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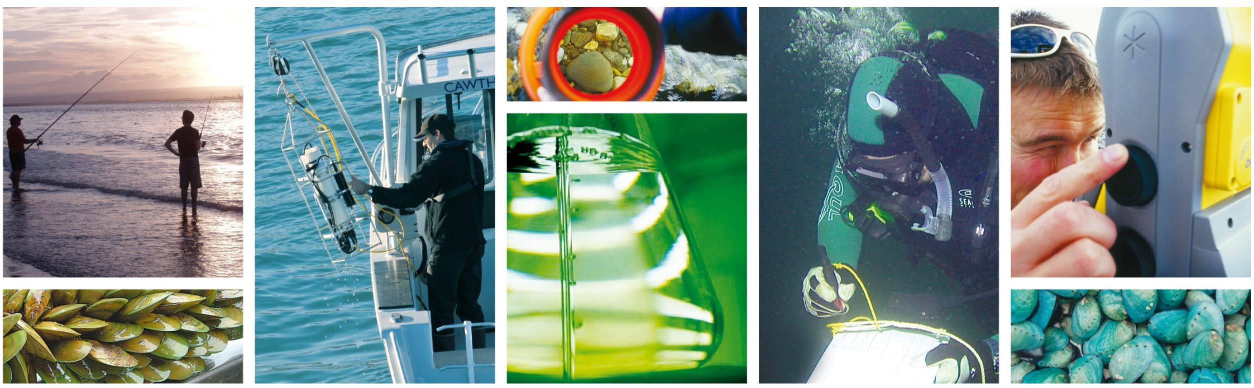
Assessment of the East Cape Physical Marine Environment for Marine Aquaculture: Wind, Waves, Currents and Temperature



RESEARCH BASED SOLUTIONS

Assessment of the East Cape Physical Marine Environment for Marine Aquaculture: Wind, Waves, Currents and Temperature

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EXECUTIVE SUMMARY

Cawthron Institute (Cawthron) was commissioned by Gisborne District Council (GDC) to investigate aspects of the physical oceanography of the Gisborne coast in relation to aquaculture feasibility. The coastline of the East Cape of the North Island of New Zealand is characterised by large areas of unpolluted, productive waters due to energetic East Cape currents and relatively low levels of terrestrial development. These characteristics may prove favourable for future aquaculture developments in the region; however, the East Cape region also presents a potentially difficult working environment for new aquaculture ventures due to its orientation and exposed coastline.

Preliminary studies on open ocean aquaculture (OOA) for shellfish in Hawke Bay show there are potentially many issues that face new ventures in these environments (Heasman *et al.* 2009). In particular, the meteorological and hydrodynamic climate at a potential aquaculture site is important in determining whether aquaculture is biologically and economically feasible.

Given the scope of the project and the large area of the region examined, this study makes use of modelled rather than measured wind, wave and current data for the region. The modelled data have been produced under contract by MetOcean Solutions Ltd., and encompass 10 years (1998 to 2008) at 10 sites in the GDC region. The sites were chosen in consultation with GDC and were selected based on optimum spatial distribution for contrasting different bathymetries, coastal aspects and representative sections of the coastline.

Conditions at the 10 sites were typical of exposed shorelines found in other places around the world where aquaculture is in existence. Conditions were relatively extreme, with strong currents and winds, and high waves. Median currents were less than ~19 cm/s, but maximum current speeds were estimated at up to ~160 cm/s (~3.1 knots). Winds tended to be below 12 m/s (~23 knots) for 75% of the time, but at some locations strong winds of up to about 45 m/s (~90 knots) were modelled. Winds of this strength may impact on the ability of vessels to access or service aquaculture sites. Median wave heights were less than 2 m, but maximum heights were ~8-11.5 m at most sites.

Distance to site and accessibility are important determining factors that need to be considered in terms of vessel size, access days and associated costs. These aspects can result in potentially challenging economic constraints, which should be seriously considered on a case by case basis prior to project initiation. The access and vessel requirements for finfish farming are different to that of shellfish culture and the use of automated feeding buoys may be required to ensure economic feasibility.

The amount of energy transferred to aquaculture structures would need to be controlled by equipment design and careful consideration of structure positioning in the water column. For finfish structures, there are both surface and submergible cages which would tolerate the conditions observed in the modelled data sets. The periodically high peak water current flows would require some consideration in the design of the structures. However, the mean water currents would support the constant supply of fresh oxygenated water that fish in cages require and would dilute and disperse waste products (*e.g.* waste feed and fish faeces). In short, the specifics of each species would also have to be well defined and each case studied independently.

Surface temperatures were predominantly in the range of 14 to 20°C, with little variation between sites or areas of the coastline. The surface temperatures do not preclude farming of the most common species of shellfish currently being farmed in New Zealand, but it would not be possible to farm some species of finfish due to their temperature requirements.

Therefore, from a physical oceanographic perspective, both shellfish and finfish aquaculture appear to be achievable in this region, but it will require more work on equipment design (in the case of shellfish aquaculture) and considerably more work on the production and economics of the selected species, before aquaculture developments can progress.

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1. INTRODUCTION

The Gisborne region currently does not have Aquaculture Management Areas (AMAs) defined as part of a regional coastal plan, and there has been growing interest from stakeholders in initiating aquaculture developments. Through an Envirolink small advice grant (698-GSDC55), Gisborne District Council (GDC), Cawthron Institute (Cawthron) and interested stakeholders met and identified further research that would be required in order to progress with determining aquaculture feasibility within the region. A gap in information on the physical oceanography (*e.g.* wind, waves, currents and temperature) of the Gisborne coast was identified. Subsequently, Cawthron was commissioned by GDC, through Envirolink 878-GSDC77, to investigate aspects of Gisborne's physical oceanography in relation to aquaculture feasibility. Knowledge on the physical setting forms the foundation for identifying potential locations for AMAs and provides a framework for further evaluating site feasibility based on factors such as sedimentation and water quality.

The coastline of the East Cape of the North Island of New Zealand is characterised by large areas of unpolluted, productive waters due to energetic East Cape currents (Figure 1) and relatively low levels of terrestrial development. These characteristics may prove favourable for future aquaculture developments in the region; however, the East Cape region also presents a potentially difficult working environment for new aquaculture ventures due to its orientation and exposed coastline.

Preliminary studies on open ocean aquaculture (OOA) for shellfish in Hawke Bay show there are potentially many issues that face new ventures in these environments (Heasman *et al.* 2009). In particular, the meteorological, hydrodynamic and temperature climate at a potential aquaculture site is important in determining whether aquaculture is biologically and economically feasible.

With respect to the physical environment, the role of currents, winds, waves and temperature are important because:

- Currents create forces on submerged structures; these may limit options for the placement of structures and may add to the cost of developing a site. Currents are also important for replenishing food supply to a site (*i.e.* shellfish), delivering oxygenated water into finfish cages or flushing potentially problematic wastes.
- Winds may affect accessibility to an aquaculture site; this will influence vessel choice so that maintenance and harvest on the structures is possible.
- Waves (and the currents associated with them) also determine vessel access and can place stress on submerged structures.
- Water temperature can exclude potential species from being farmed; some species (*e.g.* salmon) require cooler waters, and others (*e.g.* yellowfin tuna) require warm waters.

This study provides a relatively coarse overview of the physical environmental characteristics of the East Cape region to assist council and future aquaculture ventures with preliminary risk evaluations. The results of this work, while useful in the preliminary stages of site evaluation should not be used to replace a site-specific review.

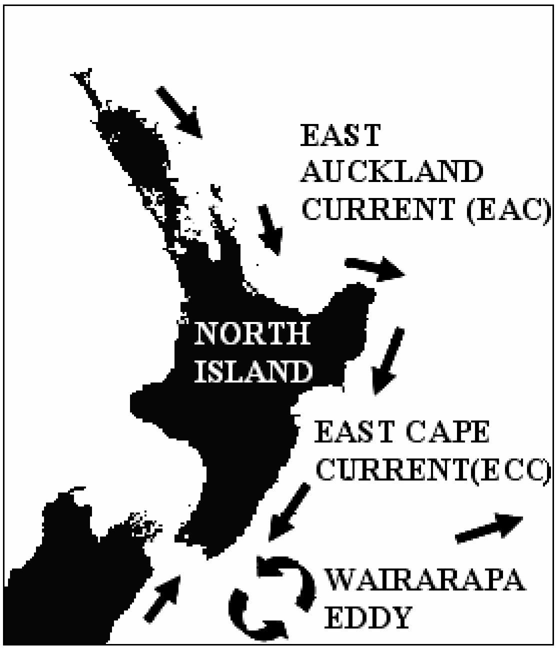

Figure 1. Map of the North Island, showing the position of the major ocean current features of the East Coast (after Heath 1985).

2. METHODS

2.1. Currents, wind and waves

Given the scope of the project and the large area of the region examined, this study makes use of modelled rather than measured wind, wave and current data for the region. Models were produced under contract by MetOcean Solutions Ltd., and encompass data for 10 years (1998 to 2008) at 10 sites in the GDC region (Figure 2). The specific methods used to generate these datasets are provided in Appendix 1 for currents and winds, and Appendix 2 for waves. The sites were chosen in consultation with GDC and reflect suitable depths (over 30 m generally considered suitable for shellfish and finfish farming), contrasting coastal aspects, representative sections of the coastline, proximity to areas with suitable access, and protection from land features (such as the Mahia Peninsula and offshore islands) (Figure 2). Some potential constraints were also taken into account when positioning the sites (*e.g.* shipping lanes and conservation areas). The sites did not necessarily represent potential aquaculture sites; rather they were indicative of conditions in the general areas. An offshore site (10) was chosen in order to compare characteristics with coastal sites along the shelf and to understand the influence of depth on wave action. Field sampling would be necessary to obtain actual data before a specific site could be considered appropriate for aquaculture development.

In some cases, similar results across multiple sites were aggregated to aid interpretation of the datasets. Current, wave and wind data are presented as direction and frequency data to highlight variability in conditions between the sites (Figure 2). The timing of wind and wave events is also analysed to determine the amount of likely site access at different times in the year, based on the ability of a vessel to be able to function in different wave and wind conditions.

The directions for waves and wind are presented using the meteorological convention of "coming from" and water current directions use the oceanographic convention of "going to". As wave heights occur as a distribution[1] of high and low waves over any given time period, these are presented as significant wave height, which is a technical description of the wave spectrum describing the mean height of the highest third of waves.

Although most of the results relate to the 10 sites, spatial maps of the region showing median currents, waves and temperatures are also presented to assist with visualising the suitability of different areas.

[1] Typically waves are modelled with a Weibull distribution. This distribution has the greatest occurrences of wave heights around the median, but with a "long tail" which allows for a small possibility for very large waves to occur. Hence there is a very small possibility the maximum possible wave may be twice as large as the significant wave height. Further technical details are available in Appendix 2.

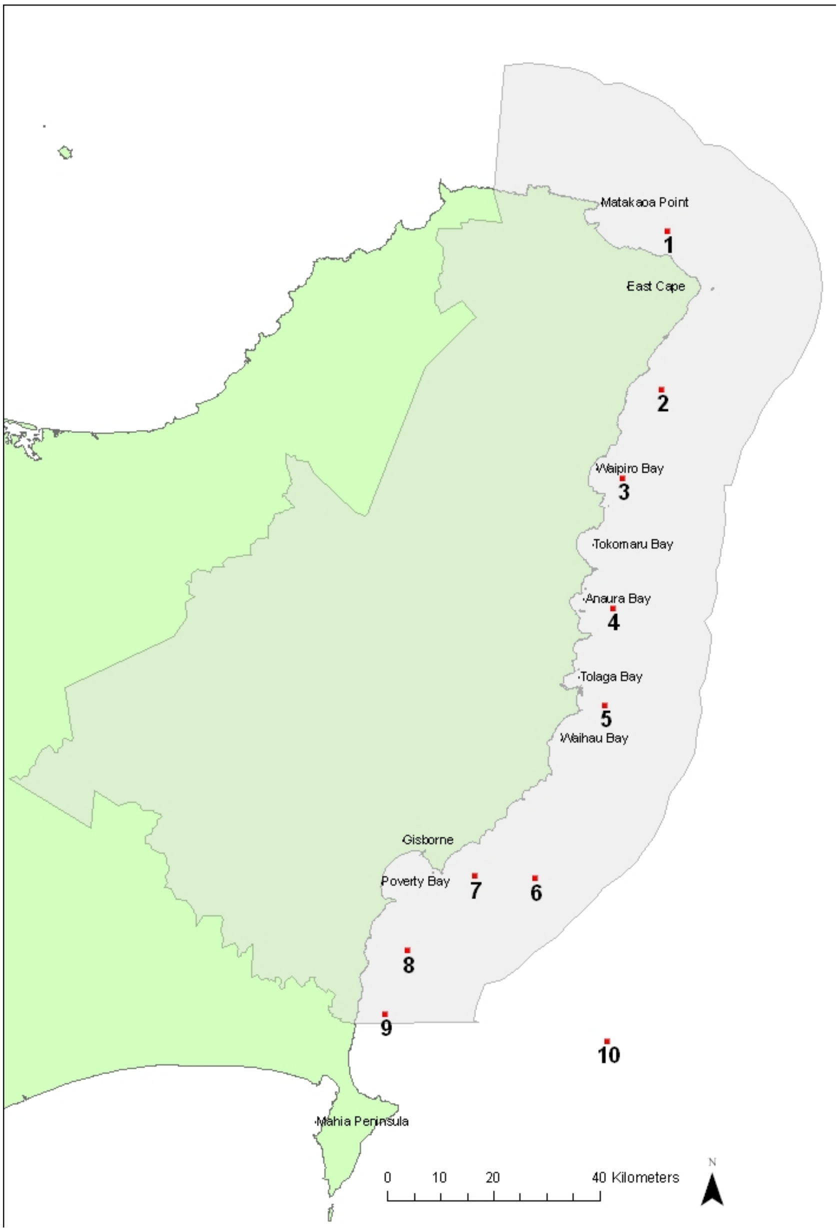

Figure 2. Map of the Gisborne District, showing the regional boundary and the 10 selected sites.

2.2. Surface temperature

Surface temperatures have been determined from remotely sensed satellite data provided by the MODIS Aqua sensor for the area of the East Cape for the years 2003 to 2007. This dataset is comprised of 1,279 images of the region. On any individual day the availability of temperature data for a given region of an image is determined by the visibility of the area at the time the region is scanned by the satellite (similar to a "snapshot" of the region). Therefore, when cloud is present it is not possible to determine surface temperatures at all locations in a given image region.

For this reason, the surface temperature maps used in this study use temporally aggregated data to provide a picture of minimum, maximum and average temperatures at all locations. The 2.5th percentile temperatures are used to show the lower temperature range, rather than the minimum temperature which can be quite variable. Similarly, the 97.5th percentile temperatures are used to show the upper temperature range. Therefore, although the temperatures presented here are representative of range observed in the region, it is possible that temperatures may drop below those shown here for a short period of time (~2-5 days). The median is also used in the spatial plots to present the average temperatures as it is less affected by outlying measurements or skewed distributions than the mean. Extracted distributions of sea surface temperatures at the 10 sites are also presented to provide information on the proportion of time different sites are exposed to various temperatures.

3. RESULTS

3.1. Site depths, distances and travel times

Sites were located in depths of ~35–62 m, with the exception of Site 10, which was positioned in ~1300 m. As stated above, the location of Site 10 was chosen in order to compare characteristics with coastal sites and to understand the influence of the coastal shelf on wave action; it is not suggested that this area would be suitable for offshore aquaculture.

Port of Gisborne (Eastland Port) was used to estimate distances and travel times, since this is currently the only harbour in the region which would be able to service the relatively large vessels that would presumably be required. If AMAs were developed in the northern region, it may be appropriate to develop some small harbours to service the sites.

Table 1. Approximate site depths, and distances and travel times to the nearest port (Eastland Port, Gisborne).

Site	Approx. depth (m)*	Approximate distance to port (km)	Estimated travel time to port (at 8 knots) (h)
1	41	152	10.3
2	43	114	7.7
3	39	96	6.5
4	35	72	4.9
5	41	53	3.6
6	62	25	1.7
7	38	14	0.9
8	44	18	1.2
9	42	31	2.1
10	1300	50	3.4

* Note: Depths were obtained from LINZ chart NZ55.

3.2. Currents

Analysis of modelled current data for the 10 sites (Figure 3) suggests that, for the majority of the 10 year period modelled (at least 75% of the time: upper quartile), recorded currents at all sites were less than ~30 cm/s, and median currents were less than ~19 cm/s. However, Sites 1 to 6 had noticeably higher current speeds than Sites 7 to 10, with maximum current speeds estimated at up to ~160 cm/s (~3.1 knots).

Current rose analyses of representative sites highlight the differences in the direction and magnitude between representative sites in the region (Figure 4, Figure 5). Currents were predominantly oriented along the coast, with Site 1 having easterly and westerly currents, and currents at Sites 2-9 were north and south. Site 10 currents were variable in direction, but predominantly eastwards.

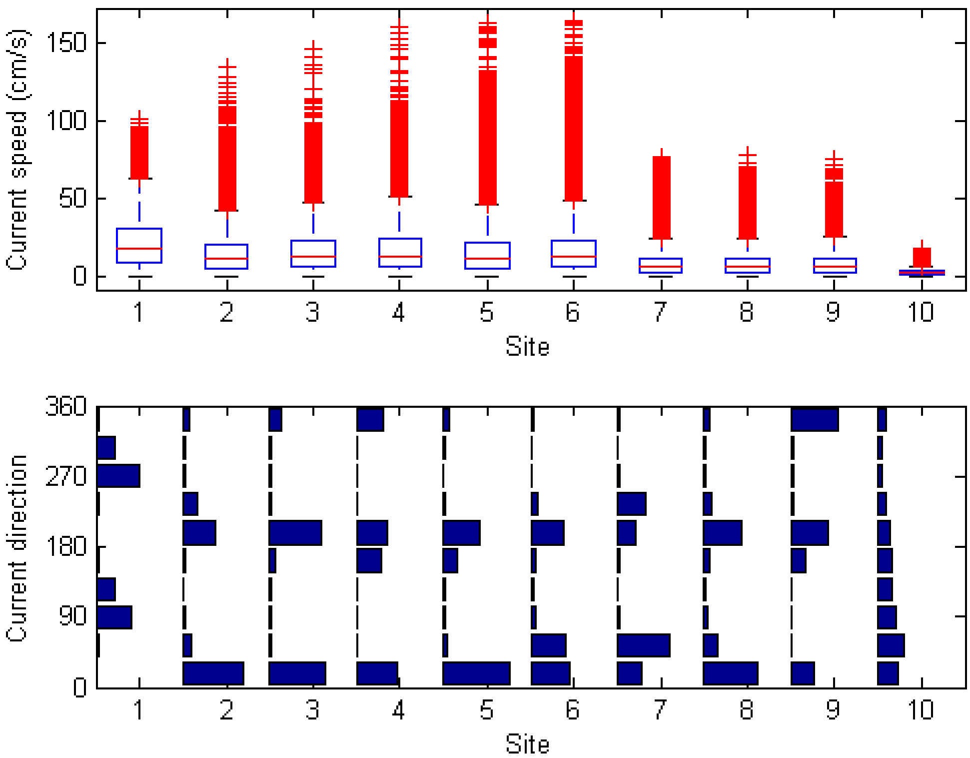

Figure 3. Distribution of current speeds (top) and directions (bottom - compass bearings using the "going to" convention) at all sites over the 10 year period. A "box and whisker" plot showing current speeds, the central red line is the median, the blue box represents the interquartile range and the lines extend to 1.5 times the interquartile range. Red "+"s mark the current speeds that fall outside of 1.5 times this range. The horizontal histogram of directions shows the relative frequency of time spent at each direction for each site.

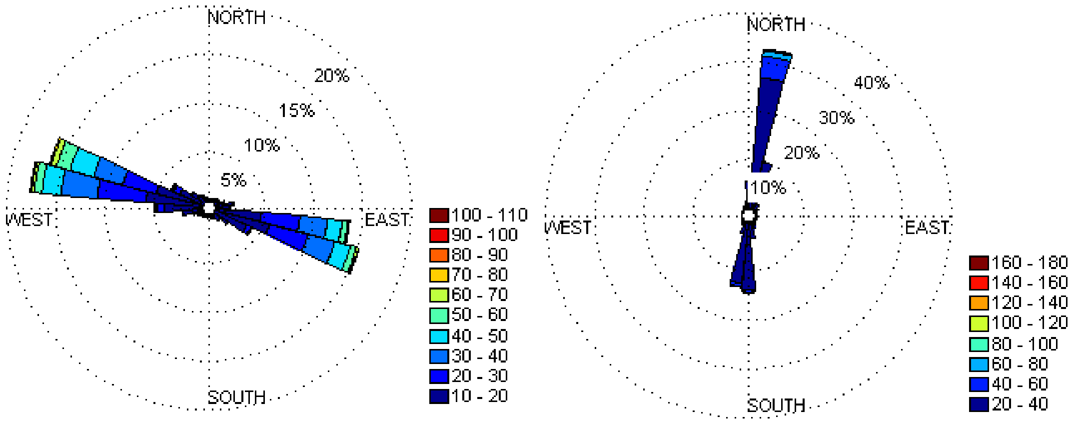

Figure 4. Current rose plots showing the direction (going to) and strength of currents at Sites 1 (left) and 5 (right - representative of Sites 2-6) over the 10 year period. The length of the bars represent the amount of time spent at a particular direction. Colours relate to the strength of the currents which is shown in the legend (in cm/s).

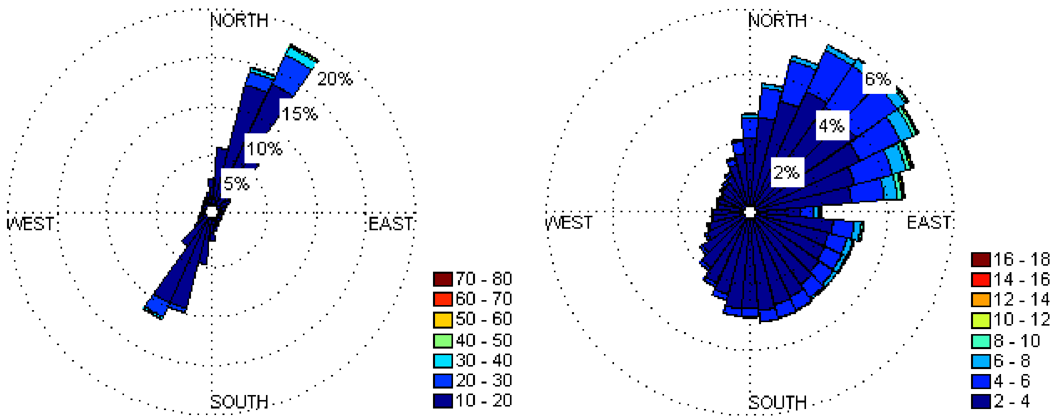

Figure 5. Current rose plots showing the direction (going to) and strength of currents at Site 8 (left, representative of Sites 7-9) and Site 10 (right) over the 10 year period. The length of the bars represent the amount of time spent at a particular direction. Colours relate to the strength of the currents which is shown in the legend (in cm/s).

A wider view of median current speeds in the region (Figure 6) shows the reason for the differences in the predicted currents between sites. The East Cape Current (ECC) and East Auckland Current (EAC) are dominant hydrographic features of the region (Figure 1). Whilst some sites are located within these currents (Sites 1-6), others (Sites 7-10) are positioned outside of the main flow. Small differences in the location of the sites can lead to quite large differences in the median currents. It is also apparent from Figure 6 that farms situated in more traditional inshore locations would not experience as high flows as those described for Sites 1-6.

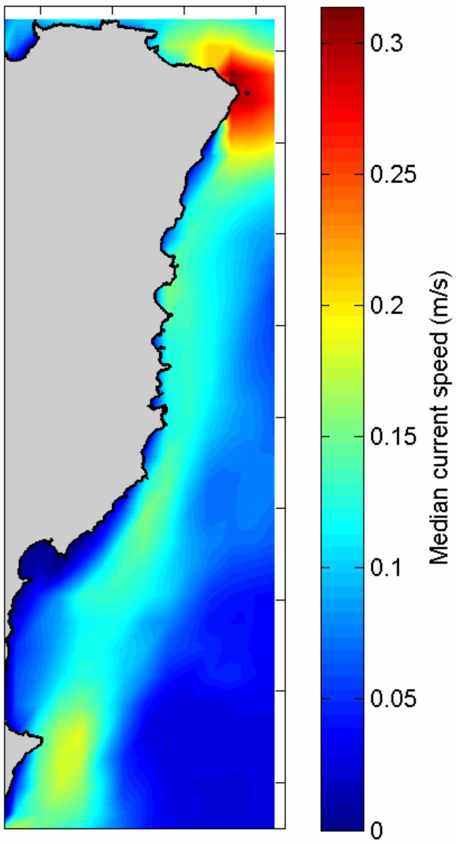

Figure 6. Modelled median current speed observed along the East Cape from the 10 year dataset (1998 to 2008). Note a band of relatively high current is observed close to the coast indicating the general location of the prominent hydrological feature of the region, the East Cape Current.

The median (~12-18 cm/s) currents modelled for Sites 1 to 6 are high, but are not outside of currents already experienced by existing structures located in energetic environments, such as finfish farms in Tory channel, Marlborough Sounds. However, the maximum currents predicted at these sites are very high (up to 160 cm/s) and would require careful structural design to prevent failure. Additional currents induced by waves at these sites would also need to be considered in any analysis because these currents could also be aligned with other water transport currents (*e.g.* geostrophic or wind-driven currents), resulting in very large forces on any submerged structures.

In addition, strong water currents (above 10 cm/sec) can influence the feeding rates of shellfish, but only if the water current is directed into the inhalant vent. It is suggested that this will seldom be the case because the grow-out structures move and wave activity changes water current direction. The increased food delivery by stronger currents may offset any negative feeding issues.

For finfish structures, the stronger water currents are very good for ensuring the oxygen levels of the water in the cage remain high and for diluting and dispersing waste products (*e.g.* waste feed and fish faeces). However, the structural design will have to tolerate the extra energy without deformation or breakage. The median water currents are slightly lower than that which is desirable for finfish cages (15 cm/sec) but correct structural design and cage selection should alleviate this issue.

3.3. Wind

The majority of winds at the selected sites originated from the west which implies that access would be expected to be generally good for nearshore sites where the east-facing orientation of the coast would provide some shelter (Figure 7, Figure 8). However, offshore sites may be more exposed to these winds and therefore the proportion of time spent at wind speeds where vessels would be unable to operate becomes important.

The distribution of wind speeds predicted at all sites (Figure 8) shows that for 75% of the time, winds tended to be below 12 m/s (~23 knots). Winds of this strength may impact on the ability of vessels to access or service aquaculture sites. At some locations strong winds of up to about 45 m/s (~90 knots) were modelled, but these would be expected to have limited influence on submerged structures at these sites.

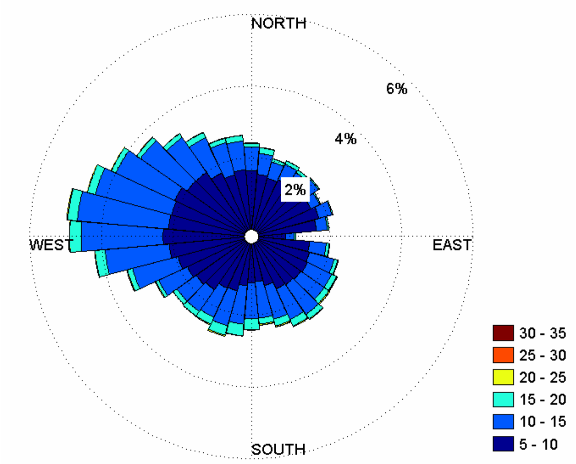

Figure 7. Wind rose plot showing the direction (coming from) and strength of wind at Site 1 over the 10 year period. Note that the frequency of directions were similar at all other sites (*e.g.* mainly westerly winds). The lengths of the bars represent the amount of time spent at a particular direction with the colours relating to the strength of the wind which is shown in the legend (in m/s). Note that 1 m/s is approximately 2 knots.

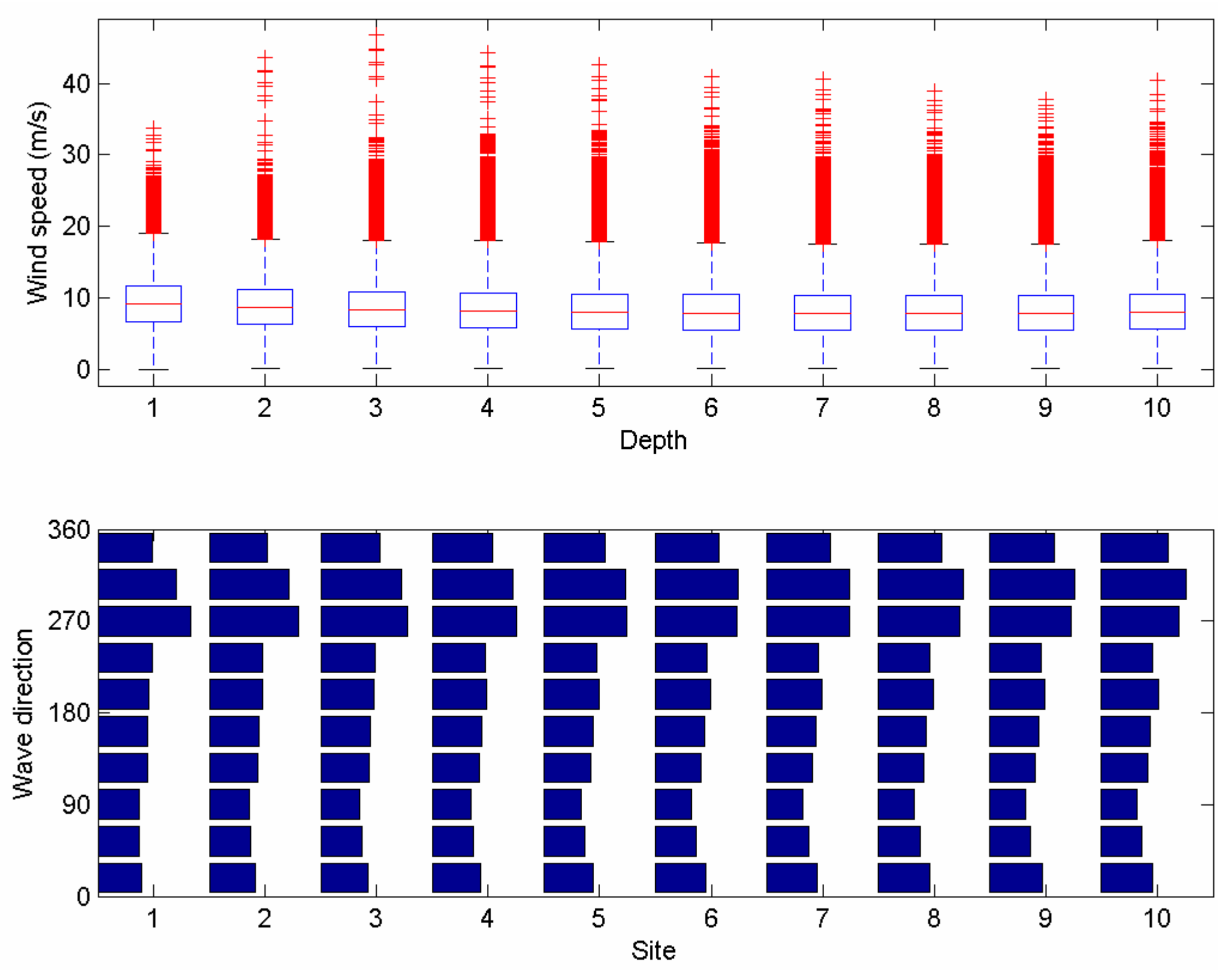

Figure 8. Distribution of wind speeds (top) and directions (bottom - compass directions using the "coming from" convention) at all sites over the 10 year period. Note that 1 m/s is approximately 2 knots/s.

In order to assess the effect of winds on access to sites, further analysis was undertaken to produce graphs showing percentage accessibility (Figure 9). This analysis shows that vessels servicing the site and the strength of the structures supporting vessel attachment would have to be sufficient to operate in and withstand winds of about 10 m/s (~20 knot) winds. Even if this criterion was met, in some years and months this may mean that access to a site was restricted to less than 50% of a given month. A more thorough analysis incorporating the periods of calm weather and steaming time to major ports would also be a priority for future analysis if a site was considered suitable on the basis of these initial results.

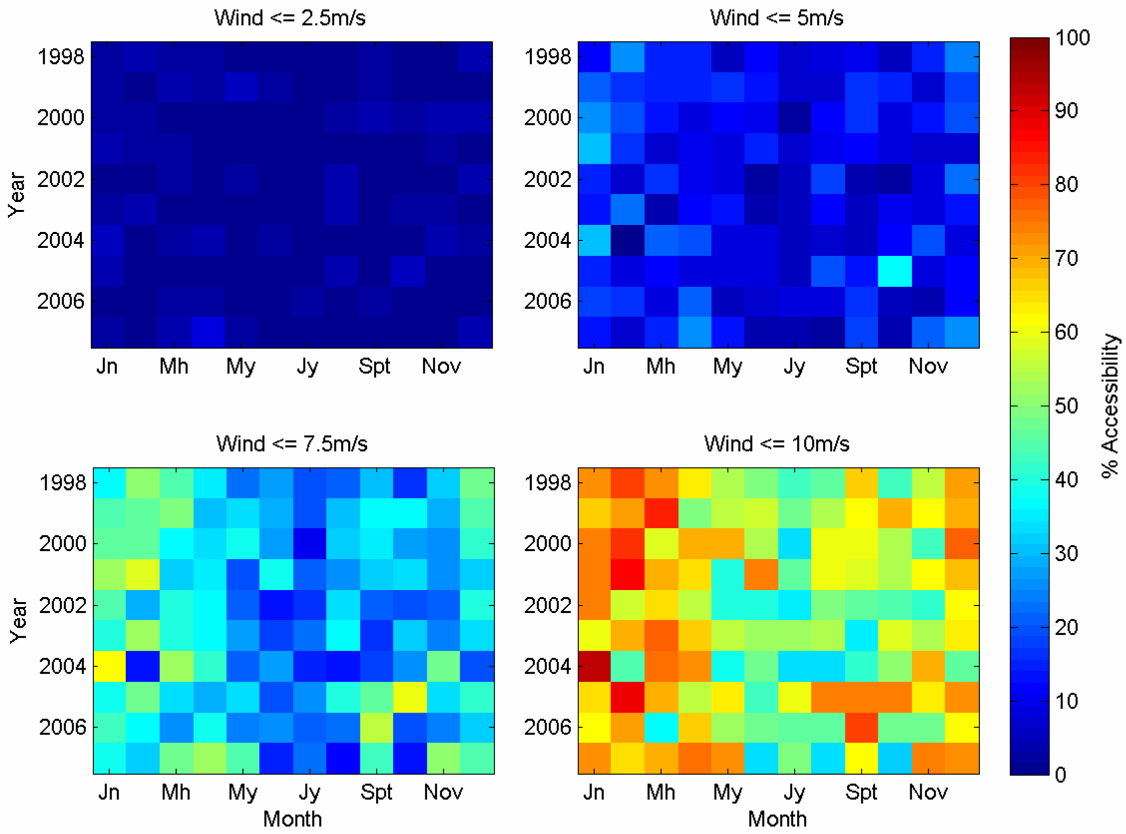

Figure 9. Percent access at Site 1, by vessels which can tolerate winds conditions of ≤2.5 m/s, ≤5 m/s, ≤7.5 m/s and ≤10 m/s respectively. In order for a vessel to gain access for greater than 50% for most months it would have to be designed to able to work in wind speeds of at least 10 m/s (20 knots).

3.4. Waves

Unlike the modelled winds, which were relatively similar between the sites, maximum wave heights and directions varied between different areas (Figure 12). Sites 2 to 9 were similar and the wind rose analysis shows these sites are exposed to frequent and high waves from the south (Figure 10). Site 10 was particularly exposed to these southerly waves with maximum significant wave heights of up to about 15 metres modelled over the period (Figure 11, Figure 12).

Site 1 was different to the other sites in that it was protected from the southerly wave events, with the most frequent large wave events coming from a north-easterly direction and maximum significant wave heights of approximately 9 metres. Over a period of four years of deployment, submerged structures in Hawke Bay have withstood maximum significant wave conditions of about 6.5 metres with 12 second period (the time between wave crests). Therefore, using existing technology, waves of the maximum size estimated for the sites shown for the East Cape are at the limits of our knowledge of how structures can cope with such conditions. However, since the effect of waves decreases with depth (*i.e.* less wave-induced current is created further from the surface) it would be possible to estimate what depth would be required to submerge the structure to produce the same forces as a smaller wave. Hence the wave conditions do not necessarily dictate the feasibility of a structure at a site; they simply provide the design criteria. This may lead to economic tradeoffs. For example, in the case of mussel long-lines, a structure that is submerged deeper in the water may not support the same length of growing rope due to the proximity of the backbone to the seabed.

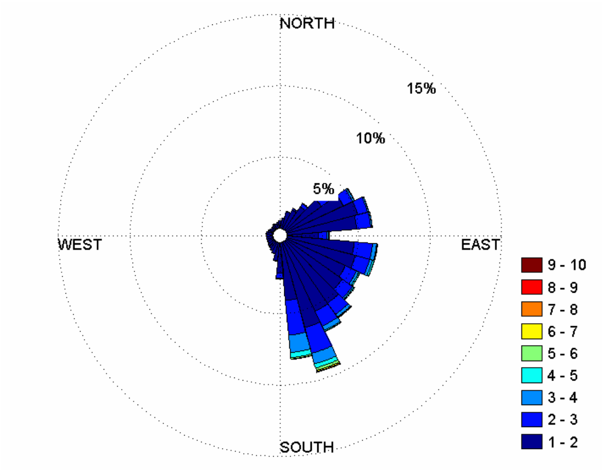

Figure 10. Wave rose showing the direction (coming from) and significant wave height (in m) at Site 2. The directions at this site were representative of most other sites (except for Sites 1 and 10) over the 10 year period.

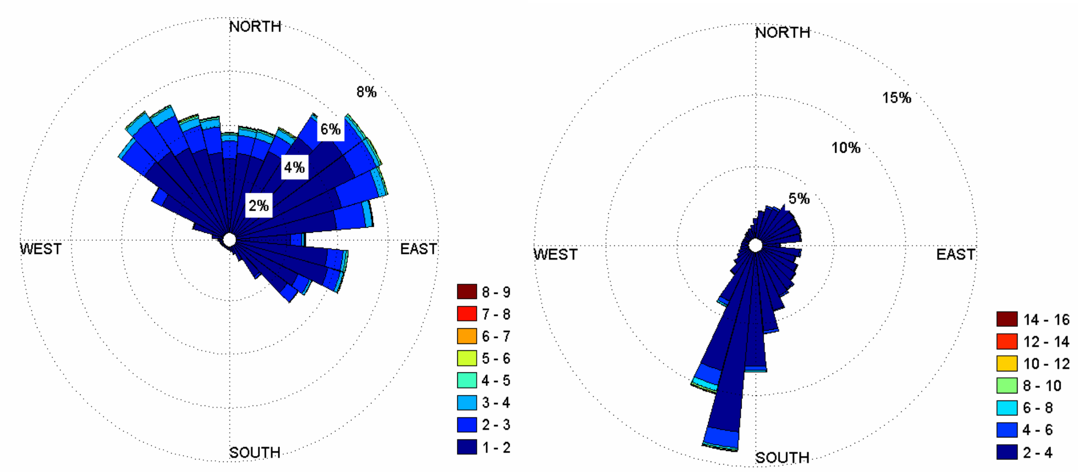

Figure 11. Wave rose showing the direction and significant wave height (in metres) at Sites 1 (left) and 10 (right). The directions at both of these sites were quite different to the wave directions at other sites over the 10 year period.

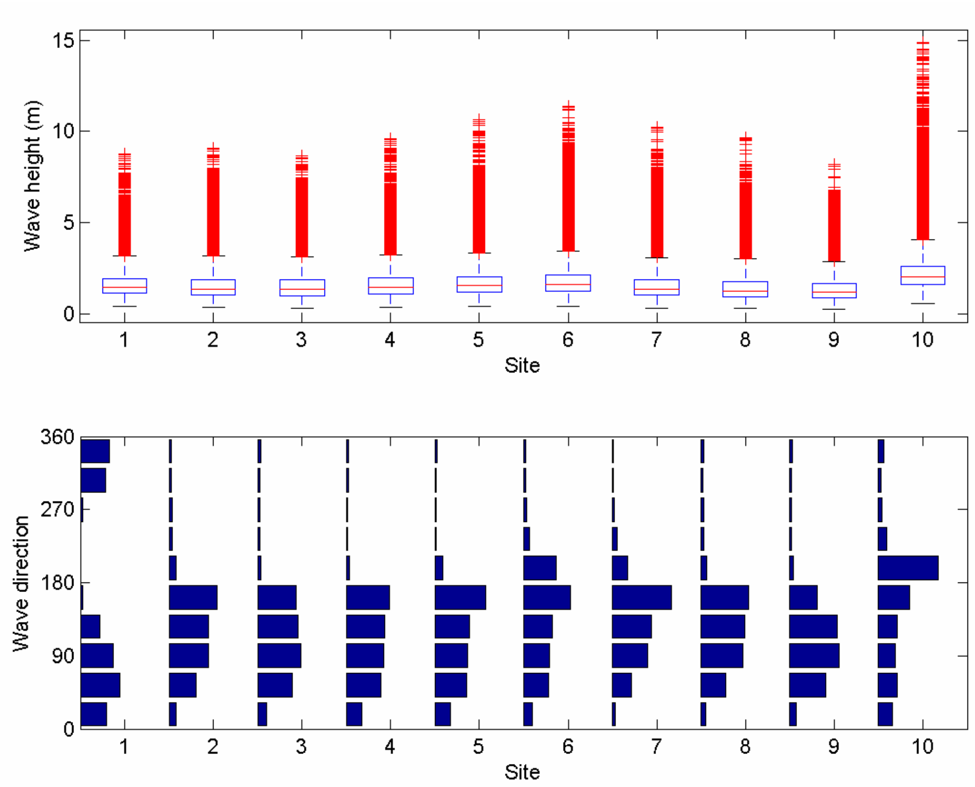

Figure 12. Distribution of significant wave heights and directions (compass bearing using the "coming from" convention) at all sites over the 10 year period. Note that wave heights and directions vary depending on location, with Site 10 showing the possibility for very high waves.

Analysis of median significant wave height data at all analysed East Cape model locations using two separate high resolution models (delineated by the break in the data - Figure 13) showed little variation in wave heights between sites of similar distance from the coast, and significant wave heights decreased with increasing proximity to the coast. Mean wave periods were also lower closer to the shore (Figure 14). This means that, although significant wave heights may be lower closer to shore (Figure 13), access to aquaculture structures by vessels may be more difficult due to steeper waves.

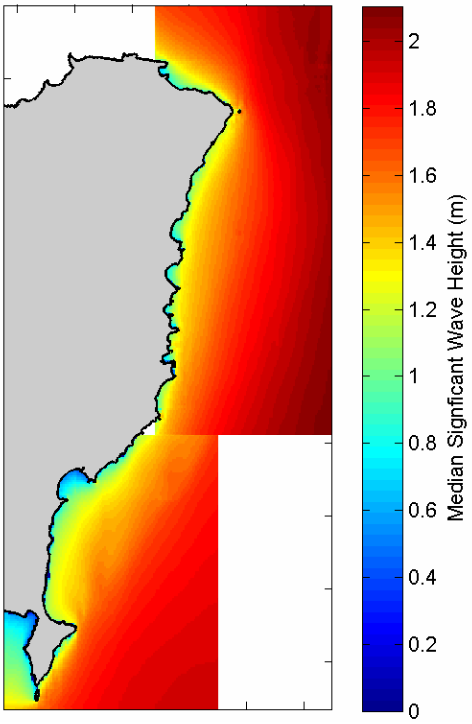

Figure 13. Median (50th percentile) significant wave heights at all locations from the two models used to derive the wave data for the 10 year period (1998 to 2008).

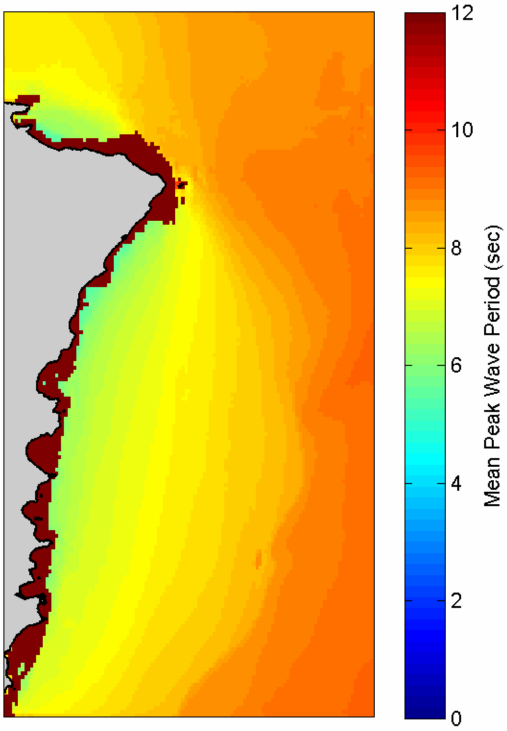

Figure 14. Mean peak wave period (in seconds) for the northern model, showing decreasing wave period (the time between wave crests) with increased proximity to shore.

Wave conditions will have an important influence on the potential for vessels to access aquaculture sites, similar to constraints posed by wind conditions (Figure 9). A similar analysis to that completed for wind is presented for waves at Site 2 (which is broadly representative of Sites 2 to 9 - Figure 15) and Site 10 (the site most exposed to large wave conditions - Figure 16). This analysis shows the same seasonal trends of access as the wind graphs – that access is greatest in the summer and lowest in the winter. The graphs also show that a suitable vessel would have to be able to operate during conditions where significant wave heights of about 2 metres were present, to be able to access the site approximately half of the time during most years. If access requirements were greater and the location (*e.g.* Site 10) was more exposed to large waves, the vessel may need to be able to work in significant wave heights of 3 metres (Figure 16). A more thorough analysis could include factors such as wave steepness (a function of the wave period and height) and test different boat designs to determine safe attachment windows for various vessel designs (*e.g.* Figure 17).

Additional issues to consider are the time and costs associated with getting vessels to and from sites. This may reduce the time a vessel could actually spend at a site, thereby further reducing the accessibility of remote sites. It may also lead to large fuel and labour cost overheads for any venture and critically affect the viability of any proposed operation. The economic implications of the site development are outside of the scope of this project but would also be an important consideration for any potential venture.

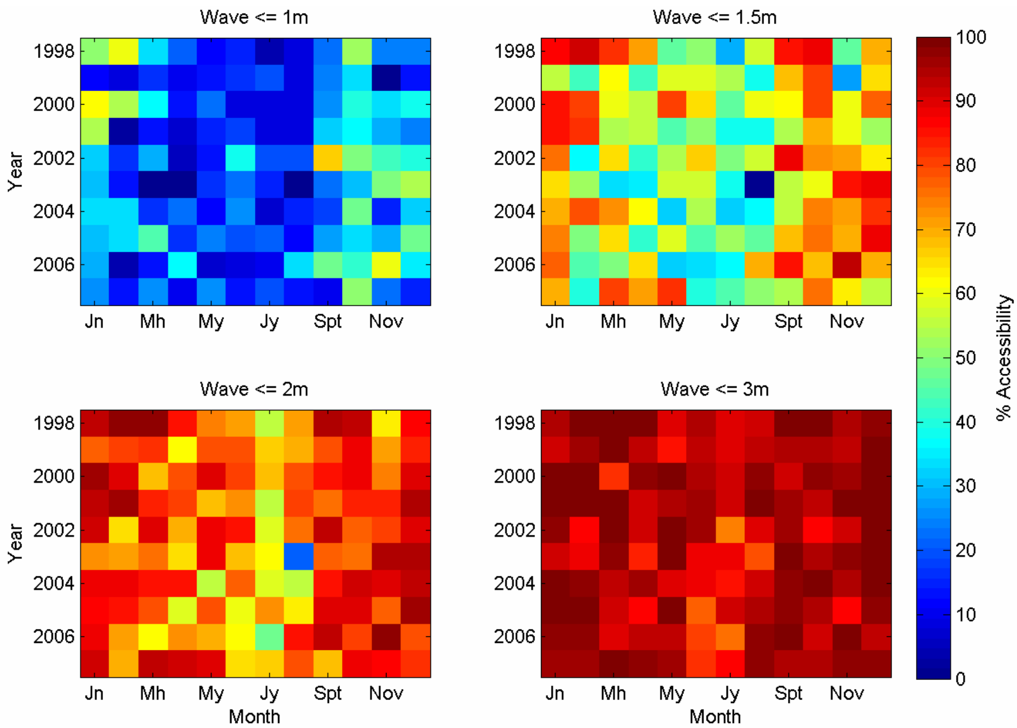

Figure 15. Percentage accessibility for a vessel tolerant of waves ≤1 m, ≤1.5 m, ≤2 m and ≤3 m (significant wave height) respectively for different years and months for Site 2 (but representative of Sites 1 to 9). This shows that vessels must be able to work in significant wave heights of at least 1.5 to 2 metres to service aquaculture structures for about 50% of the time in these regions.

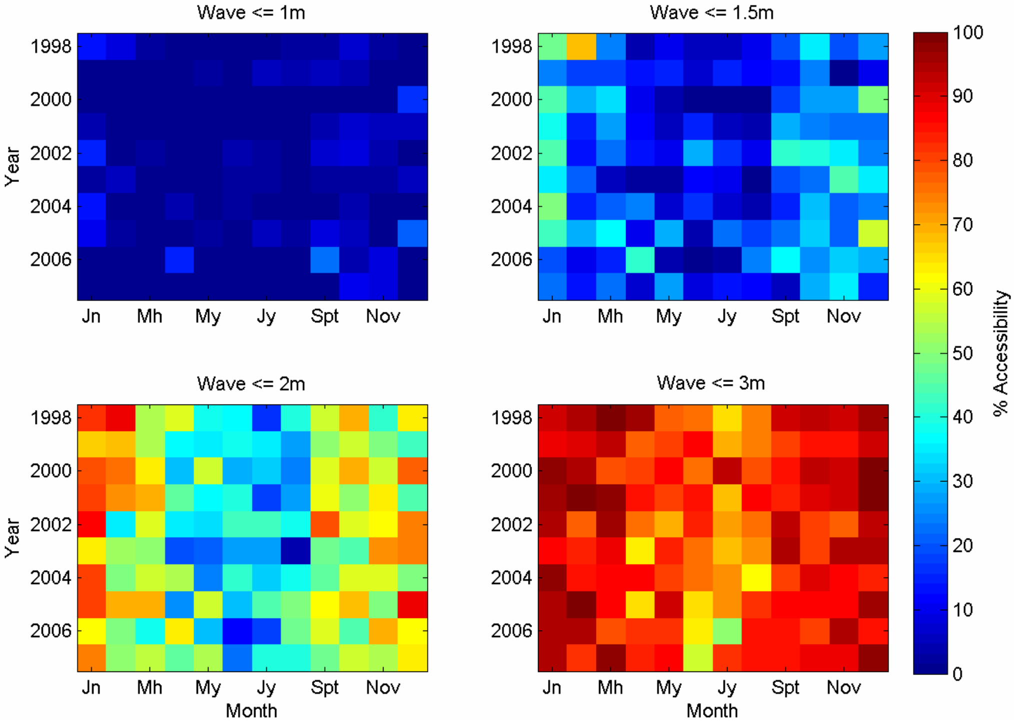

Figure 16. Percentage accessibility for a vessel tolerant of waves ≤1 m, ≤1.5 m , ≤2 m and ≤3 m (significant wave height) respectively for different years and months for Site 10 – the most exposed of all the sites analysed. This shows that vessels must be able to work in significant wave heights of at least 2 to 3 metres to service aquaculture structures in these regions for 50% of the time.

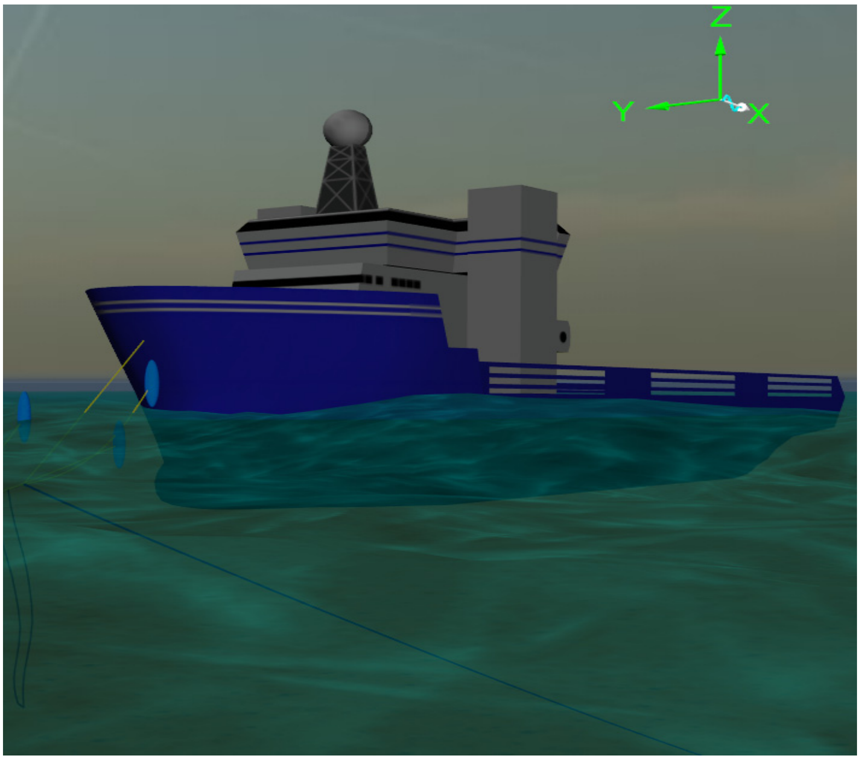

Figure 17. Example of an OrcaFlex model used to calculate vessel attachment forces on a subsurface aquaculture structure for a given wave climate.

3.5. Sea surface temperature

Surface temperatures ranged from a low of 9.87°C and a high of 22.37°C (both at Site 3) but were mainly (>75% of the time) in the range of 14 to 20°C (Figure 18). There was little variation in surface temperatures across the sites; however, there may be variability or seasonal stratification (layering of warm water over cool water) through the water column during the year and information on vertical temperature profiles may be required for decisions relating to species selection and structure placement.

Examination of the spatial distribution of surface temperatures for the whole coast shows little variation between different areas (Figure 19). However, there appeared to be slightly cooler extremes (2.5th percentile) observed closer to shore (probably as a result of coastal upwelling events or cool riverine water runoff during winter). The upper temperature extremes (97.5th percentile) were also slightly cooler (about 1-2°C) close to shore. The cooler extremes observed in the nearshore waters were also mirrored in the median temperatures which also appeared to be about 1-2°C lower than temperatures at offshore locations.

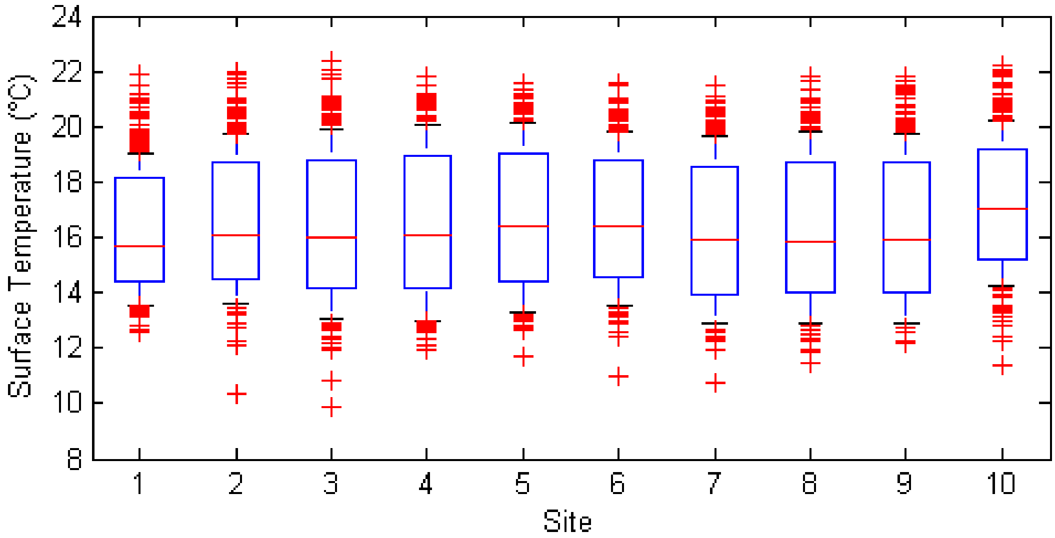

Figure 18. Temperature distributions derived from MODIS Aqua satellite sensor data for the period 1 January 2003 to 31 December 2007 (n=1279) for 10 sites along the East Cape coast. The whiskers (blue lines) only extend to a quarter of the interquartile range (the blue box).

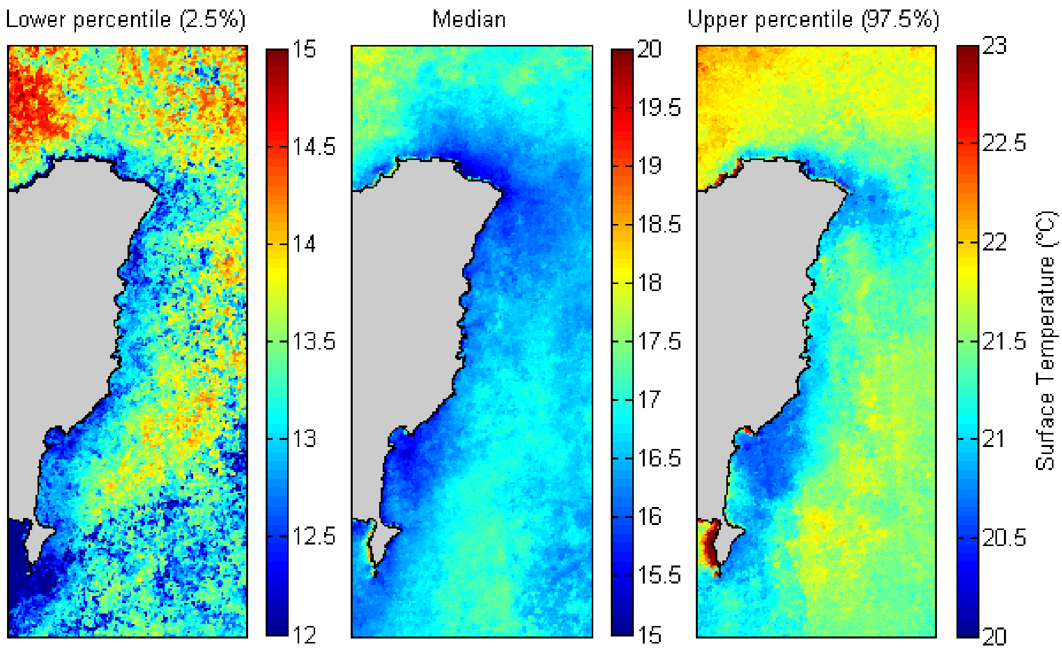

Figure 19. Lower (left), median (middle) and upper (right) surface temperatures derived from MODIS Aqua satellite sensor data from around the East Coast for the years 2003 to 2007 (n=1279).

3.5.1. Influence of surface temperature on potential aquaculture species

The surface temperature range does not preclude any of New Zealand's main shellfish aquaculture species (*i.e.* oysters, scallops, mussels). In terms of finfish aquaculture there are perhaps five likely candidates for aquaculture in New Zealand waters over the next 10 years:

Yellowtail Kingfish (*Seriola lalandi*), Grouper (*Polyprion oxygenensis*), King Salmon (*Oncorhynchus tshawytscha*), Greenbone or Butterfish (*Coridodax pullus*) and Southern Bluefin Tuna (*Thunnus maccoyii*). Each of these five species have varying temperature requirements.

- Yellowfin Kingfish – This species is predominantly a subtropical species and prefers warmer waters of ≥15°C and hence is in abundance along the Gisborne coast in the summer months. The juveniles of this species cannot tolerate cool temperatures; therefore farming of this species in these waters would be restricted to growing-out fish in excess of 500 g.
- Grouper – This fish species may have some issues at the higher temperatures extremes, however it still considered a 'possible species' subject to further trials.
- Salmon – The higher temperatures exclude salmon from this area. Generally they cannot tolerate temperatures above 18°C for extended periods. However, given that deeper waters may be cooler than the surface waters analysed in this study they cannot be totally excluded.
- Greenbone (Butterfish) – This species is found country-wide and is still being developed as an aquaculture species. It is suggested that the temperature range found at these sites would be suitable for this species. Further research is required to confirm this.
- Southern Bluefin Tuna – This species is found in warmer waters and would tend to do better there; however, they would tolerate the water temperatures at these sites.

3.6. Summary of site physical characteristics

There was little variation in median wind, waves and temperature, but there were noticeable differences in median currents, maximum wave heights and distances from the Port of Gisborne (Eastland Port) (Table 2). An assessment of the economic potential of a given site would need to consider these physical conditions.

In summary:

- Distance from the main port is an issue; particularly in combination with site accessibility due to waves, and needs to be carefully considered in an economic model.
- Currents are moderate to high. While this is a good attribute from the perspective of fish health and waste dispersion, it has some drawbacks in terms of structural engineering and conceivably fish energetics.
- Wind and waves are in the range of other OOA sites, but are towards the extreme end; nevertheless aquaculture is possible given the currently available OOA technology.
- Temperature does not preclude most common New Zealand shellfish aquaculture species, but observed sea surface temperature ranges imply that some finfish species may struggle in the region.

Table 2. Summary information of site characteristics.

Site	Approx. Depth (m)	Distance (km) / travel time (h) (at 8 knots/h) to Eastland Port	Currents (cm/sec) Median / max	Wind (knots) Median / max	Wave height (m) Median / max	Temperature (°C) Min - max
1	41	152 / 10.3	18.24 / 100.70	17.82 / 65.49	1.46 / 8.78	12.58 - 21.89
2	43	114 / 7.7	11.56 / 133.88	16.84 / 84.73	1.34 / 9.06	10.35 - 21.97
3	39	96 / 6.5	12.93 / 145.54	16.16 / 90.79	1.32 / 8.65	9.87 - 22.37
4	35	72 / 4.9	13.18 / 159.37	15.79 / 86.07	1.43 / 9.59	11.94 - 21.81
5	41	53 / 3.6	12.13 / 162.11	15.56 / 82.69	1.52 / 10.66	11.70 - 21.65
6	62	25 / 1.7	12.55 / 163.83	15.31 / 79.60	1.59 / 11.41	10.99 - 21.57
7	38	14 / 0.9	6.37 / 76.70	15.21 / 78.74	1.33 / 10.26	10.75 - 21.49
8	44	18 / 1.2	6.35 / 78.25	15.15 / 75.52	1.24 / 9.67	11.54 - 21.81
9	42	31 / 2.1	6.45 / 75.88	15.11 / 73.26	1.18 / 8.19	12.18 - 21.81
10	1300	50 / 3.4	2.74 / 17.95	15.46 / 78.72	2 / 14.87	11.30 - 22.21

4. CONCLUSIONS

The conditions found at these sites were typical of exposed shorelines found in other places around the world where aquaculture is in existence. The benefit of the exposed nature of the sites is that environmental effects should be minimised by redistribution of waste products. However, the energy at the sites is extreme at times and the amount of energy transferred to aquaculture structures would need to be controlled by intelligent equipment design and careful consideration of structure positioning in the water column.

Most species of commonly cultured shellfish would be suitable at the sites and existing submerged mussel farm structures have been shown to withstand exposed conditions in Hawke Bay. This means that it would be possible to farm most shellfish species using existing knowledge, but whether it would be economic is not clear. The distance and access to the site would need to be considered in terms of vessel size, access days and the costs involved. These aspects can result in potentially challenging economic constraints, which should be seriously considered on a case by case basis prior to project initiation.

For finfish structures the conditions are relatively demanding. However there are both surface and submergible cages which would tolerate the conditions. The periodic peak water current flows would require some consideration in the design of the structures. However, the relatively high mean water currents would support the constant supply of fresh oxygenated water that fish in cages require, and would dilute and disperse waste products (*e.g.* waste feed and fish faeces). The access and vessel requirements are different to that of shellfish culture and the use of automated feeding buoys may be required. In short, a detailed analysis of the constraints of a potential species would have to be assessed in greater detail on a case by case basis.

From a physical oceanography perspective, both shellfish and finfish aquaculture appear to be achievable in this region. The temperature regime is suitable for many shellfish and finfish species. Currents and waves – although extreme at times – should be able to be mitigated through careful structure placement and design. For both finfish and shellfish aquaculture considerably more effort on the production and economics of a selected species would be required before aquaculture developments could progress with confidence in the region.

5. ACKNOWLEDGEMENTS

The staff of MetOcean Solutions Ltd., namely David Johnson and Peter McComb are thanked for their professional assistance in providing data and methods used in this report.

6. REFERENCES

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7. APPENDICES

Appendix 1. Description of MetOcean Current Hindcast Modelling Methods (Provided by MetOcean Solutions Limited).

The MSL implementation of POM (Princeton Ocean Model) was used to hindcast the depth-averaged wind-driven and tidal currents. POM is a primitive equation ocean model that numerically solves for oceanic current motions. The details of model implementation are described in Mellor (2004). POM has been used for numerous scientific applications studying oceanic and shelf circulation.

Model equations

For the hindcast simulations, MSL-POM is used in a vertically integrated two-dimensional mode, solving the momentum and mass conservation equations given by:

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}-fv=-g\frac{\partial \eta}{\partial x}-\frac{1}{\rho}\frac{\partial P_a}{\partial x}+A_H\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)+\frac{\tau_w^x}{\rho h}-\frac{\tau_b^x}{\rho h}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}-fv=-g\frac{\partial \eta}{\partial y}-\frac{1}{\rho}\frac{\partial P_a}{\partial y}+A_H\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+\frac{\tau_w^y}{\rho h}-\frac{\tau_b^y}{\rho h}$$

$$\frac{\partial \eta}{\partial t}+\frac{\partial\left(u[h+\eta]\right)}{\partial x}+\frac{\partial\left(v[h+\eta]\right)}{\partial y}=0 \qquad \text{(1 a,b,c)}$$

where t is the time, u and v are the depth-averaged velocities in the x and y directions respectively, h the depth, η is the elevation of the surface, g the gravitational acceleration, f the Coriolis parameter, ρ the density of water, and Pa is atmospheric pressure.

AH is a horizontal eddy viscosity coefficient, calculated with a Smagorinsky parameterisation,

$$A_H=C_m\Delta x\Delta y\frac{1}{2}\left[\left(\frac{\partial u}{\partial x}\right)^2+\left(\frac{\partial v}{\partial x}+\frac{\partial u}{\partial y}\right)^2+\left(\frac{\partial v}{\partial y}\right)^2\right]^{\frac{1}{2}} \qquad \text{(2)}$$

with Cm set at 0.2.

The surface and bottom shear stress, τw and τb are due to wind and bottom friction. The bed shear stress is parameterised with a quadratic type friction law,

$$\tau_b^x=C_D\sqrt{\left(u^2+v^2\right)}u \quad \tau_b^y=C_D\sqrt{\left(u^2+v^2\right)}v \qquad \text{(3 a,b)}$$

that depends on an adjustable drag coefficient, CD ~ 10-3

The wind shear stress is parameterised by:

$$\tau_w^x = \rho_a \gamma |W_{10}| W_{10}^x \quad \tau_w^y = \rho_a \gamma |W_{10}| W_{10}^y \qquad (4\ a,b)$$

where ρa is the density of air and γ is a coefficient given by:

$$\gamma = \left(A + B|W_{10}|\right) \times 10^{-3} \qquad (5)$$

W10 is the wind velocity 10 m above sea level and A and B are coefficients with values 0.001 and 0.0001 respectively.

The model equations are solved with finite differences and explicit time-stepping.

Boundary conditions and surface forcing

The same boundary conditions are applied at all open boundaries. For the surface elevation, an Orlanski (1976)-type radiation boundary condition is applied, but with the normal component of the outgoing phase speed determined as the normal projection of the full oblique phase speed (NPO in Marchesiello *et al*. 2001). For the normal component of depth-averaged velocity, u_n , a Flather (1976) type constraint is used,

$$u_n = u_n^b + \sqrt{\frac{g}{h}}\left(\eta - \eta^b\right) \qquad (6)$$

The boundary values of u_n^b and η^b are known boundary values for the surface elevation and depth-averaged current.

Surface forcing, both the 10 m winds and atmospheric pressure were input into the model. The surface pressure is from the NCEP global reanalysis and surface winds are from the Blended Sea Winds data, as for the wave modelling. Wind velocity components and atmospheric pressure were interpolated linearly in both space and time onto the model grid.

The TPXO7.1 global inverse tidal solution (Egbert & Erofeeva 2002) was used to prescribe the tidal elevation and current velocity at the boundaries of the New Zealand grid.

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Appendix 2. Description of MetOcean Hindcast wave and wind modelling Methods (Provided by MetOcean Solutions Limited).

Numerical model

SWAN (Simulating Waves Nearshore) was used for all of the wave modelling. SWAN is a third generation ocean wave propagation model, which solves the spectral action density balance equation for wave number-direction spectra. This means that the growth, refraction and decay of each component of the complete sea state, each with a specific frequency and direction, is solved, giving a complete and realistic description of the wave field as it changes in time and space. Physical processes that are simulated include the generation of waves by surface wind, dissipation by white-capping, resonant nonlinear interaction between the wave components, bottom friction and depth limited breaking. A detailed description of the model equations, parameterisations, and numerical schemes can be found in Holthuijsen *et al.* (2007). All third generation physics are included. The Collins friction scheme is used for wave dissipation by bottom friction.

The solution of the wave field is found for the non-stationary (time-stepping) mode. Boundary conditions, wind forcing and resulting solutions are all time dependent, allowing the model to capture the growth, development and decay of the wave field.

Model domain and boundary conditions

For the wave hindcasting, a New Zealand-wide domain was used with a longitude/latitude grid with resolution of 0.05˚ by 0.05˚ (approximately 4.5 km by 5.4 km). Fully-nested spectral open ocean boundaries on the New Zealand domain were obtained from the MetOcean Solutions global WW3 hindcast, and the Blended Wind product (Section 2.3) was used to specify a spatially varying wind field.

Winds

The regional wind field is very important for wave generation. A spatially varying wind field was specified from a blended global wind product developed by MSL. These data are 10 m wind velocity vectors in a 3-hourly gridded format at a resolution of 0.25° of longitude and latitude. The wind field is a combination of the 6-hourly Blended Sea Winds data and 3-hourly model wind fields from the National Centers for Environmental Prediction (NCEP) at the United States National Oceanic and Atmospheric Administration (NOAA). The blended data product combines the benefits of measured satellite data with the temporal resolution and continuous coverage of the modelled re-analysis.

These data have been validated against coastal and open-ocean wind stations around New Zealand (including Maui A and B platforms); providing a good representation of the 10-minute mean wind speed at the 10 m elevation above sea level.

Model output

Waves were hindcast for the years 1998-2007, and directional wave spectra statistics were archived at 3-hourly intervals. The mean and maximum significant wave heights hindcast over the over the 10-year hindcast are shown in Figure 1. The hindcast wave model outputs have been validated with wave buoy data from numerous locations around New Zealand (ranging from 10-110 m depths).

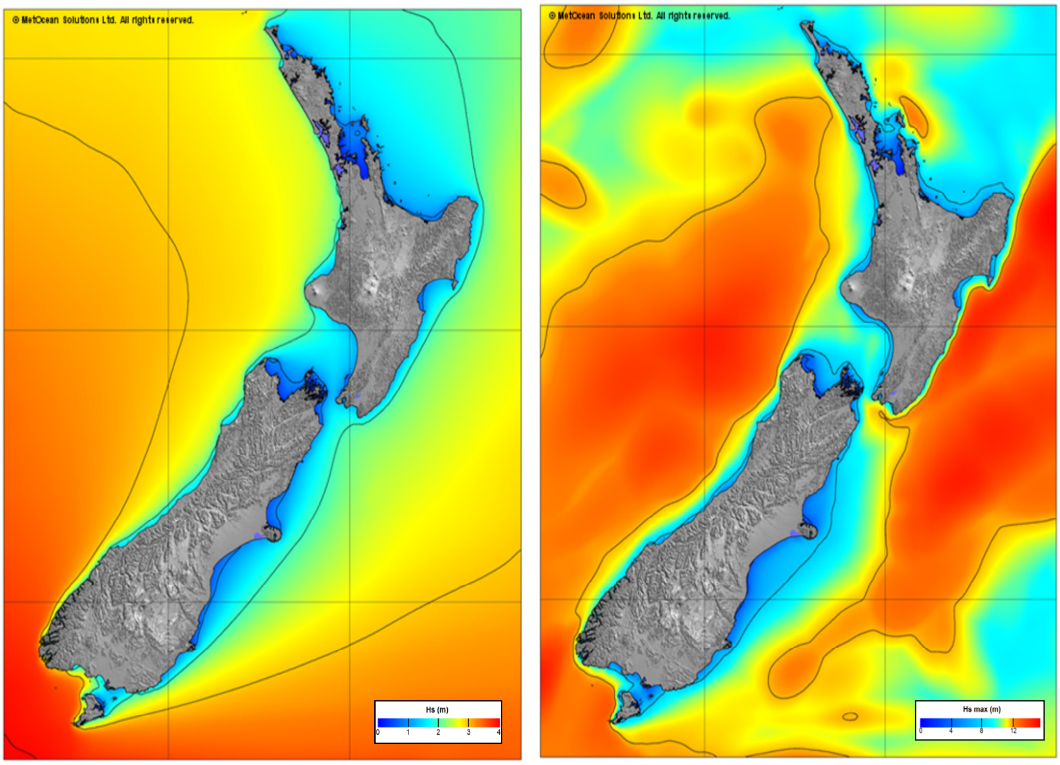

Figure 1 Mean (left) and maximum (right) significant wave heights 1998-2007.

Spectral wave statistics

Given a directional wave spectrum $S(f,\theta)$, the 1-dimensional spectrum is obtained by integrating over directions:

$$S(f) = \int_0^{2\pi} S(f,\theta)d\theta$$

From the computed spectral energy density *S(f)*, the peak frequency f_p and peak energy $S_p = S(f_p)$ of the spectrum are located. Spectral moments

$$M_j = \int_0^{\infty} f^j S(f)\, df$$

are computed, allowing further statistics to be defined:

significant height $H_s = 4\sqrt{M_0}$

mean period $T_{m1} = M_0 / M_1$

mean apparent period $T_{m2} = \sqrt{M_0 / M_2}$

mean frequency $f_{mean} = M_1 / M_0$

mean crest period $T_{cr} = \sqrt{M_2 / M_4}$

spectral width $SW = 1 - \dfrac{{M_2}^2}{M_0 M_4}$

T_{m2} is often used as a spectral approximation of the zero-down-crossing period statistics T_z.
Directional moments are:

$$M_c = \int_0^\infty \int_0^{2\pi} S(f,\theta) \cos\theta \, d\theta \, df$$

$$M_s = \int_0^\infty \int_0^{2\pi} S(f,\theta) \sin\theta \, d\theta \, df$$

The mean direction is $\theta_0 = \arctan\left(\dfrac{M_s}{M_c}\right)$

and the directional spread is $\Delta = \sqrt{2 - \dfrac{2\sqrt{M_c^2 + M_s^2}}{M_0}}$.

References for Appendix 2:

Holthuijsen LH, Booij N, Ris RC, Haagsma IJG, Kieftenburg ATMM, Kriezi EE, Zijlema M, van der Westhuysen AJ 2004. SWAN Cycle III version 40.31 User manual. Available: http://fluidmechanics.tudelft.nl/swan/index.htm.