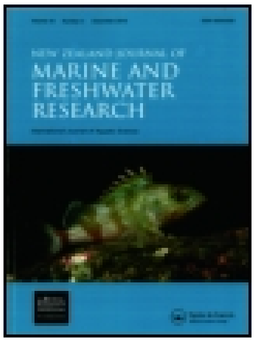

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Ocean wave characteristics around New Zealand

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Nearly 17 years wave records from deep water and shore-based stations are used to describe the ocean wave characteristics around New Zealand. The wave environment is dominated by west and southwest swell and storm waves generated in the temperate latitude belt of westerly winds. As a result, the west and south coasts are exposed, high energy shores, the east coast is a high energy lee shore, and the northern coast from North Cape to East Cape is a low energy lee shore sheltered from these winds and waves. South of New Zealand, wave energies are extremely high; the prevailing deep water wave is 3.5–4.5 m high and has a 10–12 s period, with a slight increase in wave heights in winter.

The west coast wave environment is mixed, and consists of locally generated westerly and southerly storm waves, and swell waves generated to the south. The prevailing wave is 1.0–3.0 m and 6–8 s period. There are no strong seasonal rhythms, only shorter period cycles of wave height (5 day) associated with similar quasi-rhythmic cycles in the weather.

The east coast also has a mixed wave climate with southerly swells, originating in the westerlies south of New Zealand, and locally generated southerly and northerly storm waves. The prevailing wave is 0.5–2.0 m and 7–11 s period. A short period rhythmic cycle, similar to that on the west coast, is superimposed on a weak seasonal cycle. The seasonal cycle results from an increase in the frequency of local northerly waves in summer.

The prevailing wave on the north coast is a northeasterly, 0.5–1.5 m high and 5–7 s period. Subtropical disturbances and southward-moving depressions generate a mixed wave environment and a possible seasonality reflecting a winter increase in storminess.

INTRODUCTION

Between latitudes 30°S and 70°S westerly winds blow around the Southern Hemisphere virtually unimpeded by any large land masses. New Zealand lies between 34°04′S and 47°02′S and cuts across this westerly flow. Waves generated by these westerlies dominate the wave climate on most of New Zealand's coastline.

New Zealand is isolated from other large bodies of land. In almost every direction fetch conditions for wave generation are unlimited; Australia is the closest neighbour, 2000 km to the northwest, and for all but extremely rare events this represents unlimited fetch conditions for wave generation. As a result of the prevailing winds and fetch conditions the wave climate is a high energy one.

The sparsity of reliable wave records from around the New Zealand coast has largely restricted knowledge of the wave characteristics to general descriptions such as in global scale classifications (e.g., Davies 1964), in marine climatological summaries based on ship reports (e.g., Koninklijk Nederlands Instituut 1961, Hogben & Lumb 1967), and in sailing directions (e.g., Admiralty, Hydrographic Department 1971). However, over the last 15 years increasing interest has been shown in developing the resources of the narrow coastal zone and of the continental shelf, and largely as a result of this a considerable amount of reliable data has now been amassed on deep water wave conditions around New Zealand. In this paper data from a wide range of sources is drawn together to make some first order generalisations about the wave regime around the New Zealand coast.

SOURCE OF WAVE RECORDS

For nearly 60 years the N.Z. Meteorological Service has received reports of sea state conditions from various places around the coast. Although summaries of these have been produced from time to time (McLean 1968, Kirk 1972, 1973, 1974), "the utility of this qualitative 'sea state' data is limited—wave height (the vertical distance from the top of the crest to the bottom of the trough), wave period (the time between successive crests passing a given point) and wave direction are not specified" (McLean 1968, pp. 1–2). The location of the observing stations is very often far from ideal, frequently 5–250 m above the sea or at some distance inland, and Tomlinson (1971) concluded that "a large number of the reports received very probably are in error by an unknown and not insignificant amount". Sea state conditions are also reported by shipping. Unfortunately, the number of ships' reports in the New Zealand area

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is too small for accurate wave forecasting, particularly in the zones of wave generation to the south (Crawford 1974).

Before 1968 very little reliable wave data was collected; interest was centred on tracking ocean swells, originating in the Southern Hemisphere, across the Pacific Ocean (Munk *et al.* 1963, Snodgrass *et al.* 1966). Since 1968 the search for oil on the continental shelf, using rigs that remain on station in relatively deep water for several months, has enabled instrumental wave data to be collected. The recent development of production platforms has enabled this data to be collected on a more permanent basis. Other developments in the coastal zone have demanded information about the wave characteristics in specific areas; e.g., wave data have been collected in investigations for offshore terminals, for the protection of areas badly affected by coastal erosion, for the upgrading of existing port facilities, and for the development of new harbours.

Since 1965 increasing interest has also been shown in the geomorphology of the coastal zone. Most of these studies of shoreline dynamics have adopted a conceptual approach based on the process response model of Krumbein (1963), whereby the dynamics of the coastal zone are described in relation to controlling processes, the most important of which is wave activity. Wave information has been collected by shore-based observers. Most of this research has been carried out by postgraduate research students at the universities of Auckland, Canterbury, and Waikato.

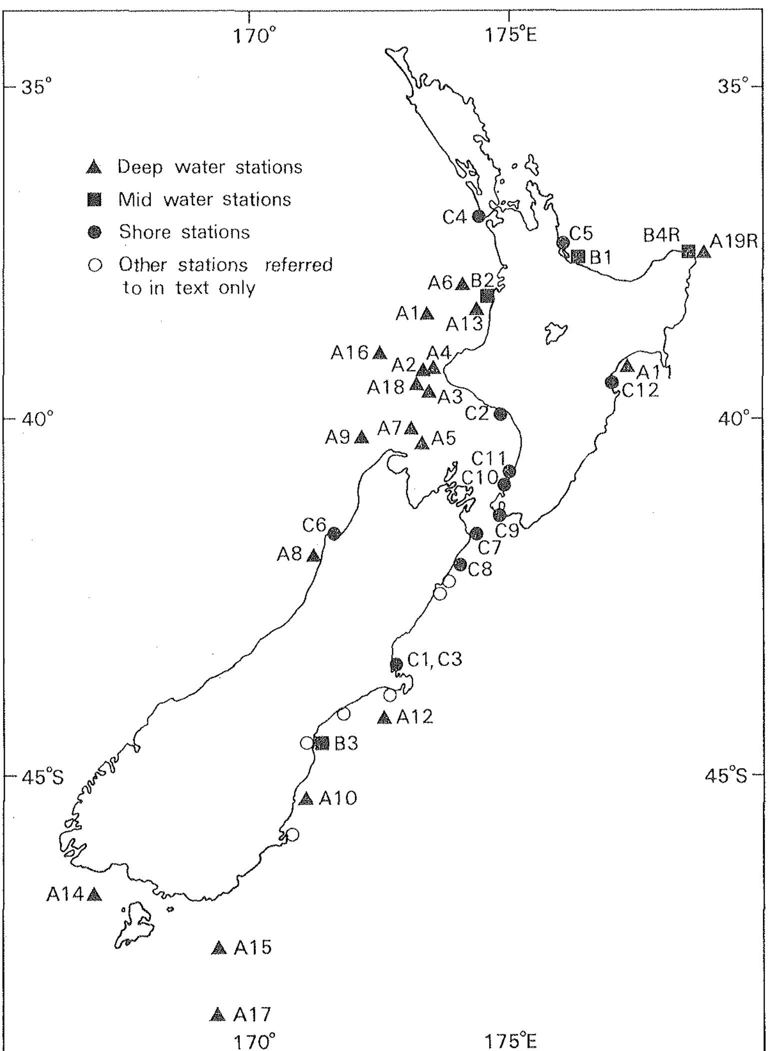


Fig. 1. Locations of stations around New Zealand at which wave data have been collected and referred to in text. Numbers refer to stations in Table 1.

DATA COLLECTED

The longest and most continuous period of instrumented wave recording in New Zealand has been at the site of the Maui Gas Platform off the Taranaki coast (Fig. 1 & Table 1). Barring occasional short gaps due to instrument problems a Datawell Wave-rider Buoy has been operational for 17 months. The hourly summaries of significant wave height (the average height of the highest one-third waves) and zero crossing period (the average period of all waves that cross the mean water level) used in the present analysis are the most comprehensive wave data recorded on the New Zealand coast. Wave records are still being collected from this site.

Wave data were also collected by all exploration rigs operating in New Zealand waters. Visual estimates of the sea height (sea being waves in the generating area), period, and direction and swell height (swell being waves that have moved out of the generating area), period, and direction are reported at 6-h intervals. Although there are omissions from this standard system all rigs reported swell height, period, and direction at least twice daily. The continental shelf between Farewell Spit and Cape Egmont is the best documented area; the *Discoverer-2, Sedco 135-F,* and *Penrod 74* rigs reported wave conditions on 765 days between November 1968 and December 1976 (Fig. 1 & Table 1). Comprehensive records are also available from *Penrod 74* from off the Southland coast (307 days). Records for shorter periods are available for the east coast of the South Island off north Otago from *Sedco 135-F,* off Banks Peninsula from the *Glomar Tasman,* and in Hawke Bay on the North Island's east coast. In addition to these visual estimates, the *Sedco 135-F* rig deployed a Datawell Wave-rider Buoy system at the various bore sites; both visual and recorded wave heights and periods are available from these sites making possible a comparison of the two techniques. Most of the rigs were operating in water depths greater than 50 m (Table 1). At such depths only nominal transformations of the wave form due to shoaling would take place (U.S. Army Coastal Engineering Research Center 1973) and, therefore, the rig records can be taken as generally representative of deep water wave conditions.

Shore-based observations are most plentiful along the east coast of the South Island with data available from a range of published and unpublished reports (Fig. 1 & Table 1). Significant wave height before breaker collapse, significant wave period (the average period of the one-third highest waves), and direction of approach are recorded by most observers. Data has also been collected from the west coast of the South Island, Wellington, Wanganui, Hawkes Bay, Bay of Plenty, and the west coast of the North Island. Included in these shore-based observations are the data collected by the Timaru Harbour Board (Hydraulic Research Station Wallingford 1970, Tierney 1977) and the Tauranga Harbour Board (Davies-Colley 1976) from pilot boats off the harbour entrances. The only data available for shore-based wave recorders on the open coast are those collected by the Ministry of Works and Development from two Datawell Wave-rider Buoys off Hicks Bay, East Cape and by Franklin (1973) from Taharoa on the west coast of the North Island. In all, the equivalent of nearly 17 years observations have been collected from the various onshore and offshore localities around the country.

Problems of the Available Records

Any attempt to draw comparisons between the various data sets either within one area or between different areas is fraught with difficulties. The biggest problem with most of the records is that the observation period is too short; regional and seasonal comparisons between data sets are difficult when only 5 of them cover a full 12 month period or longer.

Although the data collected by shore-based observers is more detailed than the 'sea state conditions' collected by the N.Z. Meteorological Service, the shore-based observations still suffer from subjectivity in having to depend on a visual observer; the rig-based data does not suffer to the same extent where wave height can be more easily measured against a fixed object. Most of the geomorphological studies specify that significant wave height has been observed. Unfortunately the rigs report only 'swell height'.

The shore-based observations are difficult to compare with each other. Each observation site has a unique nearshore bathymetry that controls the amount of wave refraction as waves enter shallow water and the resulting distribution of wave heights and directions of wave approach along the shore. For the same reason it is hard to make comparisons between shore-based and rig records.

Different collectors have used different units for recording wave characteristics. Wave period is always recorded to the nearest second and presents no problems. Direction of wave approach varies in the degree of accuracy with which it was measured; at the rigs it was recorded to the nearest 10°, but the shore-based observations are very often recorded to only 8 points of the compass. The measurement of wave height presents the biggest problem of comparison. The period for which records are available spans the period of conversion from imperial to metric units; the earliest records group wave heights into 1 foot intervals, the later ones into 1.0 or 0.5 m intervals and hence the two discrete recording intervals are not directly comparable.

Table 1. Summary of source, location, and period of observation of wave records from the New Zealand coast used in text. Br, Brown (1976); Bur, Burgess (1968, 1971); D–C, Davies-Colley (1976); DG, Del Grosso (1971); Fr, Franklin (1973) [thesis contains uncorrected data; corrected data made available by A. C. Kibblewhite, University of Auckland]; Har, Harray (1976); HRS, Hydraulic Research Stn, Wallingford (1970); Man, Mangin (1973); M.O., N.Z. Meteorological Office, ship reports; MWD, Ministry of Works & Development; Pi, Pickrill (1973); ShBPT, Shell, B.P. & Todd; St, Stephen (1974); WHB, Wellington Harbour Board; *, not included in total as duplicates visual periods; –, not applicable.

	Area	Position (°S)	Position (°E)	Depth (m)	Oil exploration data: Well	Oil exploration data: Rig	Dates of observation: Visual	Dates of observation: Wave recorder	No. days Vis.	No. days W.r.	Source
A: DEEP WATER RECORDS											
1	North Taranaki	38.5	173.3	159	Moa 1, 1A, 1B	*Discoverer-2*	8–10–68→19–1–69		104		M.O.
2	Taranaki	39.3	173.5	111	Maui 1	,,	20–1–69→27–3–69		66		M.O.
3	Taranaki	39.6	173.5	109	Maui 2	*Sedco 135F*	15–10–69→31–12–69		77		M.O.
3R					,,	,,		2–11–69→23–12–69		53*	ShBPT
4	Taranaki	39.3	173.6	109	Maui 3	,,	1–1–70→22–2–70		53		M.O.
4R					,,	,,		8–1–70→16–2–70		40*	ShBPT
5	Farewell Spit	40.3	173.4	79	Tasman 1	,,	7–3–70→26–3–70		20		M.O.
5R					,,	,,		8–3–70→24–3–70		17*	ShBPT
6	North Taranaki	38.2	174.2	91	Mangaa 1	,,	31–3–70→4–5–70		66		M.O.
6R					,,	,,		1–4–70→9–4–70		9*	ShBPT
7	Farewell Spit	40.1	173.2	104	Maui 4	,,	10–5–70→16–7–70		68		M.O.
7R					,,	,,		25–5–70→12–7–70		49*	ShBPT
8	Westland	42.2	171.2	27	Haku 1	,,	29–7–70→4–8–70		7		M.O.
8R					,,	,,		27–7–70→3–8–70		8*	ShBPT
9	Farewell Spit	40.3	172.2	127	Cook 1	,,	13–8–70→6–9–70		25		M.O.
9R					,,	,,		18–8–70→7–9–70		21*	ShBPT
10	North Otago	45.2	171.1	39	Endeavour 1	,,	24–10–70→6–12–70		44		M.O.
10R					,,	,,		29–9–70→22–11–70		21*	ShBPT
11	Hawke Bay	39.2	177.2	57	Hawke Bay 1	*Glomar Tasman*	25–11–75→12–1–76		49		M.O.
12	South Canterbury	44.2	172.5	74	Resolution 1	,,	5–7–75→5–8–75		32		M.O.
13	North Taranaki	38.5	174.4	58	Turi 1	*Penrod 74*	5–3–75→6–8–75		155		M.O.
14	Foveaux Strait	46.6	167.2	146	Parara 1	,,	17–11–75→3–2–76		80		M.O.
15	Southern N.Z.	47.4	169.5	488	Turoa 1	,,	31–3–76→1–10–76		185		M.O.
16	Taranaki	38.9	172.6	154	Tane 1	,,	10–10–76→29–12–76		80		M.O.
16R					,,	,,		18–10–76→31–10–76		14*	ShBPT
17	Southern N.Z.	48.2	169.5	681	Pakeha A	,,	20–2–77→2–4–77		42		M.O.
18R	Taranaki	39.5	173.4	110	Maui gas platform	–		15–3–76→31–12–77		606	ShBPT
19R	Hicks Bay	37.6	178.3	65	–	–		6–7–77→17–3–78		255	MWD
							Sub-total		**2014**		
B: MID-WATER RECORDS											
1	Tauranga Hbr	37.6	176.2		–	–	"1 year's records"		150		D–C
2	Taharoa Bch	38.2	174.7	12	–	–	3–6–71→30–9–71		120		Fr
3	Timaru Hbr	44.4	171.2		–	–	1–7–68→31–12–78		129		HRS
4R	Hicks Bay	37.6	178.3	12	–	–		6–7–77→17–3–78		255	MWD
							Sub-total		**654**		
C: SHORE-BASED RECORDS											
1	New Brighton, Pegasus Bay	43.5	172.7	-	-	-	22–12–67→24–4–68		123		Bur
2	C'cliff Surf Club, Wanganui	39.9	175.0	–	–	-	1–10–68→31–12–68		457		Bur
3	New Brighton, Pegasus Bay	43.5	172.7	–	–	-	5–11–75→30–4–76		177		Br
4	Piha Beach, Auckland	36.9	174.5	–	–	-	4–1–71→25–8–71		125		DG
5	Waihi Beach	37.4	175.9	–	–	-	1–4–74→9–5–75		395		Har
6	Westport Hbr	41.8	171.6	-	-	-	{1–1–52→31–12–52 {1–12–72→30–6–73		{353 {180		Man
7	Cape Campbell Lighthouse	41.7	174.3	–	–	–	20–4–73→31–5–73		43		Pi
8	Hapuku Delta	42.3	173.7	–	–	–	3–1–70→30–11–70		153		St
9	Beacon Hill, Wellington	41.3	174.8	–	–	–	20–9–76→22–1–78		436		WHB
10	Paekakariki	41.0	174.9	–	–	–	1–5–74→6–4–75		301		J. Gibb (MWD)
11	Waikanae	40.9	175.0	–	–	–	6–5–74→30–6–75		293		J. Gibb (MWD)
12	Marine Pde, Napier	39.5	176.9	–	–	–	7–74→11–75		496		K. Smith (MWD)
							Sub-total		**3531**		
							TOTAL		**6199** = *ca*	**17 years**	

All the data sets include measures of wave height, period, and direction, and the deep water observations from the rigs include simultaneous measurements of 'waves' and 'swell'. The 'waves' are not always recorded at the rigs, and when recorded are normally smaller than the swell; the analysis here is confined to the swell.

The above problems make it difficult to draw regional or seasonal comparisons from the data, but the data base is large enough to allow some preliminary generalisations about the ocean wave characteristics around New Zealand to be made.

WAVE DIRECTION

The frequency of wave approach directions for 15 stations around New Zealand is shown in Fig. 2. South of the country the prevailing wave approach direction in deep water is between south and northwest, with the greatest percentage in the sector from 245° to 285° (Fig. 2, A14, A15, A17). The westerly wind flow in the mid latitudes of the Southern Hemisphere dominates wave generation and the direction of wave travel south of New Zealand. A more southerly component is added to this direction by the tendency for ocean waves to travel in great circular paths around the globe (Munk *et al.* 1963, Snodgrass *et al.* 1966, Davies 1972).

The west coast of New Zealand, like the south coast, is a windward shore exposed to the prevailing westerly air flow. Direction of wave approach at the deep-water rigs is from the west through to southwest (Fig. 2, A13, A16, A3–9). Despite the effects of refraction, shore-based observations confirm this general direction of approach, e.g., at Piha on Auckland's west coast waves approach from south through to the west (Fig. 2, C4); at Wanganui, Burgess (1971) found the westerly quarter to be the prevailing approach direction; at Westport, Mangin (1973) found waves came from the northwest most of the time. However, the northerly aspect of the Westport coast probably means that such waves are anything from southwesterlies through to northerlies in deep water.

In terms of the dominant westerly air flow the east coast of New Zealand is almost a lee shore. However, the tendency for waves to travel in great circle paths around the globe, plus the alignment of the country in a northeast–southwest direction, means that waves generated south of New Zealand as westerlies turn northward to travel up the east coast of the country as southerlies and southwesterlies.

This is reflected in the southerly and southeasterly components in the deep-water records from *Glomar Tasman* in Hawke Bay and the Canterbury Bight (Fig. 2, A11, A12) and from *Sedco 135-F* off north Otago (Fig. 2, A10). The north Otago records also show a strong bimodality in approach directions with waves from the north through to northeast as well as from the south. This bimodality has been recorded by shore-based observers on the east coast of the South Island and is enlarged upon later.

Shore-based observations along the Otago (Elliot 1958, Hodgson 1966, Pattle 1974), Canterbury (Kirk 1967, Burgess 1968, Armon 1970, Hydraulic Research Station Wallingford 1970, Kelk 1974, Dingwall 1974, Brown 1976, Tierney 1977), Marlborough (Pickrill 1973, 1977, Stephen 1974, Kirk 1975), Wellington (Pickrill 1979) and Hawke Bay (Smith 1968) coasts have all recorded prevailing wave approach directions from the east through to the south which, in deep water before refraction, correspond to approach directions recorded in the southerly component at the three deep-water sites. Even in wave shadow areas on the northern side of the Otago, Banks, and Kaikoura peninsulas, the refracted southerly component is still recorded as prevalent within the wave environment (Hodgson 1966, Burgess 1968, Duckmanton 1974, Brown 1976).

The northeast coast of the North Island from North Cape to East Cape is sheltered from the prevailing westerly and southerly winds and waves that dominate the wave climate on the west and south coasts and influence the remainder of the east coast. Deep-water records from East Cape (Fig. 2, A19R) show the predominant approach direction to be from the north through to east. Similar prevailing directions have been reported from Tauranga (Davies-Colley & Healy 1978; Fig. 2, B1), from Waihi (Harray & Healy 1976), and from the east coasts of the Coromandel (Christophersen 1977) and Northland peninsulas (Gillie 1979). Weather systems pass across New Zealand from west to east, and associated northwesterly and southerly winds blow offshore on this northern coast. The northeasterly waves originate from tropical cyclones passing north of New Zealand, from blocking anticyclones, and from depressions moving down from the northwest, all of which produce strong northeast winds (Christophersen 1977, Gillie 1979).

Pullar & Selby (1971) suggested that the southerly swell of the east coast may be refracted around East Cape into the Bay of Plenty. However, the continental shelf off East Cape is less than 4 km wide (Cullen 1977), restricting the refraction of wave energy around the cape, while the tendency for waves to travel in great circle paths means that this swell is travelling toward the northeast. The refraction of southerlies into the Bay of Plenty is most unlikely.

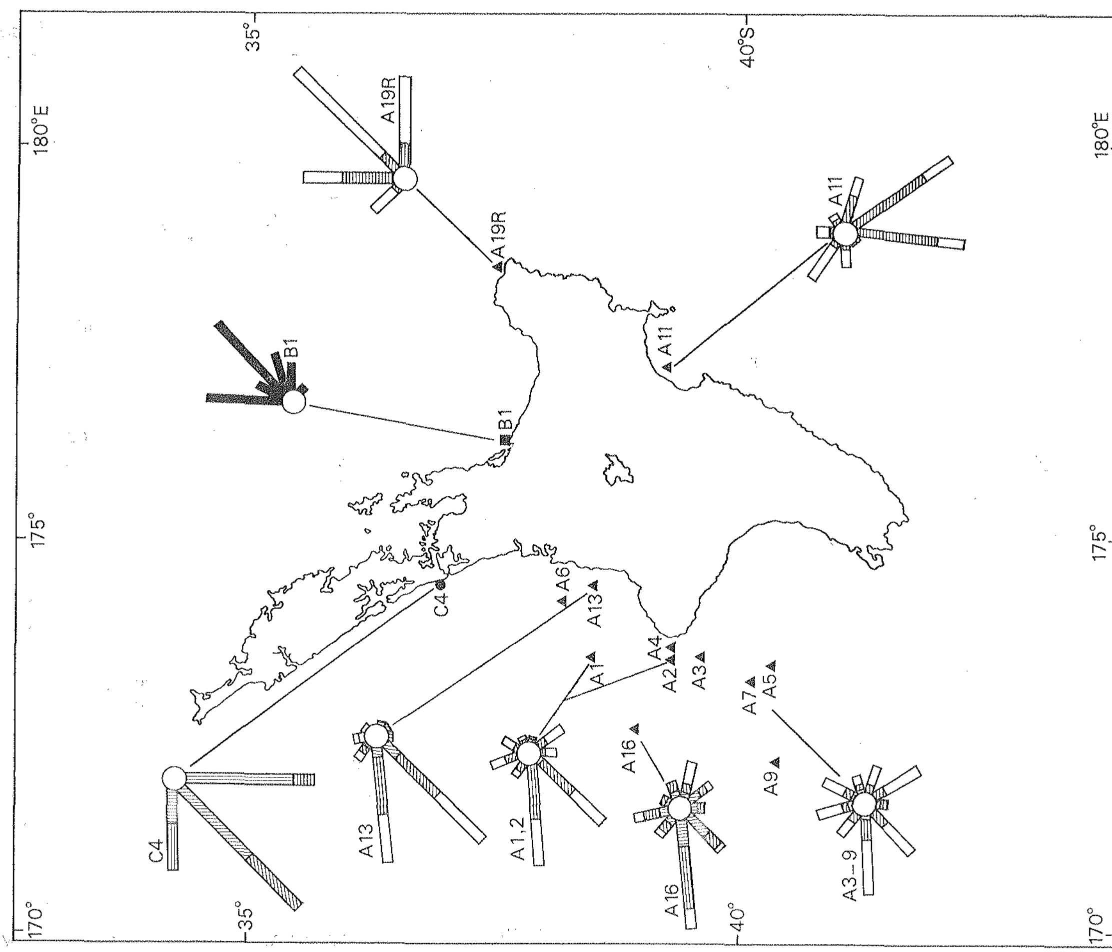
WAVE HEIGHT

The records from the oil rigs are the most reliable indicators of deep-water wave heights around New

Zealand, particularly since the southerly through to westerly waves approach much of the shoreline obliquely and undergo extensive refraction. Other studies have shown the distributions of wave heights in the open ocean to be very much greater than in coastal waters (e.g., King 1972, p. 48), and, as might be expected, the distribution of wave heights at the rigs is higher than at the shore.

Records from the three *Penrod 74* sites off the Southland coast give some idea of the extreme energy conditions generated by the westerlies in the unlimited fetch conditions of the southern oceans (Fig. 3, A14, A15, A17). Mean wave height was 4.0 m at the two most southerly sites and 3.7 m in the western approaches to Foveaux Strait (Table 2). At the southernmost site wave height fell beneath 2.0 m for less than 3% of the time and exceeded 10 m 1.7% of the time.

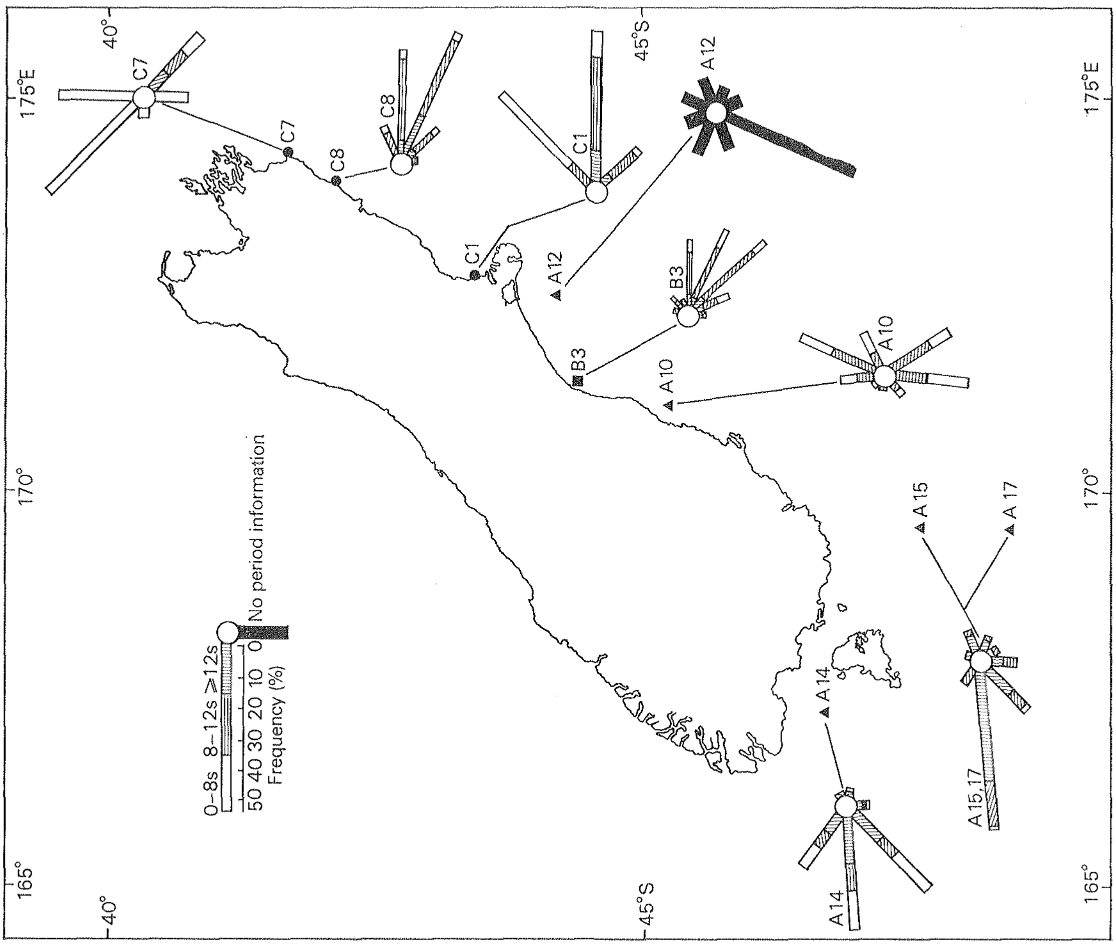
Wave heights estimated by the *Discoverer, Sedco 135–F,* and *Penrod 74* rigs off the west coast of New Zealand all have similar distributions; mean wave heights of 2.2, 2.4, 2.5, and 2.8 m were recorded at four stations (Fig. 3, A1–2, A3–9, A13, A16). At the Maui production platform the average significant wave height recorded by the Datawell Wave-rider Buoy was 2.5 m (Fig. 3, A18R). Although the west coast may be a windward shore, wave heights are clearly much lower than off the southern coast of New Zealand. Mean wave heights recorded by shore-based observers along the west coast of both islands are typically half those recorded in deep water. Mean wave height at Piha was 1.0 m (Del Grosso 1971), 1.8 m at Taharoa (Franklin 1973), 1.2 m at Wanganui (McLean & Burgess 1974) and 0.9 m at Westport (Mangin 1973) (Fig. 3, C4, C6). Only at Taharoa were waves greater than 3.0 m recorded at the shore.

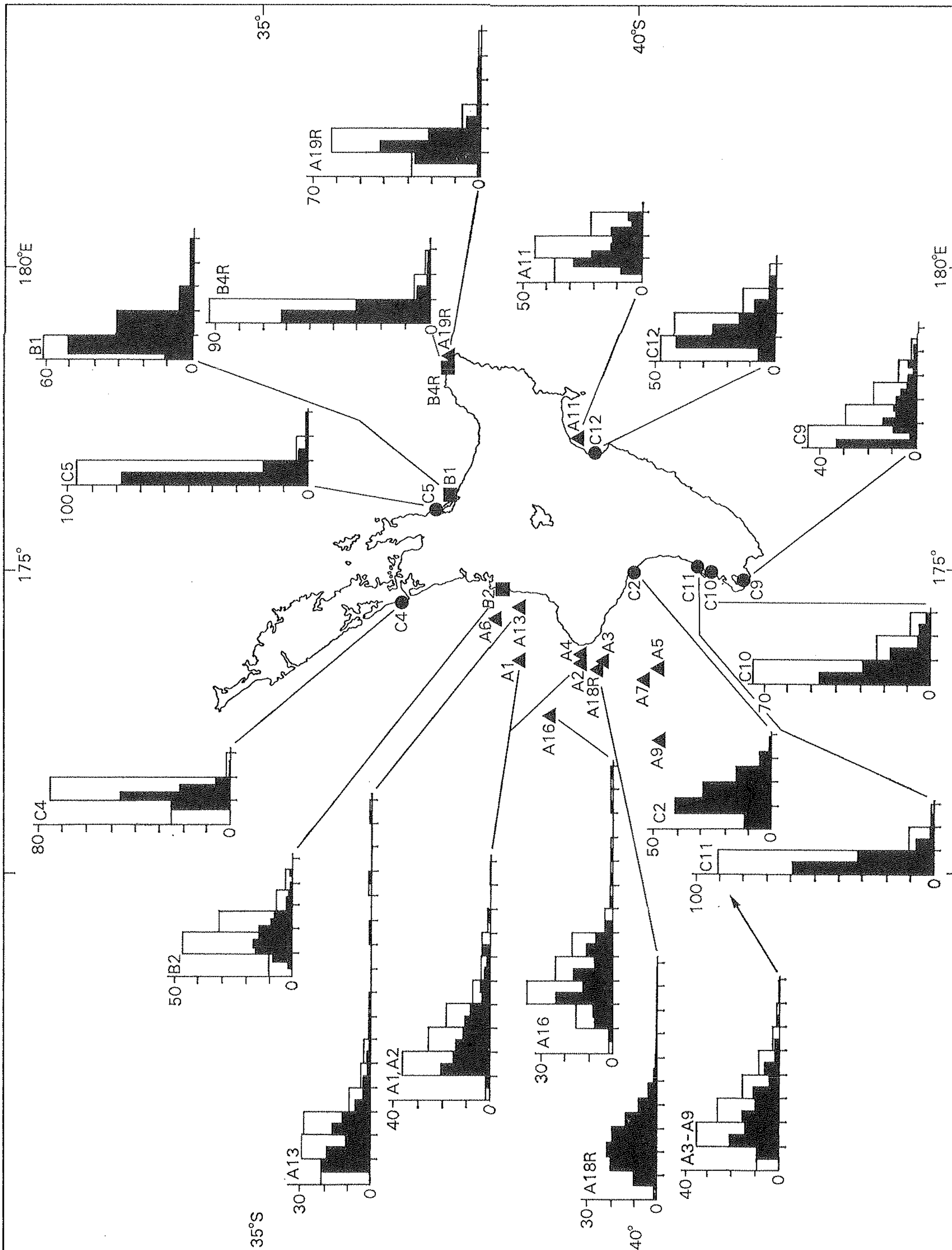


The west Wellington coast and north coast of the South Island are in the wave shadow behind Farewell Spit and wave heights are correspondingly much lower (Fig. 3, C10, C11).

The visual records from the *Sedco 135–F* and *Glomar Tasman* rigs show that the east coast of New Zealand has lower wave heights than the west coast; mean wave heights of 1.7 m were recorded off north Otago, 2.4 m in the Canterbury Bight, and 1.2 m in Hawke Bay (Fig 3, A10, A11, A12). Off the entrance to Timaru Harbour mean wave heights of 1.3 m were recorded (Hydraulic Research Station Wallingford 1970) (Fig. 3, B3). The shore-based observations do not show such a contrast between the east and west coasts; typical distributions show mean heights to be 1.4 m at Timaru (Kirk 1967), 1.0 m in Pegasus Bay (Fig. 3, C1, C3; Burgess 1968, Brown 1976), 0.7–1.3 m on the Hapuka River delta (Fig. 3,

Fig. 2. Percent frequency direction of wave approach in three groups of wave period; 0–8 s, 8–12 s, and > 12 s.




35°
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A13
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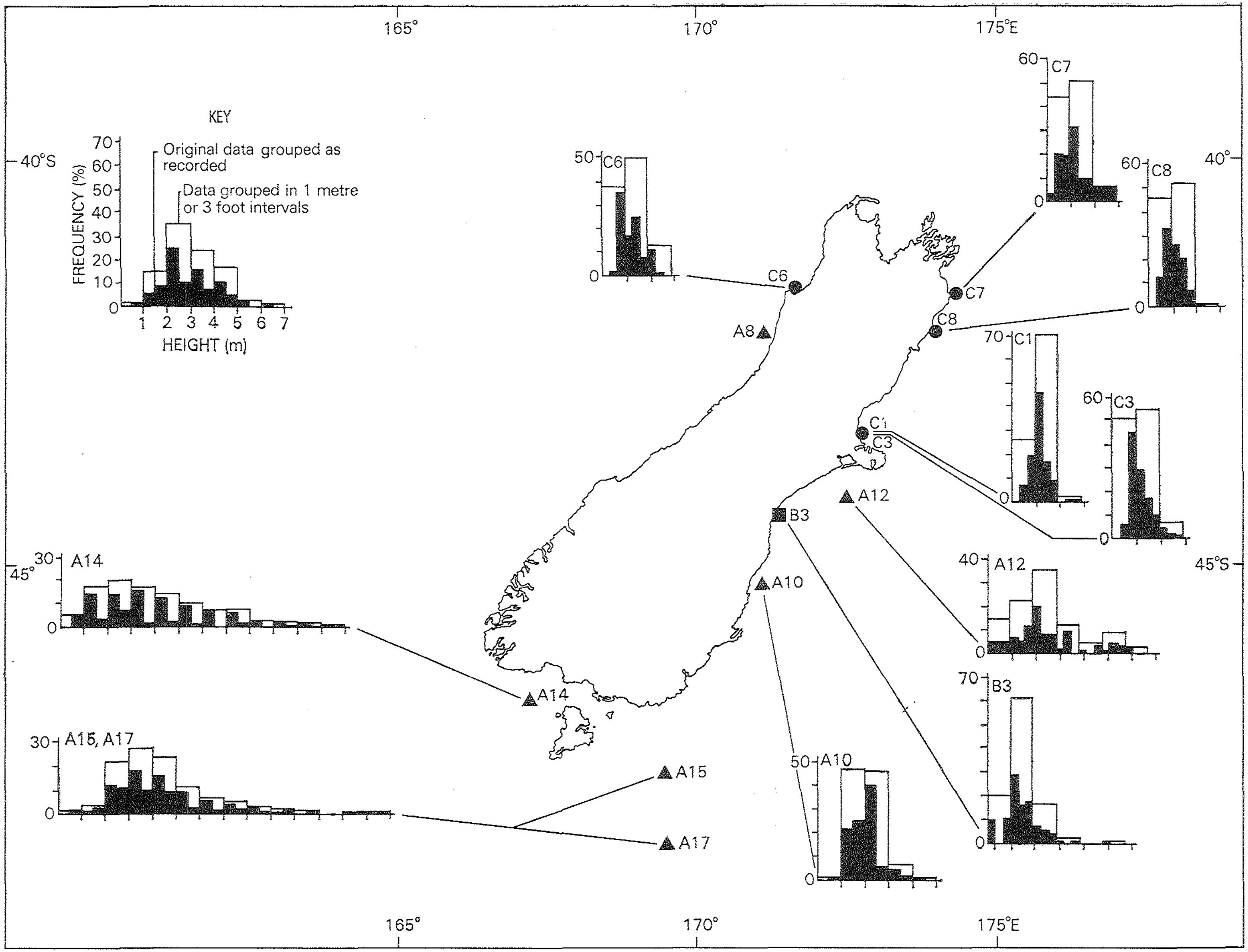


Fig. 3. Percent frequency distribution of wave heights around New Zealand. Numbers refer to stations in Table 1

C8; Stephen 1974), 0.9 m at Cape Campbell (Fig. 3, C7; Pickrill 1973, 1977), 1.2 m on the south Wellington coast (Fig. 3, C9; Pickrill 1979) and 1.2 m in Hawke Bay (Fig. 3, C12). Storm waves on the east coast rarely exceed 3 m (Fig. 3, B3, C1, C3, C7, C8, C12) except on the south Wellington coast where southerly wave trains arrive at the shore unrefracted and storm waves may exceed 4 m. Similar height distributions have been reported from other stations on the east coast of the South Island (Elliott 1966, Hodgson 1966, Kirk 1967, Armon 1970, McLean 1971, Kelk 1974, Duckmanton 1974, Pattle 1974) and from Hawke Bay (Smith 1968).

Records show the north coast of New Zealand to have lower wave heights than the south, west, or east coasts. Mean heights of 1.4 m were recorded in deep water off East Cape and storm waves rarely exceed 3 m (Fig. 3, A19R). In shallower water, mean heights of 0.5 m and 0.8 m were recorded in Hicks Bay and off Tauranga respectively, while further north on the beach at Waihi the mean height was only 0.4 m (Fig. 3, B1, B3, C5). Storm waves at the shore probably exceed 2.5 m only occasionally.

Although little is known of the wave characteristics on the east coast of the Auckland Peninsula, inferred wave energy levels from the distribution of sediments on the continental shelf (Schofield 1970) show that the east coast of the peninsula is subject to much lower energy levels than the west coast. The east Auckland wave climate is probably broadly similar to that in the Bay of Plenty.

WAVE PERIOD

Wave period is less affected by wave refraction than wave height and direction. However, open ocean studies in the Northern Hemisphere have shown that wave period at the coast is longer than in the open ocean (e.g., King 1972, p. 49). The shorter period waves are probably attenuated by the time they reach the coast. Wave periods recorded at the rigs are generally shorter than at the nearby coastal

Table 2. Summary of wave height statistics for stations shown in Table 1. η, number of observations; $H\frac{1}{3}$, significant wave height; T_z, wave period; D, wave direction; H/T, wave steepness; xT_z, mean wave period; $xH\frac{1}{3}$, mean wave height.
†, data on figures; +, data in text; *, data not used; –, no data.

	η	T_z	$H\frac{1}{3}$	D	H/T	xT_z	$xH\frac{1}{3}$
A1, 2	613	†	†	†	†	7.49	2.40
A3–9	778	†	†	†	†	7.05	2.52
A3R–5R, 7R	1081	+	+	–	*	7.13	1.82
A6R	66	+	+	–	*	6.89	2.08
A8R	47	†	+	–	*	8.43	2.49
A9R	109	+	+	–	*	7.22	2.69
A10	106	†	†	†	†	7.40	1.77
A10R	115	+	+	–	*	7.71	1.35
A11	253	†	†	†	†	7.76	1.25
A12	63	–	†	†	–	–	2.38
A13	505	†	†	†	†	8.34	2.21
A14	342	†	†	†	†	> 9.67	3.70
A15, 17	825	†	†	†	†	>12.60	4.01
A16	259	†	†	†	†	10.73	2.85
A16R	319	+	+	–	*	6.66	2.56
A18R	12066	†	†	–	†	6.69	2.53
A19R	1918	†	†	†	†	6.47	1.36
B1	150	–	†	†	–	–	0.96
B2	331	†	†	–	†	12.80	1.80
B3	127	†	†	†	†	9.37	1.33
B4R	1145	†	†	*	†	7.17	0.49
C1	146	†	†	†	†	8.57	1.04
C2	457	†	†	*	–	10.23	1.30
C3	300	†	†	*	†	8.82	1.02
C4	124	†	†	†	†	11.89	0.96
C5	394	†	†	*	†	11.13	0.39
C6	334	†	†	*	–	9.57	0.89
C7	80	†	†	†	†	4.86	0.89
C8	155	†	†	†	†	9.77	0.91
C9	917	†	†	*	†	8.82	1.21
C10	301	†	†	*	†	6.78	0.75
C11	293	†	†	*	†	6.66	0.52
C12	496	†	†	*	†	11.02	1.22

stations (Fig. 4). The differences between the deep and shallow water wave periods are accentuated by differences in the techniques of data collection; zero crossing period, as calculated from the deep water records, is biased to the shorter periods but the significant period as used by visual observers is biased to the longer periods.

Off the south coast, wave periods are the longest recorded around New Zealand; more than 50% of the waves were longer than 14 s (the highest recording interval reported), and less than 3.5% were shorter than 8 s (Fig. 4, A15, A17). It was not possible to calculate mean wave period, but it is longer than 12.5 s (Table 2). At the more northerly *Penrod 74* site, in the entrance to Foveaux Strait (Fig. 4, A14), wave periods are slightly shorter.

Wave periods are shorter off the west coast. The period most frequently reported by the rigs was 6–9 s; in deep water wave period rarely exceeds 12 s (Fig. 4, A1–2, A3–9, A8R, A13, A16, A18R). Mean wave period typically ranged between 6.7 and 8.3 s. (Site A16 provides the exception to this otherwise consistent pattern from west coast rig data.) The shore-based stations generally reported longer periods than the rigs with means of 8.3 to 12.8 s. (Fig. 4, B2, C2, C4, C6). Very few waves with periods greater than 16 s or shorter than 7 s were reported.

Deep water wave periods recorded off the east coast of New Zealand are broadly similar to those off the west coast (Fig. 4, A10, A11). Waves with a period of 8 s are the most common with mean periods of 7.8 and 7.5 s. Wave periods recorded on shore are longer and show a consistently similar distribution from Hawke Bay through to Otago. On the Otago Peninsula, Hodgson (1966) found that 81% of all observations fell within the 6–12 s range. Records from Timaru (Fig. 4, B1), the Canterbury Bight (Kelk 1974), Pegasus Bay (Fig. 4, C3, C1), the Hapuka delta (Fig. 4, C8), the Kaikoura Peninsula (Duckmanton 1974), the Wellington south coast (Fig. 4, C9) and Hawke Bay (Fig. 4, C12) all have more than 81% within this range. Typically the mean and prevailing periods both range between 8 and 9 s. The Cook Strait records (Fig. 4, C7) are slightly anomalous with a mean period of 4.9 s and a bimodal distribution reflecting local northerly waves generated in restricted fetch conditions within Cook Strait and longer period southerlies (Pickrill 1977).

Off the north coast of New Zealand, wave periods in deep water are broadly similar to those recorded on the east and west coasts, with a mean of 6.5 s and a range of 6–9 s for most of the time (Fig. 4, A19R), shoaling transformations lengthen this period in shallower water (Fig. 4, B4R). On the beach at Waihi, mean periods are 11 s with a range of 5–15 s (Fig. 4, C5).

SEASONALITY

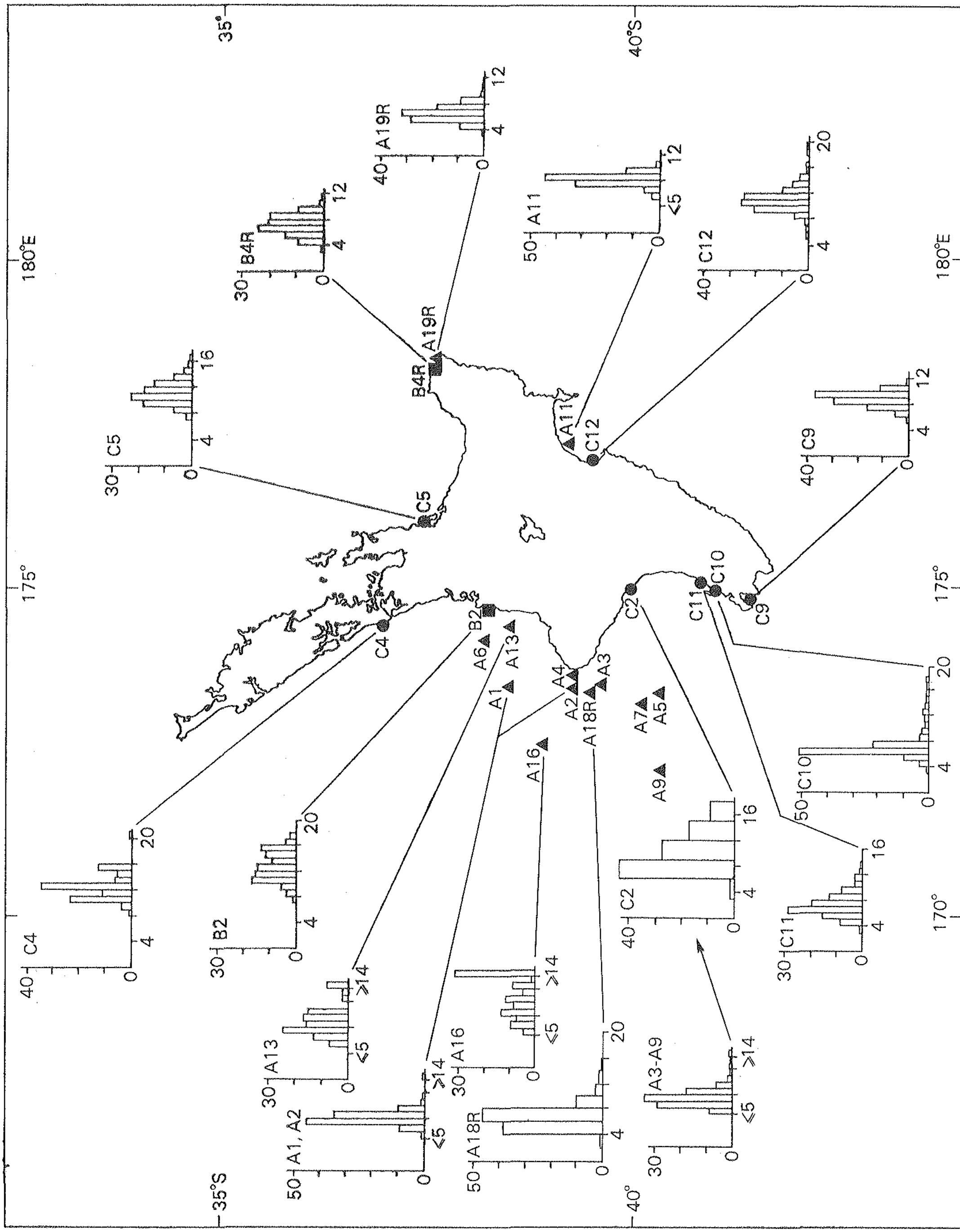
Wave studies in the Northern Hemisphere commonly stress seasonal differences in the wave climate; increased storminess in winter results in a predominance of high energy, steep storm waves in winter and lower energy, less steep swell waves in summer. The available information on the New Zealand coast suggests this is not so in the Southern Hemisphere.

Very few of the wave data collected extend over long enough periods to make a discussion of seasonality meaningful. Only one of the exploration rigs (Table 1, A15) stayed on station for more than 6 months and 10 of the shore-based observers extended their observations for this period or longer. The most useful results are those from the Maui platform spanning a nearly continuous 17 month period.

South of New Zealand, seasonal patterns are difficult to identify. Wave heights increase in winter while wave periods lengthen (Fig. 5A, A15, A17); there may be a winter increase in wave energy. Although it is difficult to make firm conclusions based on only a little over 6 months' records, the distribution of heights and periods from the preceding summer in the entrance to Foveaux Strait (Figs. 3 & 4, A14) support the suggestion of slightly longer periods and longer heights during the winter months. The lower heights and periods in summer are associated with waves from a wider range of directions (Fig. 5A); in winter and autumn, when the belt of strongest winds in the westerly air flow lies across southern New Zealand, the dominant direction of wave approach is from the west or southwest; in summer, when the belt of strong westerlies moves southward, winds and waves from other directions can be generated.

A seasonal breakdown of the Maui data in Fig. 5B shows little variation in the distribution of wave heights and periods on the west coast. Visual observations from this coast also failed to identify any clearly defined seasonality in wave height, period, steepness, or direction (Burgess 1971, Del Grosso 1971, Mangin 1973). Storm events, which are not seasonal, and day-to-day changes are the dominant controls of the wave climate on this coast.

The wave environment on the east coast is made up of waves from two directions, northeast and south; seasonality reflects a change in the proportion of waves from these directions. This seasonality is most fully developed on the south Wellington coast, which is completely sheltered from northerly waves by the land mass of the North Island. As a result, waves approach this coast only from the south. In a seasonal breakdown of 14 months' records, Pickrill (1979) demonstrated a seasonal cycle in this southerly component, with an increase in the frequency of


35°
40°S
180°E
175°
170°
35°S
40°
C4
B2
A13
A1, A2
A16
A18R
A3-A9
C2
C11
C10
C9
C12
A11
A19R
B4R
C5

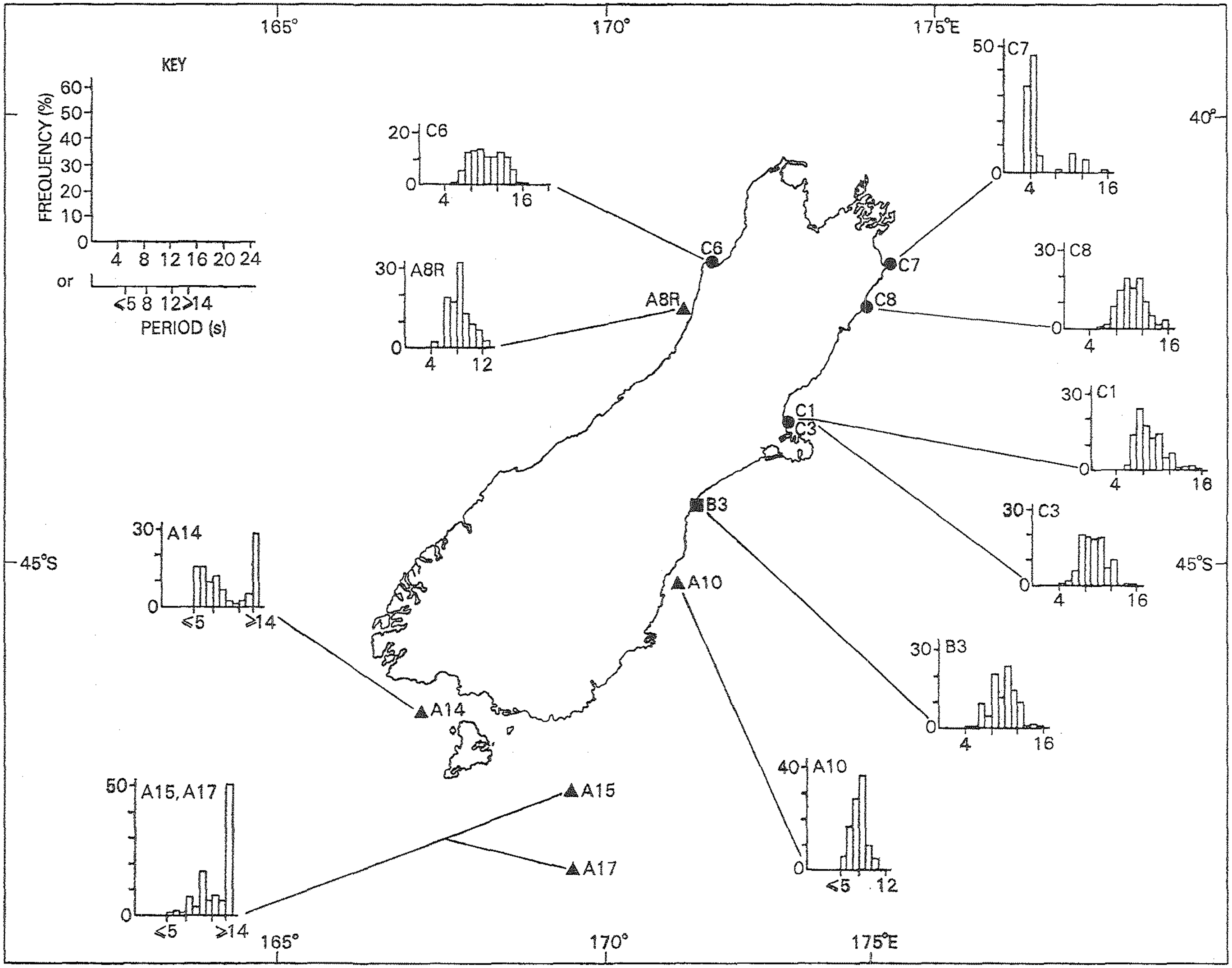


Fig. 4. Percent frequency distribution of wave period around New Zealand. Numbers refer to stations in Table 1.

southerlies in winter (reflected in a decrease in the frequency of calms) and an increase in wave height from 1.5 m in summer to 2.0 m in winter.

Seasonality on the rest of the east coast is not so well defined. In Pegasus Bay, the Canterbury Bight, off the Otago Peninsula and Hapuka delta, a slight winter increase in the frequency of waves from the south has been recorded (Hodgson 1966, Kirk 1967, Burgess 1968, Stephen 1974, Brown 1976), along with a small increase in wave height and wave period (except in Pegasus Bay where wave heights are uniform throughout the year in the wave shadow behind Banks Peninsula). This seasonality is brought about by an increase in the proportion of locally generated northeasterlies in summer (Brown 1974, Carter & Herzer 1977) with shorter wave periods and lower wave heights. Seasonality reflects a change in the proportion of waves from the two directions—there is no change in the range of wave characteristics between seasons; long period, high energy southerlies and shorter period northeasterlies may come at any time of the year.

Gillie (1979) analysed 9 years' records of sea state conditions from Leigh on the north coast, and showed spring and early summer to be the calmest periods, with an increase in storminess in winter paralleling an increase in the frequency of subtropical depressions. However, further south in the Bay of Plenty there is no evidence for seasonality in the wave environment; storm events appear to be the dominant influence (Harray 1976).

SHORT PERIOD CYCLICITY

Although there are no overriding, strong, seasonal rhythms in the wave climate as in the Northern Hemisphere, there may be a shorter period cyclicity associated with the passage of weather systems across New Zealand. The day-to-day weather in New Zealand is largely controlled by an eastward-moving sequence of anticyclones and troughs of low pressure. The interval between successive low pressures is very variable and a steady, quasi-cyclic rhythmic pattern with a fairly constant interval of 5–11 days between successive troughs of low pressure may develop (Tomlinson 1976). The low pressure systems are generally associated with unsettled weather and strong winds—ideal for wave generation—and the intervening highs are associated with more settled weather and low wind speeds less favourable for wave generation. The quasi-cyclic rhythmic pattern in the weather might be expected, therefore, to be reflected in the wave climate.

In a detailed spectral analysis of wave records from the Maui platform (Stn A18R) R. B. Davies & R. A. Pickrill (unpubl. results) show that there is a 5-day cycle in wave heights, and a similar 5-day cycle in surface barometric pressures recorded over the same period at New Plymouth airport 80 km to the east. Cross-spectral analysis between these two series shows that there is a statistically significant relationship between the two when wave heights are lagged by roughly 1 day. Periods of high pressure with settled weather and low wind speeds are associated with low wave heights; periods of low pressure with unsettled weather and strong winds are associated with greater heights. There is, therefore, a relationship between short period cyclic weather patterns and the wave heights on the west coast of New Zealand.

A similar analysis of wave height and surface atmospheric pressure values from the Penrod rig (Stn A15) south of New Zealand failed to produce any significant frequencies in either series (R. B. Davies & R. A. Pickrill unpubl. results), but there is some coherence between the two series. In a less rigorous analysis of records from Pegasus Bay, 6–7-day cycles of wave height and direction have been identified (Brown 1976).

Direct relationships between wind and wave direction, and between wave height and wind speed, exist on the east coast of the South Island (Pickrill 1977). From the strength of these relationships it can be shown that the northerly is a locally generated wave, and that the southerly is a mixture of swell travelling into the area from the south and locally generated seas. These relationships are most fully developed in southern Cook Strait (Pickrill 1977) but are also identifiable in Pegasus Bay (Brown 1976) and off the north Otago coast (Pattle 1974).

REGIONAL WAVE CLIMATE OF NEW ZEALAND

From the above discussion of wave characteristics, four broad regional groupings can be distinguished. These can be identified most easily using a bivariate plot of wave height against wave period, similar to that proposed by Draper (1966) and adopted by the U.S. Littoral Environmental Program (LEO) as a standard method of portraying wave data (Balsillie 1975). Lines of constant wave steepness (H/L) have been plotted on these graphs (Fig. 6) on the assumption that:

$$L = 1.26T^2$$

where L is wave length (m) and T is wave period (s).

Southern New Zealand

South of New Zealand the wave environment is of extremely high energy, the prevailing deep water wave being a westerly through to southwesterly, 3.5–4.5 m high and 10–12 s period (Fig. 7). Very rarely do wave heights and periods drop beneath 2 m and 6 s respectively. However, the range of con-

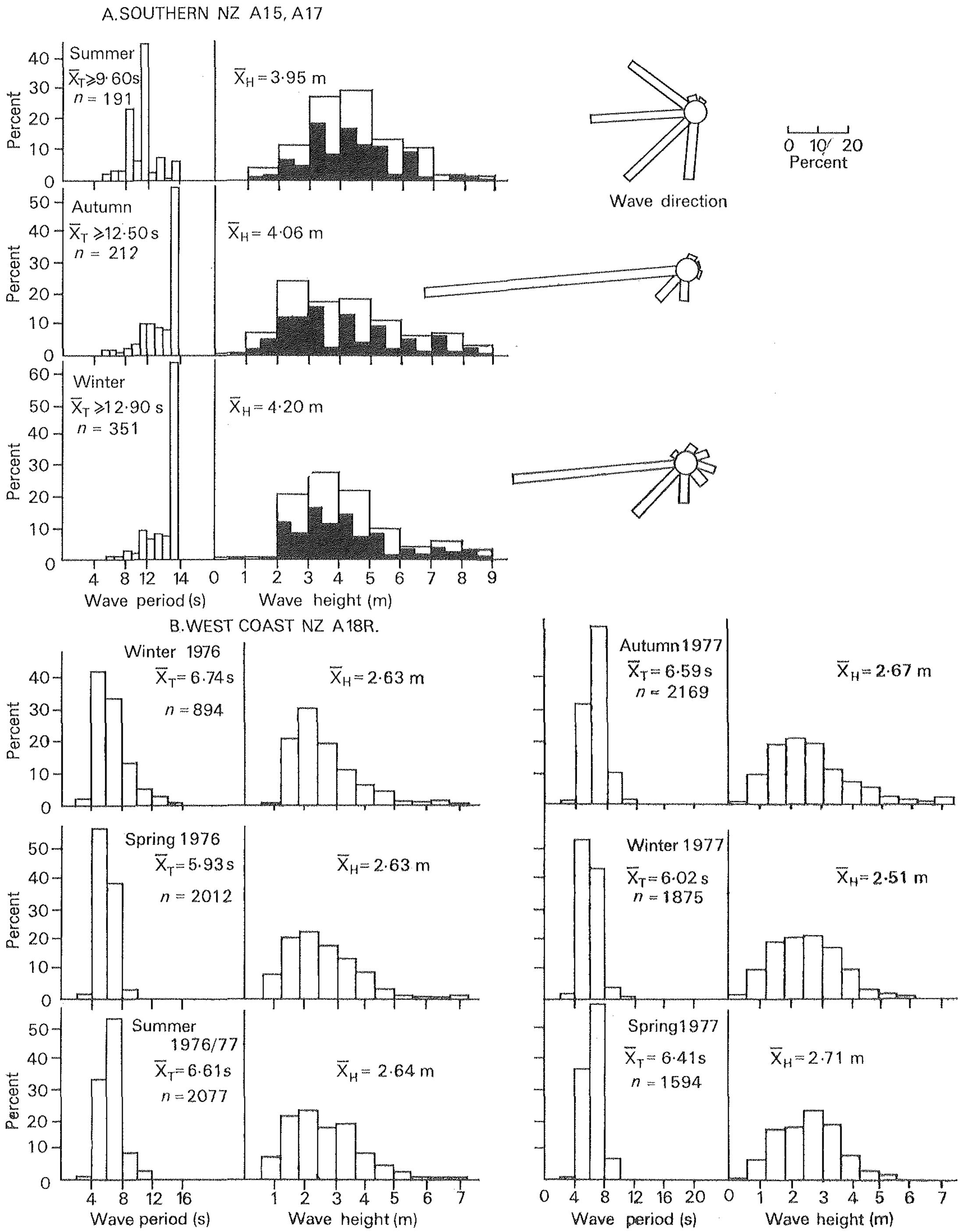
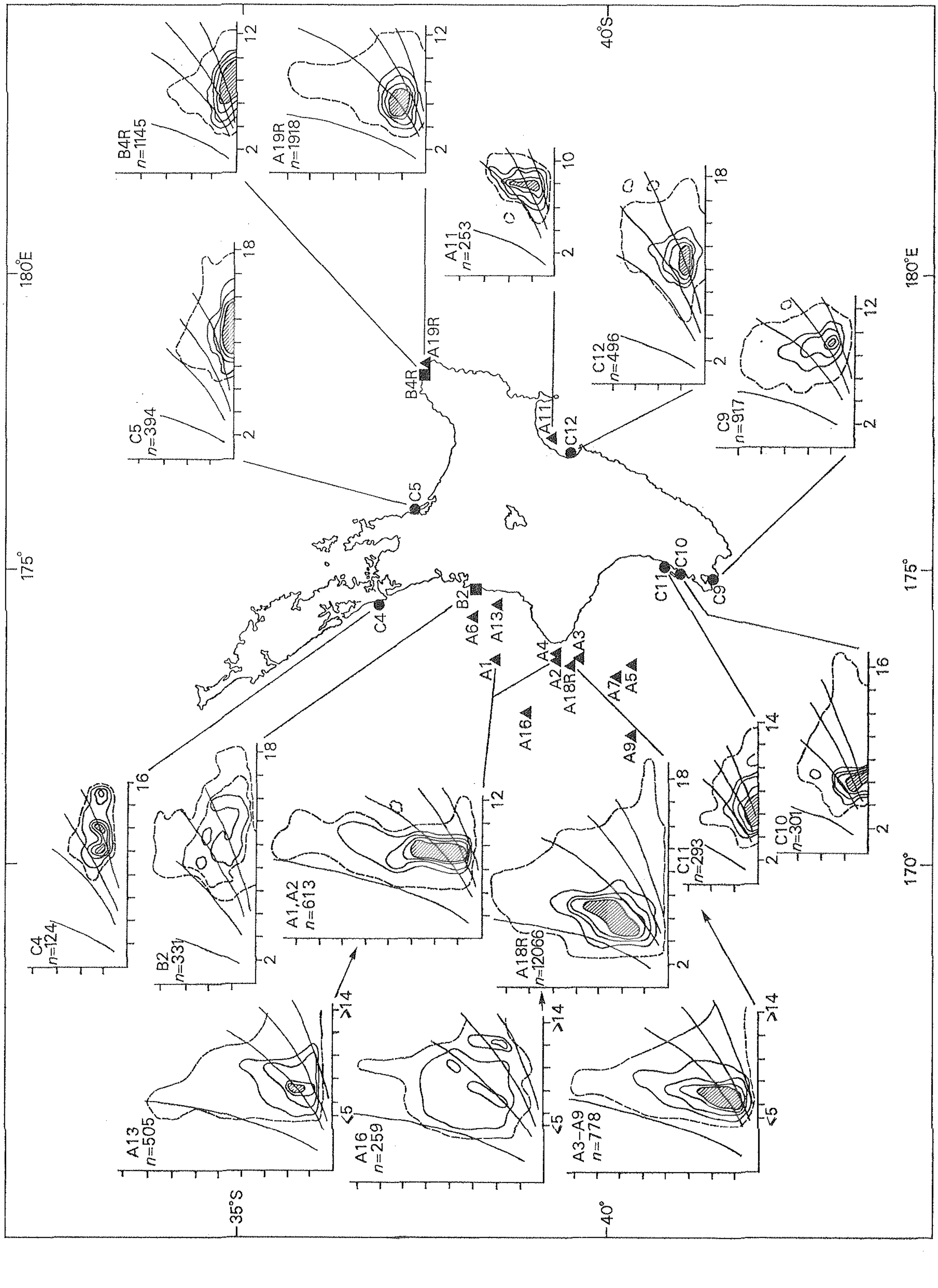


Fig. 5. Seasonal breakdown of wave height, period, and direction for (A) southern New Zealand, (B) western New Zealand. Seasons defined as: summer—Dec, Jan, Feb; autumn—Mar, Apr, May; winter—Jun, Jul, Aug; spring—Sep, Oct, Nov.



B4R n=1145
A19R n=1918
A11 n=253
C5 n=394
C12 n=496
C9 n=917
C4 n=124
B2 n=331
A1,A2 n=613
A18R n=12066
C11 n=293
C10 n=301
A13 n=505
A16 n=259
A3–A9 n=778
B4R
A19R
A11
C12
C5
C10
C11
C9
C4
B2
A6
A13
A1
A4
A2
A3
A18R
A7
A5
A16
A9
180°E
175°
170°
35°S
40°S
40°

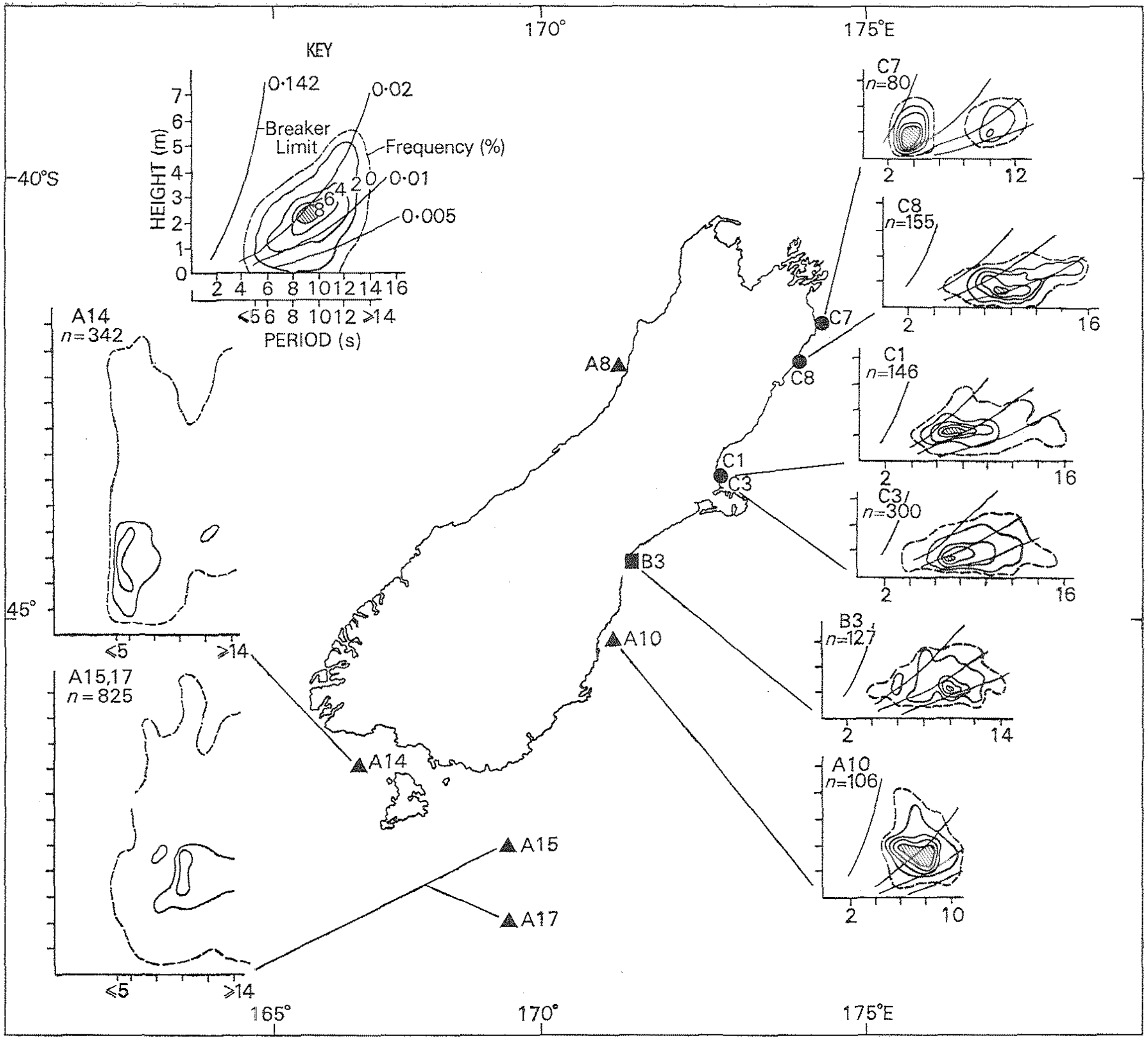


Fig. 6A. (*above*) Scatter diagrams relating wave height to wave period contoured in terms of percent frequency distribution. Stns A11, B2, C4, & C9 plotted by 1 foot to 1 s areas; stns A19R, B4R, C5 C10, C11, & C12 plotted by 0.5 m to 1 s areas; stns A1–2, A3–9, A13, & A16 plotted by 1 m to 1 s areas; stn A18R is plotted by 2 ft to 2 s areas. Contour values not comparable, but general distributions are. Lines of constant wave steepness and breaker limit delineated.

Fig. 6B. (*left*) Scatter diagrams relating wave height to wave period contoured in terms of percent frequency distribution. Stns B3, C1, C3, C7, & C8 plotted by 1 foot to 1 s areas; stn A10 plotted by 0.5 m to 1 s areas; stns A14, A15, & A17 plotted by 1 m to 1 s areas. Contour values not comparable, but general distributions are. Lines of constant wave steepness and breaker limit delineated.

ditions is extremely variable and almost every possible combination of wave height up to 11 m and wave period up to and over 14 s has been recorded. Wave steepness ratios are high (typically > than 0.02) indicating that the oceans south of New Zealand are a zone of active wave generation rather than a swell-wave environment. A winter increase in wave height and wave period is probably associated with small seasonal variations in both the strength of the mid-latitude westerlies and in latitudinal shifts in the zone of strongest winds.

Western New Zealand

Off the west coast of central New Zealand the prevailing deep water wave is a southwesterly through to westerly, 1.0–3.0 m high, and 6–8 s period (Fig. 7). Shoaling transformations change this to a 0.5–1.5 m, 9–12 s wave, when observed from the beach.

The west coast, like the south coast, is a windward shore; wave steepnesses are high and reflect active wave generation under the prevailing westerlies. However, in these more northerly latitudes the westerlies are not as strong; this is reflected in the smaller wave heights and periods.

There are no strong seasonal cycles in the wave climate; short period (5 day), rhythmic fluctuations associated with the passage of weather systems across the Tasman Sea are more important. As a result the wave climate is mixed, with locally generated storm waves and longer period swell originating from high energy storm centres to the south (Munk *et al.* 1963, Snodgrass *et al.* 1966).

Eastern New Zealand

The landmass of New Zealand shelters the east coast from the prevailing westerlies. The prevailing deep water wave is a southerly, 0.5–2.0 m high and 6–9 s period. Onshore this is transformed into a 0.5–1.5 m, 7–11 s wave (Fig. 7). The orientation of the country on a northeast–southwest axis produces a mixed wave climate; westerlies generated south of New Zealand move up the east coast as the prevailing swell (reflected in lower wave heights and wave steepness than on the west coast), and locally generated waves originate from the north through to the south.

A slight winter increase in wave height and wave period associated with an increase in the frequency of locally generated northerlies and a decrease in the frequency of southerlies in summer suggest a weak seasonality in the wave climate.

Although the west, south, and east coasts of New Zealand are all high energy shorelines, wave heights are reduced in localised areas sheltered from the west and south. In particular, the west Wellington coast (Figure 8, C10, C11), the northern coast of the South Island, and the northern sides of the Otago, Banks, and Kaikoura peninsulas and Capes Campbell and Kidnappers are all lower energy lee shores (Gibb 1962, Hodgson 1966, Burgess 1968, Gibbard 1972, Pickrill 1977).

Northern New Zealand

The shortage of data from northern New Zealand makes it difficult to draw firm conclusions about the wave environment between North and East capes. However, like the northern coast of the South Island, it is a lee shore sheltered from the prevailing westerly and southerly waves. As a result wave heights are smaller than on the other three coasts. The prevailing deep water wave is a northerly through to easterly 0.5–1.5 m high and 5–7 s period; at the beach this is probably transformed into a 0.4–0.8 m, 9–12 s wave (Fig. 6). Wave steepnesses are similar to those off the East Coast indicating a similarly mixed, but lower energy storm and swell wave environment. Swell-waves probably originate from subtropical disturbances north of New Zealand and shorter period seas are generated by local weather patterns. A winter increase in the frequency of storms suggests there may be a weak seasonality in this wave environment.

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