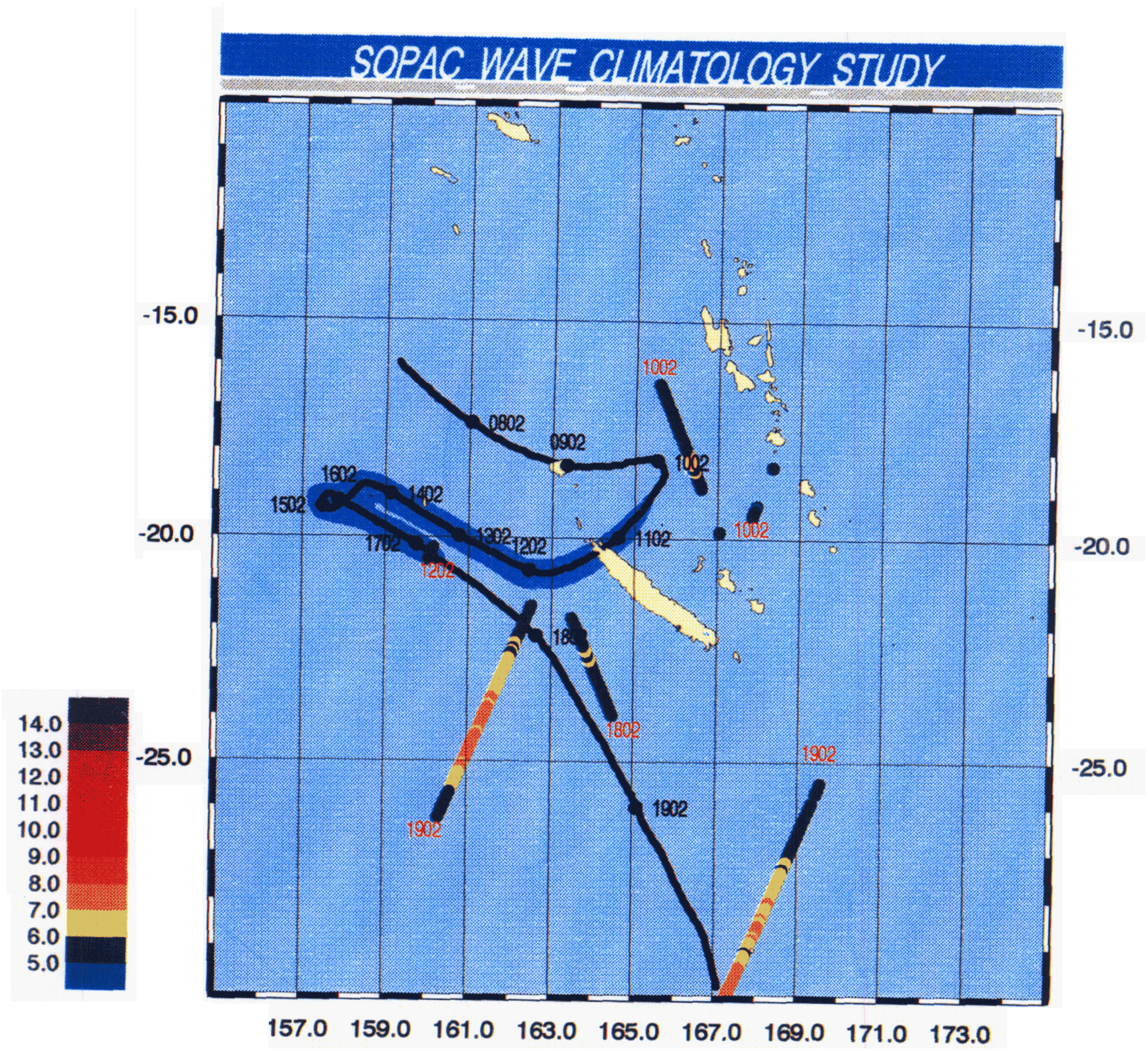

Fig.20 Satellite signifcant wave height measurements exceeding 5m close to the track of Tropical Cyclone Harry from 8/2-89 to 19/2-89 Is Indicated. The day of each satellite pass is also shown. The blue shaded area indicates the region which experienced hurricane force winds

5.5 Long Period Swell

On two occasions during the measurement period at Vanuatu, peak wave periods reached 20 seconds. The first occurred on 19th January 1991. The source of this long period swell seems to have been extensive strong wind fields to the south of Australia during the days prior to the event. This event is discussed further in the Wave Climate of Western Samoa report in this series. 20 second swell was measured at all stations operating at that time (Tongatapu, Tuvalu and Western Samoa) indicating a broad band of swell spreading northwards through the region.

The second occasion with 20 second peak period occurred on 22nd-23rd September 1992. Again, very strong westerlies south of Australia and in the Tasman Sea seems to have been the source. The Fiji Waverider also recorded 20 second swell at this time. In Fig. 21 are shown simultaneous time series of various wave parameters from both Fiji and Vanuatu during this event.

During the directional wave measurements at Efate one event has been identified during which both swells from north west and south are present at the same time together with easterly wind seas. This occurred during early February 1993. In Appendix B one can see that the wave direction at the peak period and the peak period itself both change rapidly from record to record. Although to the inexperienced eye this may look like noise on the data close examination shows that there were multiple peaks on the wave spectrum with similar energy content. For this reason the peak period can rapidly change from one record to the next. The associated direction will then also change from the direction associated with one peak to the next.

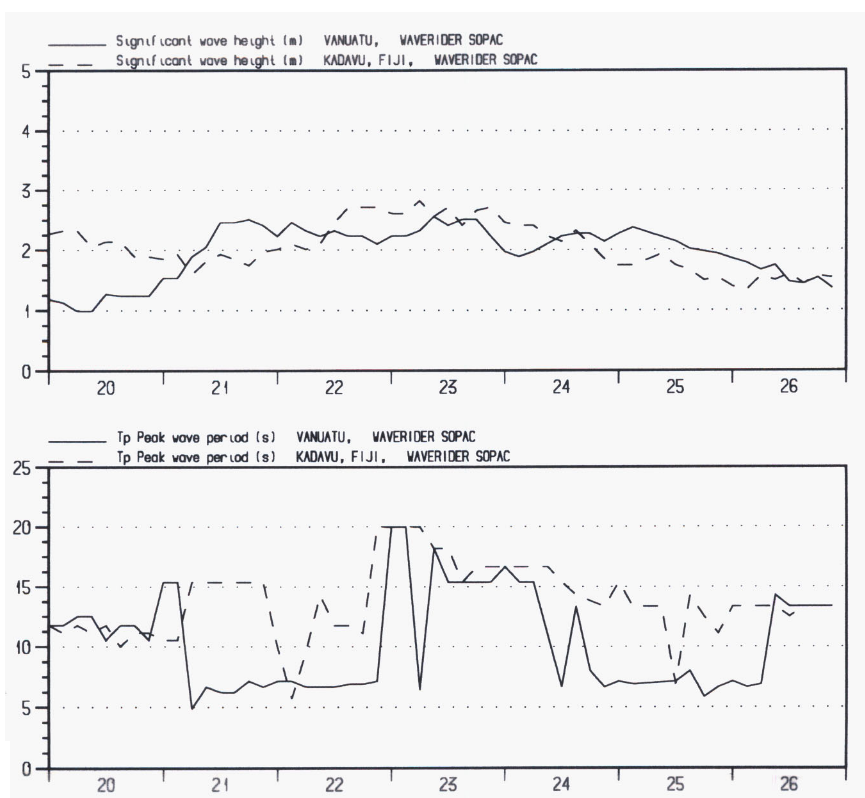

Fig. 21 Time series of significant wave height (m) and peak wave period (s) from the Efate Waverider (solid line) and the Waverider off the south coast of Kadavu Island, Fiji during the long period swell event in September 1992.

6. Conclusions

The purpose of SOPAC's wave data collection programme has been to map the wave energy resource of several South Pacific island nations including Vanuatu.

Due to a series of unfortunate incidents with the buoys, the fact that the wave measurement period coincided with a rare climate anomaly in the South Pacific (a double year El-Niño) and the influence of tropical cyclones in some months has resulted in some uncertainty concerning the temporal representativity of the wave measurements carried out at Efate. The data confirms, however, that the Vanuatu group is endowed with a relatively high resource of the same order of magnitude as an area on the south coast of Java where a wave power plant is being built.

Although wave power levels are on average not as high as the higher northern latitudes, e.g., European Atlantic coastlines, the resource is considerably more steady through the year.

The dominant contributions to the wave power in the Vanuatu group are derived from the easterly trade winds and southerly and northeasterly swells. The highest coastal wave power levels are therefore to be found on the south east to north east facing coasts. Due mainly to the geographical orientation of the islands, the best locations for wave power in the southernmost islands of the group (including Efate) are likely to have a significant higher resource than in the northern part of the group.

Although the resource is relatively stable throughout the year in the Vanuatu group there is considerable variability in wave power levels on other time scales from minutes to years. The tendency for high single waves to appear in groups leads to wave energy varying strongly on the time scale of minutes. There is also variability, on the time scale of days and weeks, in the swell component associated with the passage of storms further south and north and, for wind seas, due to trade wind variability and passage of tropical cyclones which are particularly important in this area. On the longest time scale, the El-Niño Southern Oscillation phenomenon may potentially have a significant impact on coastal wave energy levels due to anomalies in trade wind directions, variability in swell in some years and influence on the frequency of tropical cyclones.

Significant wave heights exceeding **10** m have been measured by satellite in the Vanuatu group in association with tropical cyclones which occur in this region sometimes 2-3 times per year. On two occasions significant wave height measured by the buoy on the coast of Efate exceeded 5 m due to close passage of Tropical Cyclones Tia and Kina. The GEOSAT satellite altimeter recorded high significant wave heights in the Vanuatu group in **6** cyclones during the **1986-7, 1987-8** and **1988-9** cyclone seasons.

The foundations have been lain in this project for estimates to be made of the wave energy resource at any location in the Vanuatu group. The data will also be useful with respect to coastal defence, harbour design and improved wave forecasting. Various points need to be stressed to the potential user of this data. First, there are large gradients in the wave conditions in the neighbourhood of the islands and as such the wave measurements should be considered to be site specific. The length of the record is also short compared to the dominant El-Niño Southern

Oscillation climate cycle and the data cannot necessarily be considered to be representative for the long term. Finally, wave direction measurements have confirmed that wave energy is derived both from easterly trade wind seas, southerly and north-easterly swells. Information on wave direction is crucial for the estimation of the coastal wave climate.

In the final section we give recommendations as to how the wave climate can be estimated away from the measurement site and what future work would be beneficial. All data collected in this project has been installed at the SOPAC Secretariat in Suva, Fiji.

7. Recommendations

In the course of this project, in addition to the wave measurements and wave climatology work, a number of training workshops have been held for nationals of several countries including Vanuatu. At the present time, in-country knowledge of ocean waves, wave power technology and Waverider buoy operation and maintenance exists. Some wave measuring equipment is also available in the region. In order to maxirnise the benefits from this training activity it is imperative to continue to the next natural stage of carrying out site specific assessments for wave power. In fact, the Fiji Ministry of Energy has already set up its own wave power programme to look at the wave power potential at **3** or 4 sites in the Fijian Archipelago where energy requirements are presently covered by fossil fuels. It is recommended that Vanuatu follows a similar procedure. This is described in the following.

Short term measurements (**3-6** months) could be made using a Directional Waverider at an offshore measurement location, simultaneously with Waverider measurements as close to each of the chosen sites as possible. This data can then be used to construct a long term wave climate at the site in question using calibrated global wave model data, coastal wave modelling and available satellite data.

It is also recommended that SOPAC produces a regionwide brochure describing the results of the wave climate program with emphasis on the wave energy resource, the state-of-the-art of wave power technology internationally, and the potential in the South Pacific. This document would then be invaluable both as an information source within the countries themselves and to attract foreign companies involved in wave power to the region.

It has been pointed out earlier in this report that the measurement series is probably not representative for the long term due to, amongst other factors, influence the rare double year El-Niño which occurred during the measurement period. It is therefore considered to be worthwhile to extend the data base compiled at SOPAC with the ongoing satellite measurements from the ERS-1 and Topex/Poseidon satellites which followed GEOSAT, which is widely used in this report. These data will also be useful directly to SOPAC in their coastal science projects. Cyclone data are, in particular, often captured by the satellites.

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Appendix A

Time series plots of wave and wind parameters; 1990 - 93

Hm0:	**Significant wave height (m)**
Tp:	**Spectral peak wave period (s)**
Tm-10:	**Energy (wave) period (s)**
Tm02:	**Mean wave period (s)**