Sea Level and Shallow Water Current Variability in Pagasa Island, Philippines

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ABSTRACT

Significant wave height, sea level, and currents at 0, 2, 4, and 6m were measured using a doppler current meter deployed at the northern reef of Pagasa Island from 16 October 1997 to 3 March 1998. Tidal components of sea level and current data were extracted using harmonic analysis and subtracted from the original series to obtain residuals. These were then correlated with each other and with atmospheric variables (wind speed and atmospheric pressure). The tidal components accounted for about 98% of the variance in sea level but only 4-5% of the variance in the currents. Power spectral density correlations indicate that residual sea level variations may be due to set-up by wave action. Strong non-tidal residual components of the flow suggest conditions favorable for offshore transport which may promote long-distance dispersal of propagules.

Key words: Reef circulation, current and sea level variability, Pagasa Island, Kalayaan Island Group

INTRODUCTION

Pagasa Island is located in the northwestern part of the Kalayaan Island Group (KIG) and is one of the biggest islands in the Spratlys area, a group of oceanic shoals and small islands in the South China Sea. With a land area of only about 0.22 km^2, it sits on the eastern edge of an atoll named the Pagasa Reef Complex (Fig. 1). Adjacent reef areas are typically about 30-60 nm away and the question of whether these reef communities are linked to each other remains unanswered. One basis for reef connectivity is the transport of propagules, which can serve as agents for the exchange of genetic material. Shallow-water currents in reef areas can either enhance offshore advection of propagules where ocean currents can carry them to neighboring reefs or result in local entrainment where propagules are retained within the reef system. Initial genetic studies of two reef fish species show high gene flow among sample populations from nearby reef systems (Mamauag et al., unpubl). To provide initial insights on the

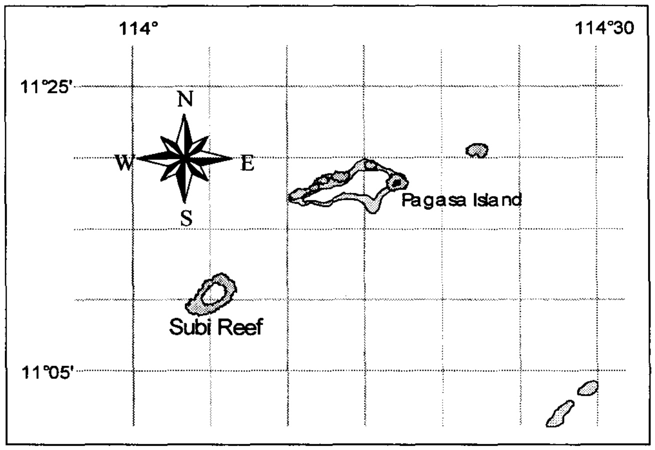

Fig. 1. Pagasa Reef Complex

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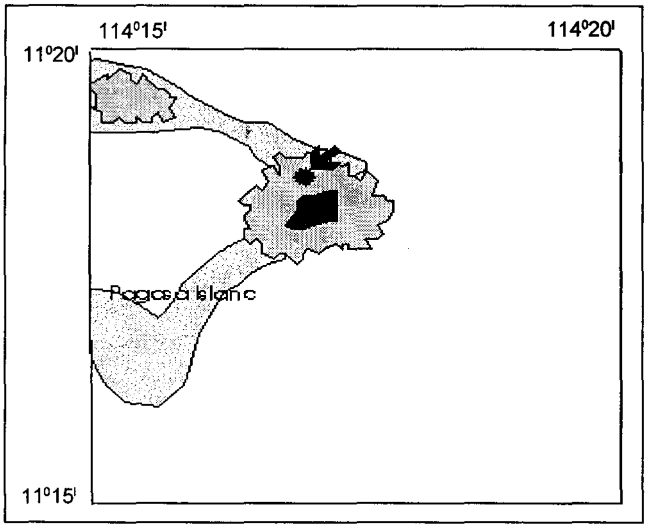

Fig. 2. Location of current meter (Pagasa Island)

characteristics of the reef circulation in Pagasa Island, this paper aims to characterize the sea level and shallow-water current variability and its correlation with wind and atmospheric forcing.

METHODOLOGY

An Aanderaa Doppler Current Meter (DCM12) was deployed at a depth of 10m on the northern reef of Pagasa Island from 16 October 1997 to 13 April 1998. The DCM12 measures sea level, significant wave height, and currents at the surface, 2m, 4m, and 6m depths at hourly intervals. The location of the current meter is shown in Fig. 2. A portable automatic weather station was also deployed in Pagasa Island to measure atmospheric pressure and wind speeds during the same period.

Analysis of the time series data involved the removal of the tidal component of the sea level and current velocity data using harmonic analysis (Emery and Thomson, 1997). This was done to obtain the residual sea level and current velocity variations. Correlation of the residual sea level, current, and significant wave height data with wind and atmospheric pressure from the weather station was conducted to determine dominant forcing parameters which influence shallow-water dynamics in Pagasa Island.

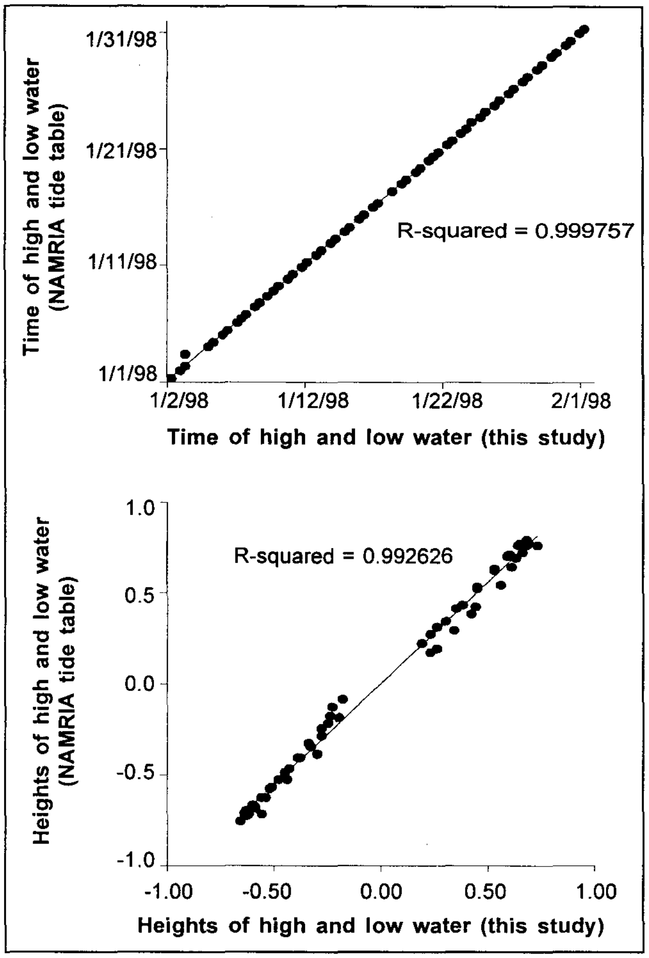

Fig. 3. Comparison of NAMRIA tide table and Kalayaan research program tide prediction

RESULTS

The results of the harmonic analysis are summarized in Table 1 for the tidal sea level heights and in Table 2 for the tidal currents at different depths. The dominant components for the tidal height variations are the diurnal components, O_1 and K_1 while the dominant semidiurnal component is the M_2. For the tidal currents, the dominant components are P_1 and K_1. Comparison of the tides predicted using the harmonic constants derived from this study with that of the National Mapping and Resource Information Authority (NAMRIA) shows very small differences (Fig. 3). The tides in Pagasa Island are predominantly mixed, mainly diurnal with a Form Ratio ($F=[O_1+K_1]/[M_2+S_2]$) value of 2.3 with a spring tide range of 1.17m. The Form Ratio is the ratio

Table 1. Harmonic constants for sea level tidal variations

Components	Amplitude (cm)	Phase (^{0})
Q1	5.23	248.91
O1	26.18	265.22
M1	2.13	295.60
P1	11.66	303.99
K1	32.41	312.62
J1	1.03	327.23
2N2	0.64	318.76
MU2	1.10	296.61
N2	3.38	287.18
M2	17.63	312.60
L2	0.63	047.58
S2	7.82	342.52
K2	2.03	359.10
M3	0.32	279.57
MSK5	0.15	180.17
2MS6	0.15	273.06

of the amplitudes of the dominant diurnal (O_1 and K_1) and semidiurnal (M_2 and S_2) tidal components (Pond and Pickard, 1983).

The observed tidal and residual sea level time series shown in Fig. 4 and the U-component of velocity at 2m below the surface shown in Fig. 5 show contrasting features. While the tidal variations in the sea level record accounted for about 98% of the total sea level variance, the tidal currents accounted only for about 4-5% of the total current variance. This difference may indicate that tidal forcing in Pagasa Island is highly influenced by the tidal potential rather than by flow convergence driven by shallowing bathymetry.

Autocorrelation functions of the daily-averaged time series of the significant wave height, residual sea level, wind speed, and atmospheric pressure were calculated and are shown in Fig. 6. The wave height and residual sea levels show relatively smooth autocorrelation functions compared to wind speed, which indicates a higher persistence of sea level variations. The wind speed data show a drop in correlation coefficient (r) at small lags ($\approx$3 days) which is expected as local wind

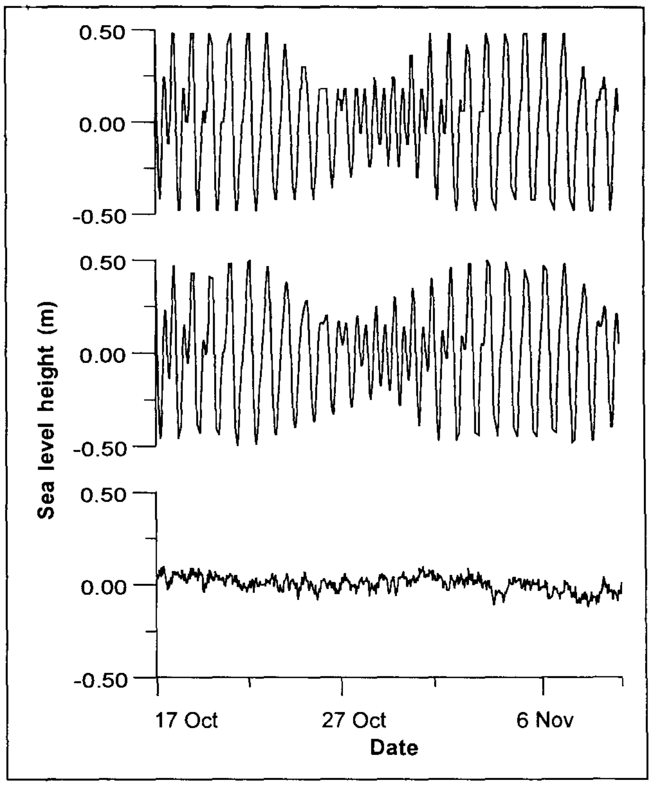

Fig. 4. Observed tidal and residual sea level oscillations

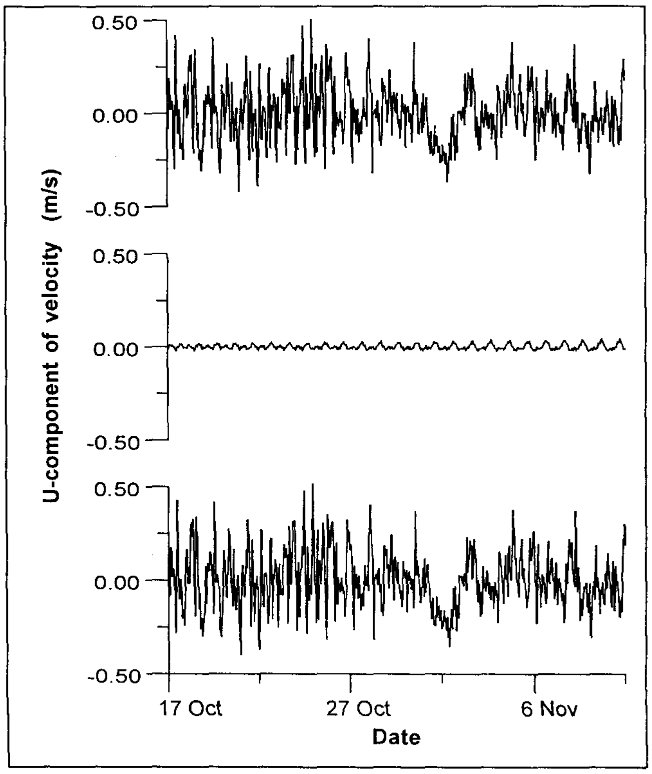

Fig. 5. Observed tidal and residual current oscillations

Table 2. Tidal current amplitudes at different depths

Components	u0	v0	u2	v2	u4	v4	u6	v6
P1	1.71	3.66	0.89	1.63	2.47	2.47	1.25	2.31
K1	1.99	3.50	0.88	3.12	3.22	3.22	1.59	2.66
S2	0.98	2.28			1.08	1.08	0.91	1.20
N2			0.94	0.75				
M2			0.52	1.63				
NO3			0.77	0.55				
MN4			0.31	0.81				
MK4			0.58	0.81				
S5			0.40	0.25				
2M(NU)6			0.12	0.60				
SQ3	0.91	0.70						
MSN6	0.02	0.65						
MNK5					0.37	0.41		
3MNKS7					0.33	0.03		
M8					0.05	0.33	0.14	0.32
MKN6	0.28	0.93	0.14	0.65				
3MO7	0.21	0.56	0.42	0.22				
2MSK7	0.43	0.61					0.39	0.27
2SM6			0.23	0.43				
2MSP7			0.28	0.15	0.29	0.24		
4MS6							0.27	0.19
3MK8	0.71	0.52						

variability is higher. At lags of about 45 days, the correlation coefficient is relatively high (>0.6) for significant wave height.

Cross correlation of the four parameters, however, did not show any significant correlation with $r^2<0.5$. However the calculation of the power spectra (energy as a function of frequency) and the correlation of the spectra with each other yielded relatively high correlations between significant wave height and residual sea level and between residual sea level and wind (Table 3).

The analysis procedure was repeated for the current velocity measurements at 0, 2, 4, and 6m depths and the power spectral density functions were correlated with the residual sea level, significant wave heights, wind speed, and atmospheric pressure. The power spectral density functions of the u and v components are shown in Figs. 7 and 8, respectively. The correlation matrix shown in Table 3 summarizes the spectral correlations and shows the influence of waves on the current variation with the significant wave height more highly correlated with the u-component of the currents compared to the v-components. This pattern can give an indication as to the northwesterly direction of the incoming waves. The correlation between the power spectra of the wind speed was also higher at 2m than at 0m, presumably because oscillatory wave-driven motion contaminates the surface currents.

DISCUSSION

Despite the strong tidal component present in the sea surface elevation record, the tidal current component is approximately an order of magnitude weaker than the measured currents. The circulation within the reef areas is therefore driven mainly by the wind or by offshore currents impinging on the reef areas. These shoals and islands typically have very steep bathymetric slopes and narrow shelves and the interaction of the currents with these islands can generate wake features which can affect early life history stages of reef associated organisms by aggregation, retention near reefs, onshore and offshore movement, concentration of planktonic food, and interaction with other plankters (Kingsford, 1990). Wolanksi and Hamner (1988) suggest that headlands, islands, and reef systems generate complex three-dimensional secondary flows (e.g., wakes) which result in frontal features which are known to be biologically active sites (Le Fevre, 1986).

During short visits to the sites, no wake features were observed. Thus, the existence of wakes in Pagasa Island remains to be confirmed. Measured maximum current magnitudes were in the order of $0.5ms^{-1}$. If the magnitudes of the prevailing currents were of the same order, the Reynolds number can be calculated and the values obtained can be compared to a rough scale,

Table 3. Correlation coefficients (r) between power spectra of significant wave height, residual sea level, wind speed, and atmospheric pressure with measured currents at different depths

	wave	sea level	wind	pressure	0m		2m		4m		6m	
					u	v	u	v	u	v	u	v
wave	1.00											
sea level	0.93	1.00										
wind	0.63	0.84	1.00									
pressure	0.53	0.75	0.90	1.00								
u0	0.91	0.77	0.35	0.28	1.00							
v0	-0.03	0.04	0.14	0.44	-0.09	1.00						
u1	0.81	0.95	0.94	0.87	0.57	0.14	1.00					
v1	0.80	0.87	0.80	0.82	0.55	0.30	0.86	1.00				
u2	0.94	0.78	0.39	0.35	0.94	0.00	0.59	0.68	1.00			
v2	0.27	0.24	0.28	0.46	0.24	0.51	0.27	0.47	0.38	1.00		
u3	0.93	0.76	0.37	0.35	0.93	0 03	0.57	0.68	1.00	0.41	1.00	
v3	0.32	0.26	0.22	0.42	0.32	0.50	0.23	0.48	0.46	0.97	0.49	1.00

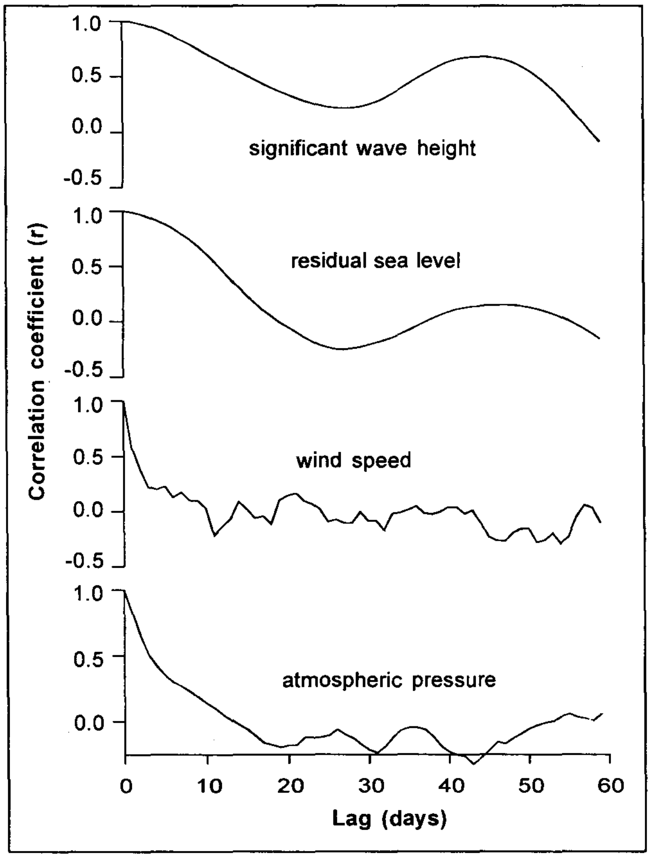

Fig. 6. Autocorrelation functions of significant wave height, residual sea level, wind speed, and atmospheric pressure

derived using laboratory tank experiments, which would describe the type of wake feature that can be generated (Tomczak, 1988). The Reynolds number for islands in deep water is given by

$$Re = (uL)/A_h \qquad (1)$$

where u is the speed of the prevailing current, L is the dimension of the island or reef, and A_h is the coefficient of horizontal momentum exchange. Using $u=0.5ms^{-1}$, L=10 km (the length of the Pagasa Reef Complex), and a typical value of $A_h=10^5m^2s^{-1}$ results in Re=0.05 which produces laminar flow with no flow separation around the reef. If these estimates are reasonable, then currents around Pagasa Island would probably enhance the offshore dispersal of propagules. However, uncertainties on the magnitude of the eddy coefficient and the effect of the irregularly shaped island or reef system can yield a very wide range of Reynolds numbers, and consequently may result in different classes of wake features. Further studies are necessary to confirm the existence of this feature.

The higher correlation between residual sea level and significant wave height suggests that the sea level variation in the reef area may be controlled by the piling up of water against the reef by incoming waves (wave

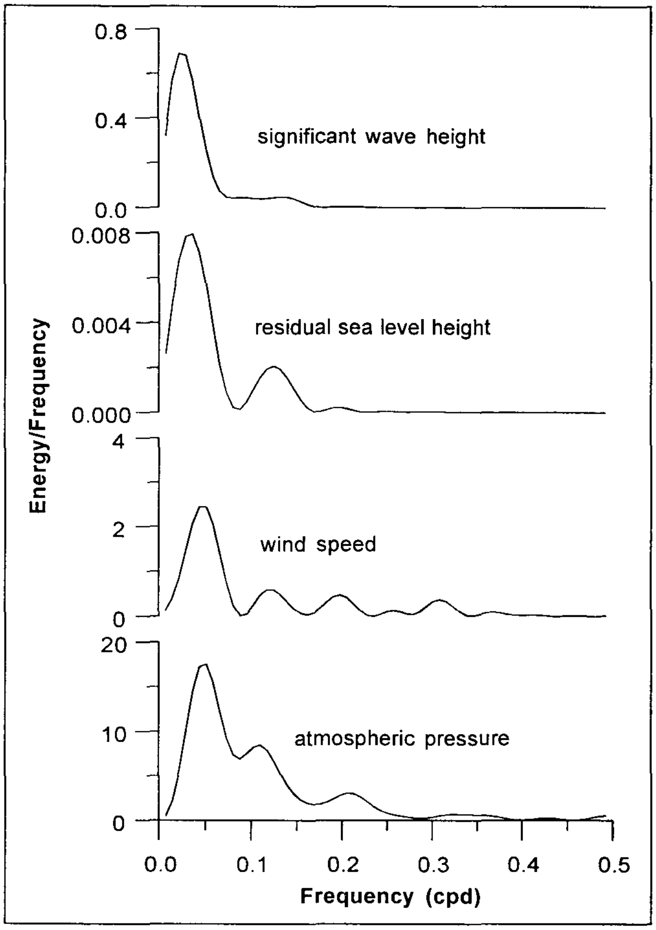

Fig. 7. Power spectral density functions of significant wave height, residual sea level height, wind speed, and atmospheric pressure

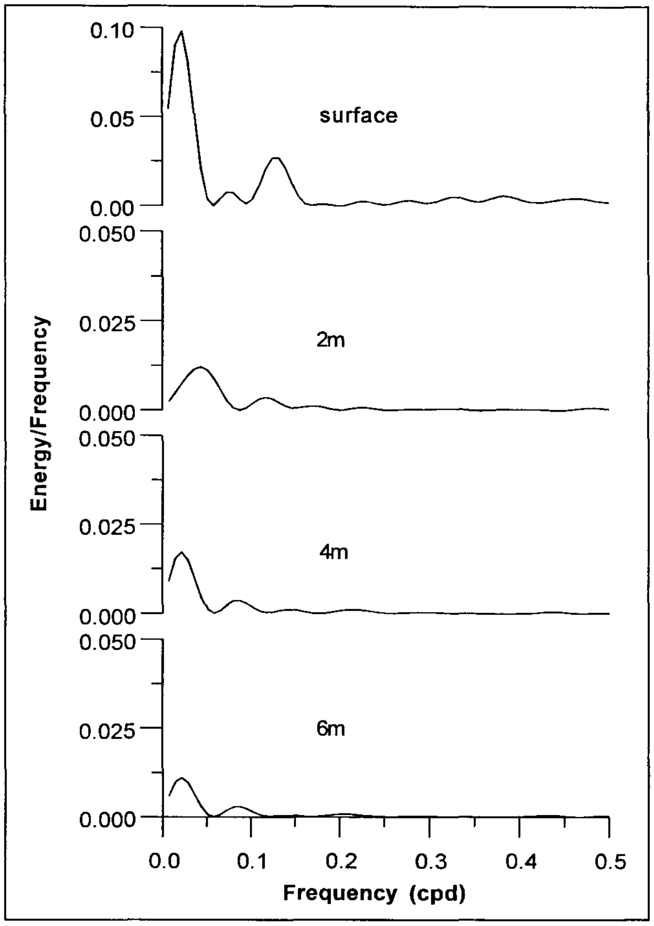

Fig. 8. Power spectral density functions of the u-component of velocity

setup). This mechanism has been identified as one of the primary processes controlling the inflow of water across the reef crest and into the lagoon (Hearn, 1988).

The consequences of the wind-dominated currents which can vary with the monsoon season can have a significant impact not only in the advection patterns of propagules but also on sedimentary material. It has been suggested that the direction of reef expansion and growth can be influenced by predominant wave climate (Graus, 1977) with reef expansion occurring parallel to the general direction of wave propagation. The direction of the incoming waves as inferred from the higher correlation between the energy spectrum of the u-component of the surface currents with that of the significant wave height indicates that the direction of wave propagation follows that of the monsoonal winds and is consistent with the orientation of the major axis of the Pagasa Reef Complex. This seems to be the case for Pagasa. However, the asymmetry of the reef flat with the northern reef which is wider than the south may indicate the dominance of the southwest monsoon.

SUMMARY AND CONCLUSIONS

Based on the calculated power spectra, the high correlation between the significant wave height and residual sea level suggests that the incoming waves may be controlling the inflow of water across the reef crest into the lagoon and the residual sea level variation in the reef area. Congruent to these findings, it can be inferred that the waves are propagating from the general direction of the northeast monsoon, as shown by the

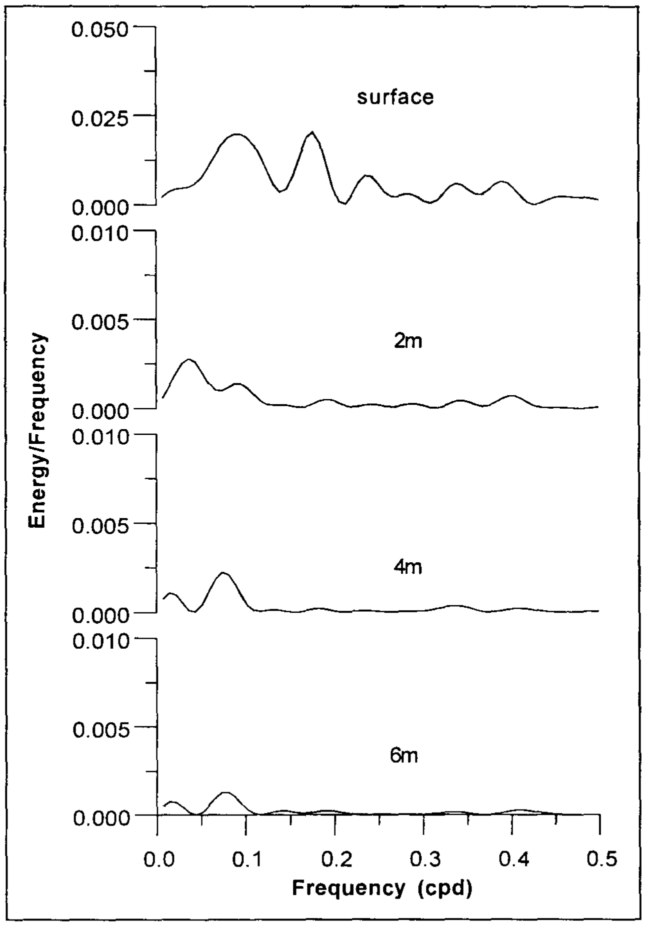

Fig. 9. Power spectral density functions of the v-component of velocity

correlation between the power spectra of the wave height with the near surface u-component of the currents. In spite of the strong tidal component present in the sea surface elevation record, the tidal current component is very weak. Thus, circulation within the reef areas is driven mainly by the wind or by offshore currents impinging on the reefs. Initial estimates of offshore current magnitudes based on measured reef current speeds indicate that secondary flows from wake features is unlikely to occur. However, uncertainties with the eddy viscosity coefficients and the irregular shape of the island and reef system do not rule out the existence of wake features. Nevertheless, the absence of entrainment due to island wakes suggests that offshore transport of suspended material, particularly along the direction of the winds and oceanic currents can contribute to longer advection distances for propagules and direction of reef expansion and growth in the Pagasa reef complex.

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