Extreme wave indices for New Zealand coastal and oceanic waters

Updated to 2017

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Executive summary

The Ministry for the Environment (MfE) has commissioned NIWA to update Coastal and Ocean Extreme Wave Indices, previously developed (Gorman 2016) in order to quantify the occurrence of extreme wave events in New Zealand on an annual basis.

The Extreme Wave Indices are based on numerical model outputs provided by NIWA's operational wave forecasting models, which were used to quantify the number of storm events exceeding selected thresholds of significant wave height and duration, within chosen coastal regions and ocean areas. Following consultation, three thresholds were selected, based on significant wave heights exceeding 4.0 m, 6.0 m and 8.0 m. In each case a 12-hour duration threshold was used.

The Coastal Extreme Wave Index is computed by counting events exceeding the thresholds within each of the 18 Coastal Marine Forecast Areas (as used in MetService marine forecasts). The Ocean Extreme Wave Index is derived by counting exceedances within each of six zones into which New Zealand's Exclusive Economic Zone was subdivided.

In the previous report (Gorman 2016), values of the Indices for 2008-2015 were presented, derived from NIWA's NZWAVE-12 operational wave forecast. Results for 2015 were also compared with corresponding results from a new forecast (NZWAVE-8) that has now become operational.

In the present report, indices previously derived for the years 2008-2015 have now been extended to 2016 and 2017, based on the NZWAVE-8 forecast.

These results are also available to the project team in shapefile format, for public online access.

1 Introduction

In 2016 NIWA developed a Coastal Extreme Wave Index, and an Ocean Extreme Wave Index, commissioned by the Ministry for the Environment (MfE) in order to quantify the occurrence of extreme wave events in New Zealand on an annual basis. These were to form part of a wider set of environmental indicators being developed to measure and disseminate information on changes in New Zealand's marine environment (for example, Environment Aotearoa or Tier 1 indicators).

Recommendations for the form of these indicators had been developed in previous work (Pinkerton, Bell et al. 2015) carried out by NIWA on MfE's behalf. In particular, it was advised that extreme wave indices could be derived from numerical wave model outputs by computing the exceedances of certain wave height and storm duration thresholds within selected regions.

In a previous report (Gorman 2016) we described the implementation of Coastal and Ocean Extreme Wave Indices. Some results of validation of NZWAVE-12 forecasts against available wave data from five wave buoys are also presented. Results are then presented for each of three selected thresholds, in the form of maps of annual exceedances in both coastal and ocean regions, and time series plots showing temporal variation of exceedances on interannual and seasonal time scales, derived from model outputs from 2008 through 2015.

In the present study, we update these results for the calendar years 2016 and 2017.

2 Methods

2.1 Wave forecast models

As part of NIWA's EcoConnect[1] forecasting system for weather-related hazards, a wave forecast model has been operated four times per day since mid-2007 to provide forecasts on a domain covering the New Zealand region. This employs the Wavewatch III® spectral wave model code (Tolman 2009), and takes inputs from two other EcoConnect models:

- wind fields are taken from the NZLAM-12 weather model (four daily 48-hour forecasts)
- swell entering the region through the model boundaries are provided by a global wave model, run daily at NIWA using inputs from the UK Met Office's global weather forecast.

From mid-2007 to mid-2016, these regional forecasts were provided by the NZWAVE-12 model, implemented on a regular latitude/longitude grid covering the 243 cells of longitude from 144.000°E to 184.333°E at (1/6)° resolution, and 303 latitude bins from 54.555°S to 21.000°S at (1/9)° resolution. The extent of this domain approximately matches that of the NZLAM-12 weather model, covering almost the full extent of New Zealand's Exclusive Economic Zone, and extending westward across the full extent of the Tasman Sea. As weather systems in the region generally travel from west to east, this westward extension improves the ability to accurately predict weather and wave conditions reaching New Zealand.

In mid-2014, an 8-km resolution wave model ("NZWAVE-8 ") was initiated on a similar spatial domain to NZWAVE-12, and which uses the same NZLAM-12 inputs. This uses a regular latitude/longitude grid covering the 353 cells of longitude from 143.320°E to 184.570°E at 0.1172° = (15/128)° resolution, and 431 latitude bins from 54.453°S to 20.859°S at 0.0781° = (10/128)° resolution. This replaced NZWAVE-12 as the operational model in mid-2016.

Hourly values of wave statistics for each grid cell output by both models are archived, including significant wave height, mean and peak wave periods, mean and peak wave direction. Archived outputs from NZWAVE-12 are available from mid-2007 to mid-2016, while data from NZWAVE-8 are available from mid-2014 to the present.

For both models, four forecasts are/were run each day, starting at 00, 06, 12 and 18 hours UT. These generally cover a 48-hour forecast period, although initially the NZWAVE-12 00UT and 12UT forecasts were only run for 6 hours to provided updated restarts for the longer forecasts. For present purposes, only the first 6 hours of each successive forecast are used, representing the latest (and hence, normally, most accurate) forecast for each output time.

In the initial study (Gorman 2016), results were presented from the NZWAVE-12 model, covering complete calendar years 2008 through 2015. Results from NZWAVE-8 for 2015 were also included for comparison. Some results of verification of the NZWAVE-12 model against data from five wave buoys (four around the New Zealand coast, plus one located off the Tasmanian west coast) were also presented.

[1] http://www.niwa.co.nz/fisheries/our-services/fisheries-and-ecoconnect

In the present study, we provide updated results through to 2017, derived from the NZWAVE-8 model.

2.2 Exceedance statistics

For each model grid cell, the archived forecast wave statistics provide a time series of significant wave heights at hourly intervals. For our purposes, significant wave height is defined as four times the square root of the variance of sea surface elevation due to wave motion (H_{m0}). Another commonly used definition is the mean value of the highest one-third of individual wave heights ($H_{1/3}$), but this statistic is not available from the outputs of spectral wave models. The two definitions generally give similar values, with $H_{1/3}$ typically 5%-10% smaller than H_{m0} (Holthuijsen 2007).

For a given threshold value H_{thresh} of significant wave height, a “storm event” can be defined as a continuous period during which the significant wave height equals or exceeds H_{thresh}. We can also define a duration threshold T_{thresh}, and count the number of storm events lasting greater than or equal to T_{thresh}.

In the testing phase, height thresholds H_{thresh} of 1.0 m to 10.0 m, in 1.0 m increments, were used, in combination with duration thresholds of 3, 6, 12 and 24 hours, before selecting one or more specific combination of thresholds to be used in defining the extreme wave indices.

After discussing initial results in a workshop with project team members on 11 February 2016, it was agreed that a duration threshold of 12 hours would be most suitable. This allows semi-diurnal tides to cover their full low water to high water range, maximising the likelihood of coastal effects such as inundation or coastal erosion to arise from the storm. It was also noted that the marked variation in wave climate within the New Zealand region mean that what can be considered “extreme” will also vary around the country. It was decided that three wave height thresholds should be considered, and that these values should be related to high percentiles of the significant wave height occurrence distribution.

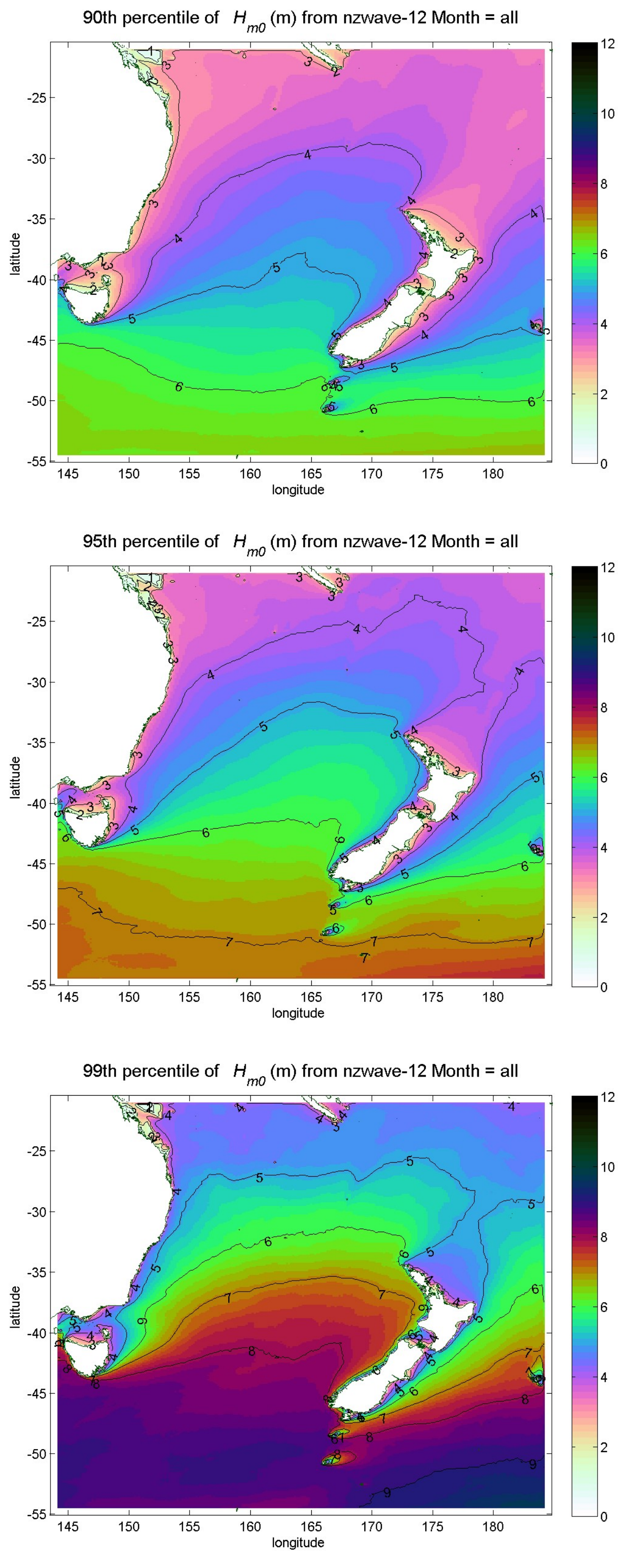

Figure 2-1: Percentile values of significant wave height from NZWAVE-12 outputs over the years 2010 through 2015. The 90th (top panel), 95th (middle panel) and 99th (bottom panel) percentiles are shown.

Figure 2-1 shows the 90th, 95th and 99th percentile values of significant wave height derived from the NZWAVE-12 forecast model, using 6 years of outputs (2010 through 2015). These plots illustrate the spatial variation in wave climate in the New Zealand region, with the most energetic wave conditions occurring in the Southern Ocean, where typically strong winds are a persistent source of swell, which travels up from the southwest into the Tasman Sea and Pacific Ocean. While individual storm events in the Tasman Sea and Pacific Ocean can produce energetic local wave conditions anywhere on the open coast, from a wide range of directions, the degree to which the New Zealand land masses intercept this southwesterly swell to create a "swell shadow" (most noticeably to the northeast of the North Island) is a significant controlling factor in the long-term average wave climate.

We observe that 8 m significant wave heights are exceeded at the 99th percentile level in the most exposed southern parts of the New Zealand region, so this can be considered a suitable threshold value to represent the most energetic conditions within the whole region. In the waters northeast of the North Island, at the other extreme, 99th percentile wave heights are in the range 4-5 m, while intermediate values are seen off the west coasts of both islands, and the east coast of the South Island and lower North Island. Hence a 4 m threshold should be sufficiently low to still obtain reasonable numbers of events in these more sheltered waters. This value is also exceeded at the 90th percentile level for large areas of coastal waters off the west and east coasts. Adding an intermediate value, we subsequently focus on significant wave height thresholds of 4, 6 and 8 m.

An alternative approach to using several different fixed thresholds might be to define different threshold for each area, according to, for example, the (spatial) mean or maximum value of the 95th percentile significant wave height *within that area*. This could be done on an annual or monthly basis. Then the number of exceedances would be of similar magnitude across all regions, which would offer some advantages in tracking year-to-year variations in wave climate. This does have the disadvantage of being a somewhat more complex and less "concrete" concept for the intended public audience.

2.3 Spatial partitioning of outputs

We wish to consider separate extreme wave indices for both coastal waters and deep ocean waters.

The *coastal extreme wave index* should provide a measure of wave climate in discrete stretches of coastline. For this purpose, we have chosen the 18 New Zealand Marine Weather Regions (Figure 2-2), used by MetService in issuing Marine Weather Forecasts. These are defined by separating the coasts of the North Island, South Island and Stewart Island into segments between specified landmarks, with an offshore boundary 60 nautical miles (nm) from the coast (LINZ 2015). The "Chatham Islands" region covers all waters around those islands, except where the eastern boundary of the model grid cuts off a small portion of the 60 nm limit. The resulting regions are shown in Figure 2-3.

The *ocean extreme wave index* is intended to cover ocean waters within New Zealand's Exclusive Economic Zone, subdivided into a small number of regions with broadly similar wave climate. In the absence of suitably previously-defined delineations, we subdivide New Zealand's EEZ (except where it extends beyond the eastern and southern limits of the model domain) into 6 regions (Figure 2-4) similar to those suggested by the Tier 1 indicators report (Pinkerton, Bell et al. 2015). These regions are distinguished by the degree of exposure to the main influences of New Zealand's wave climate. For example, the "South" region is fully exposed to the persistently strong SW to southerly swells originating in the Southern Ocean. The "East" region has some exposure to these swells, along with waves generated in the subtropical Pacific, while the “West” and “Northwest” regions are exposed to waves the Southern Ocean and the Tasman Sea. The “Northeast” region is sheltered from Southern Ocean swells, but is exposed to the tropical and subtropical Pacific Ocean, while conditions in the sheltered “Cook Strait” region would be expected to be dominated by local weather conditions. The endpoints of the coastal boundaries of these regions correspond to a subset of the locations used to mark the endpoints of the Marine Weather Regions used for the coastal index. Shapefiles[2] of the EEZ boundaries were used to specify the offshore limits.

Ideally, the ocean areas would cover the full extent of the EEZ, but the available model domains do not quite allow this, cutting off a portion of the North, East and South areas. A slightly higher number of exceedances could be expected if the full extent of the EEZ were available, particularly in an extended South area, of which the “missing” segment has the highest-energy wave climate. But, noting the somewhat arbitrary nature of the area definitions, and that relative changes in the indices are of more importance than their absolute values importance, it may be considered better to accept this limitation than to be forced to use an alternative model source (e.g., a lower resolution global simulation).

[2] Sourced from Land Information New Zealand data. Crown Copyright Reserved.

Figure 2-2: Map of the New Zealand Marine Weather Regions. From http://commons.wikimedia.org/wiki/File:NZ_regions.svg.

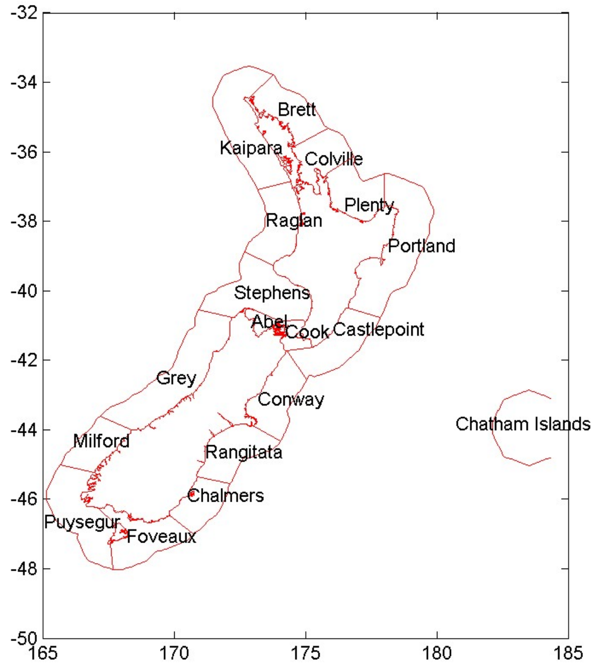

Figure 2-3: Regions defined for deriving coastal extreme wave indices.

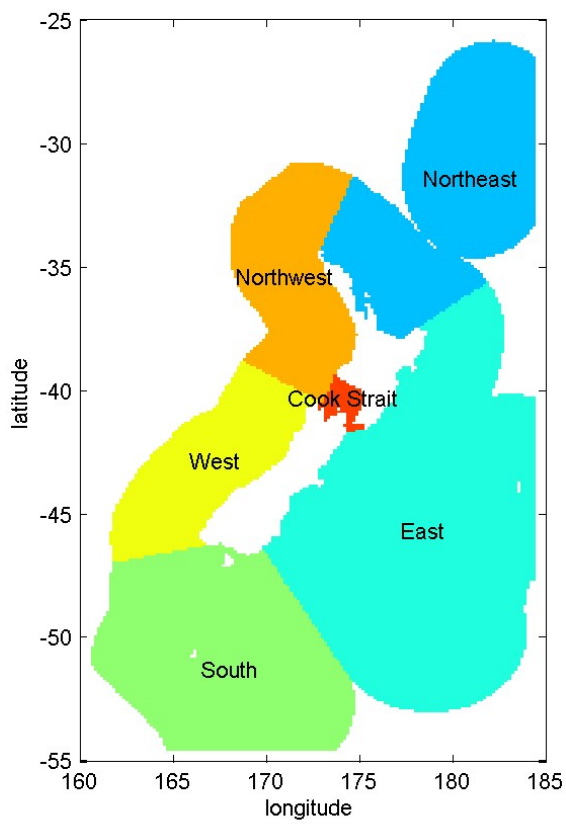

Figure 2-4: Regions defined for deriving ocean extreme wave statistics.

2.4 Calculation of extreme wave indices

For each cell of the model domain, the number of storm events exceeding each combination of height and duration threshold was summed for each calendar month, and for each calendar year. This gives a spatially-varying exceedance number, defined for the full model domain. Then a single value for the number of exceedances within each (coastal or ocean) region was found by taking the (spatial) maximum of exceedances found within the respective region. The use of a spatial maximum rather than, say, a spatial mean, was intended to give a measure of the extremes of wave climate within each region. The maximum does, however, have the disadvantage of being less statistically robust quantity than a mean, being sensitive to the timing and location of individual storm events.

The annual exceedance values, for a selected set of thresholds, are then used to define the coastal and ocean extreme wave indices.

The monthly values are also of interest, to illustrate interannual variability in the wave climate. Given the different number of days in the months, these are first converted to an annual exceedance rate:

$$Annual\ exceedance\ rate = Number\ of\ exceedances\ in\ a\ month\ \times \frac{Number\ of\ days\ in\ the\ year}{Number\ of\ days\ in\ the\ month}$$

3 Results

In this section we present Coastal and Ocean Extreme Wave Index results for 2016 and 2017, in the form of maps of exceedances for those years, for each of the three thresholds considered. These results have also been made available in shapefile format.

We also use corresponding results from the years 2008 through 2017 to illustrate temporal variability, on both interannual and seasonal time scales.

3.1 4.0 m significant wave height threshold

Results for 2016, derived from the NZWAVE-8 forecasts and using H_{thresh} = 4.0 m, and T_{thresh} = 12 hours, are plotted below for the coastal regions (Figure 3-1) and the ocean regions (Figure 3-2). Corresponding results for 2017 are plotted in Figure 3-3 and Figure 3-4. Consistent with the 2015 results reported previously (Gorman 2016), we see that events exceeding this threshold occur on an approximately weekly basis in the more exposed coastal marine forecast regions on the South Island southern and western coasts (Foveaux, Puysegur, Milford, Grey), and for the Chatham Islands. Somewhat reduced occurrences of order 20-40 events per year are found on the North Island west coast (Stephens, Raglan, Kaipara), again consistent with 2015 results. The east coast of the South Island (Chalmers, Rangitata, Conway) and lower North Island (Castlepoint, Portland) showed significantly lower occurrences in 2016 and 2017 than were observed in 2015. Most regions (Colville, Plenty) to the northeast of the North Island and in the greater Cook Strait region (Cook, Abel) all saw fewer than 10 exceedances, however Brett, on the far northeast coast, which had similarly low occurrences in 2015 showed more than 10 occurrences in both 2016 and 2017.

Looking at the more extensive ocean regions (Figure 3-2) we see that the East, South and West regions, as for 2015, all have similar levels of exceedance, around 70 per year, indicating that this threshold is exceeded around every 5 days within these regions. This is a typical timescale for passage of large scale weather systems, most of which will produce waves over 4 m significant height within them, and these ocean regions have sufficient area of open water clear of land influences for virtually every passing weather system to trigger an exceedance somewhere within them.

The interannual variation of these same results over the years 2008-2017 are shown in Figure 3-5, for coastal regions, and Figure 3-6, for ocean regions, extending similar plots for 2008-2017 presented previously (Gorman 2016). After 2014 produced a particularly energetic year for most regions, a subsequent decline in 4 m exceedances was observed for many regions, particularly on the east coast. Increasing trends were observed in both the far south (Foveaux) and far north (Brett).

Seasonal variability is illustrated by plotting the mean exceedance rates for each month (averaged over the 8 years of the NZWAVE-12 record) in Figure 3-7, for coastal regions, and Figure 3-8, for ocean regions.

The summer months (December, January, February) generally have the lowest exceedance rates of the year, with higher exceedances in winter and spring. For the Northeast ocean region, and the coastal regions within it, the seasonal cycle is relatively simple, between a single summer minimum and a single winter maximum. For many regions exposed to Southern Ocean swell, there tends to be a double maximum, in both winter (June or July) and in spring (September or October).

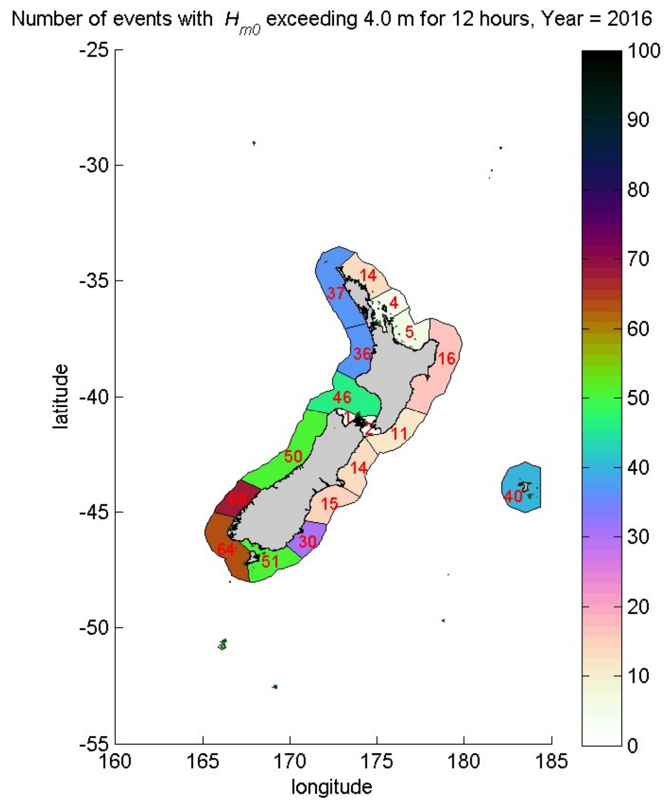

Figure 3-1: Maximum number of storm events in each coastal region exceeding 4.0 m significant wave height for 12 hours or more, for 2016. Computed from NZWAVE-8 forecast outputs.

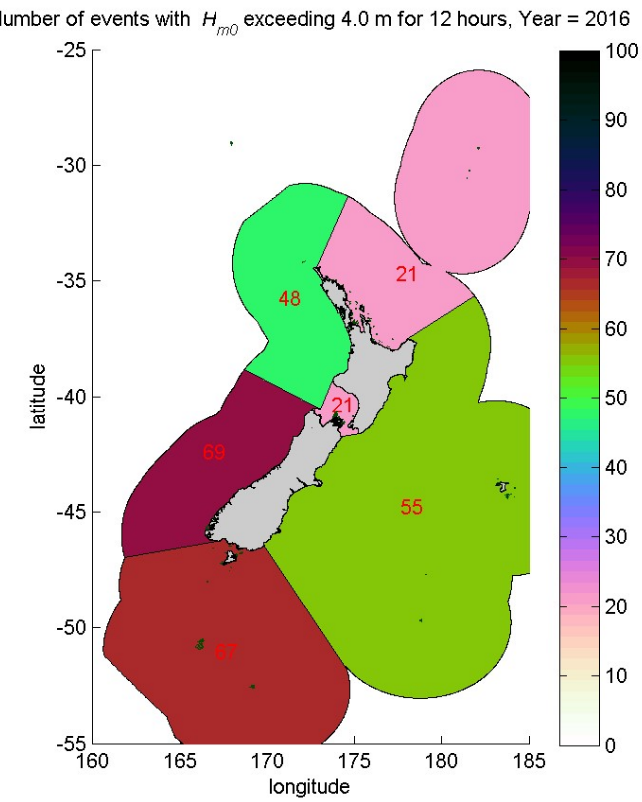

Figure 3-2: Maximum number of storm events in each ocean region exceeding 4.0 m significant wave height for 12 hours or more, for 2016. Computed from NZWAVE-8 forecast outputs.

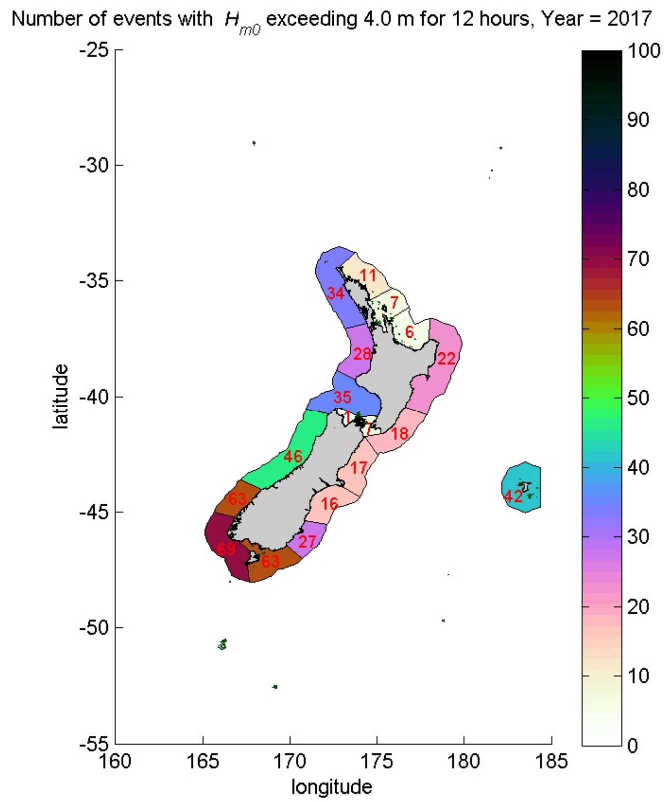

Figure 3-3: Maximum number of storm events in each coastal region exceeding 4.0 m significant wave height for 12 hours or more, for 2017. Computed from NZWAVE-8 forecast outputs.

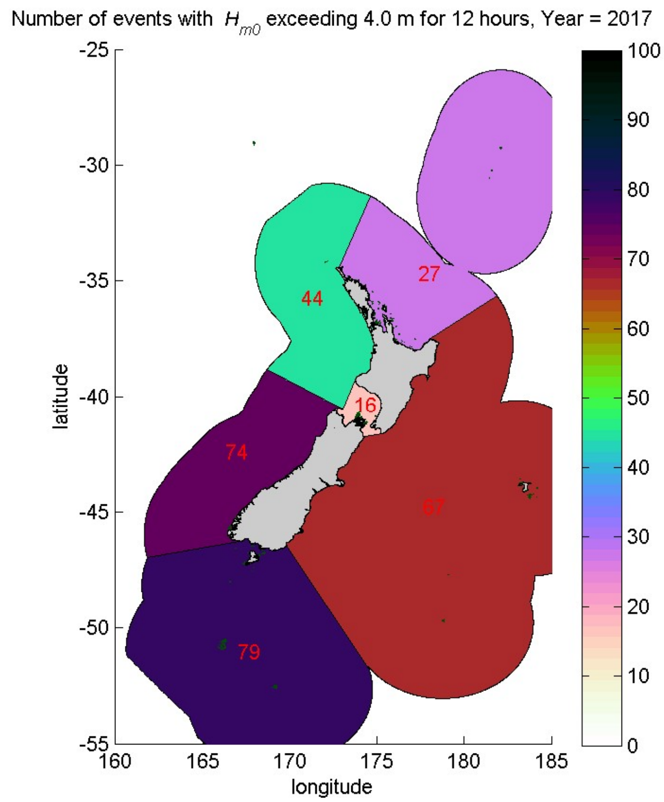

Figure 3-4: Maximum number of storm events in each ocean region exceeding 4.0 m significant wave height for 12 hours or more, for 2017. Computed from NZWAVE-8 forecast outputs.

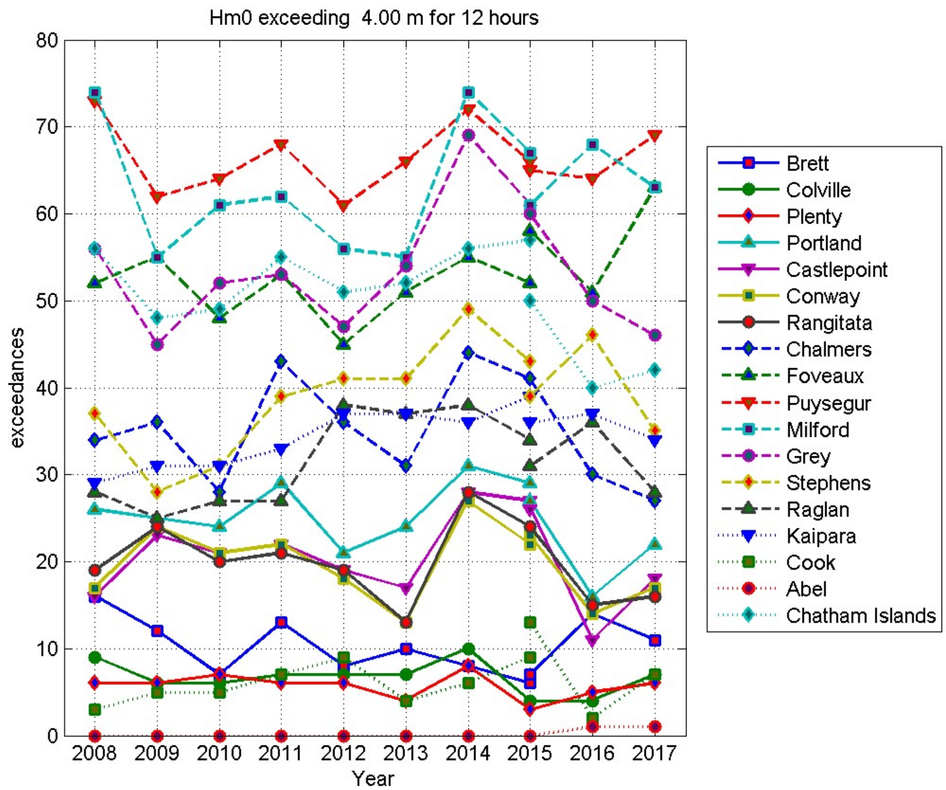

Figure 3-5: Yearly variation in the maximum number of storm events in each coastal region exceeding 4.0 m significant wave height for 12 hours or more. Results for 2008-2015 from the NZWAVE-12 forecast are shown, along with 2015-2017 results from the NZWAVE-8 forecast.

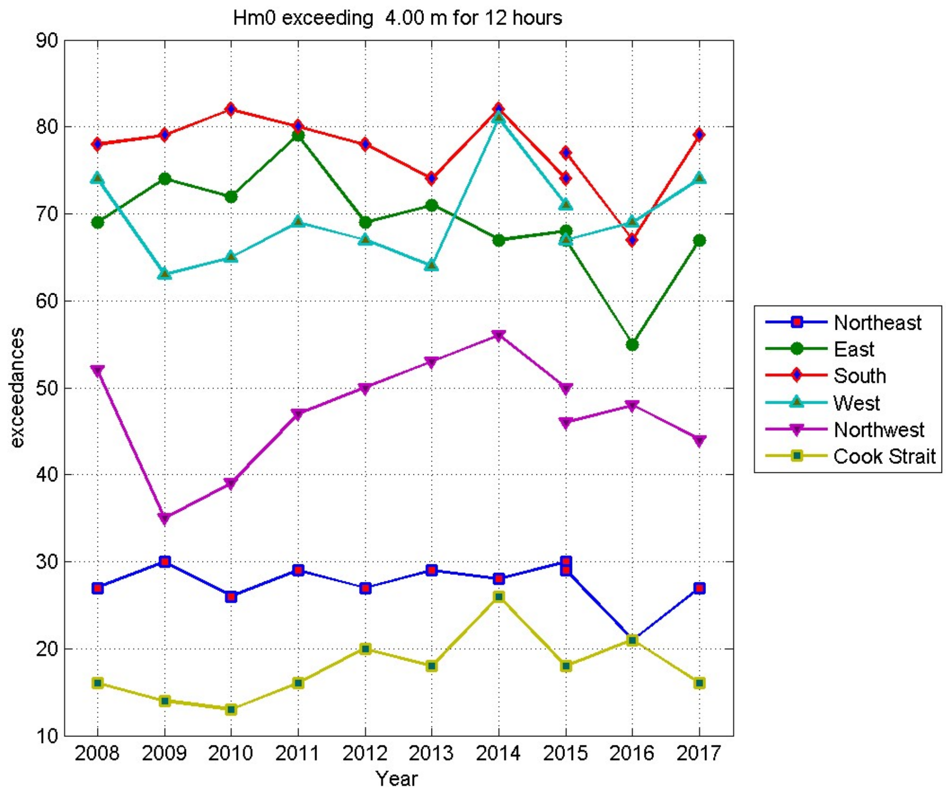

Figure 3-6: Yearly variation in the maximum number of storm events in each ocean region exceeding 4.0 m significant wave height for 12 hours or more. Results for 2008-2015 from the NZWAVE-12 forecast are shown, along with 2015-2017 results from the NZWAVE-8 forecast.

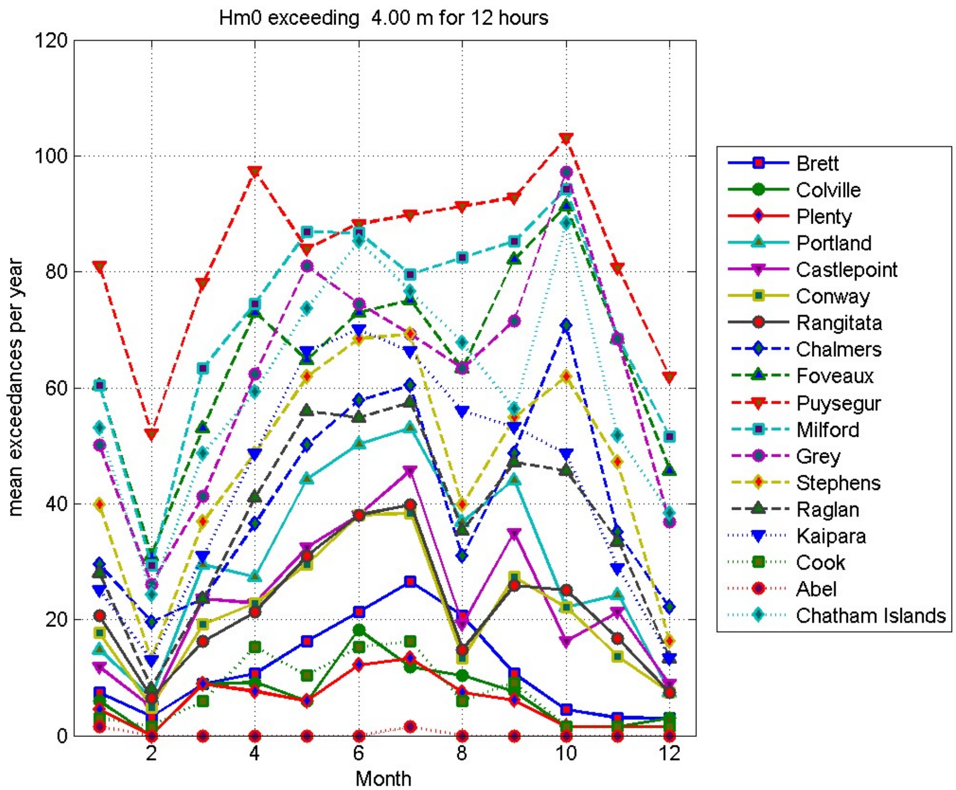

Figure 3-7: Monthly means of the occurrence of storm events in each coastal region exceeding 4.0 m significant wave height for 12 hours or more. Averaged over the years 2008-2015, from NZWAVE-12 outputs.

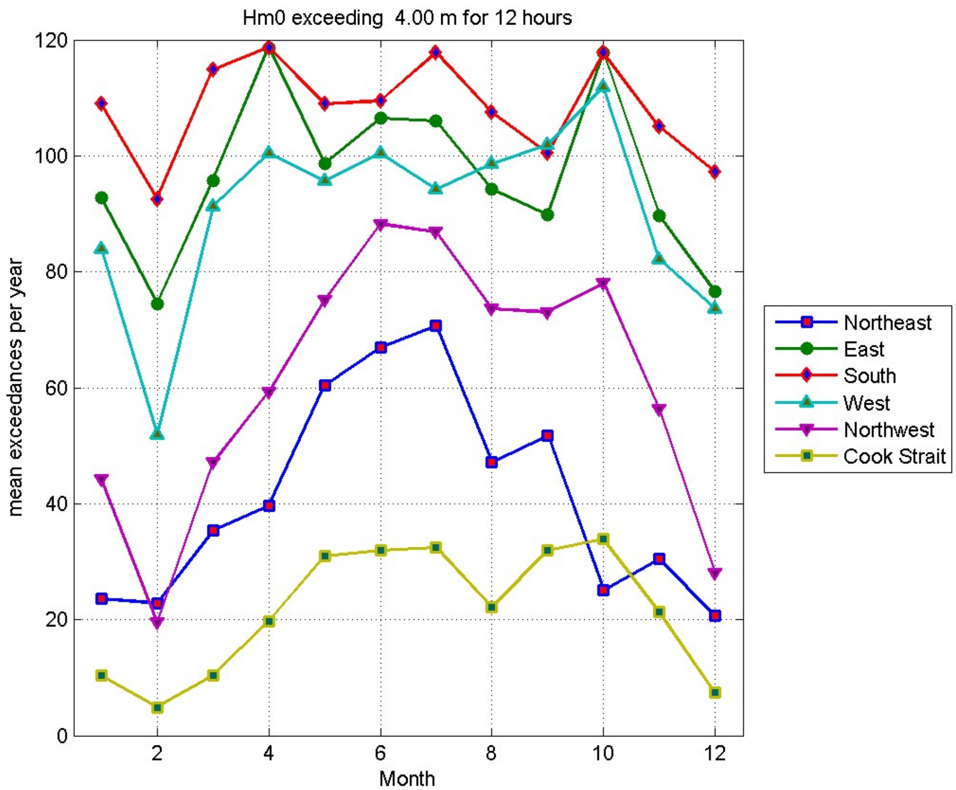

Figure 3-8: Monthly means of the occurrence of storm events in each ocean region exceeding 4.0 m significant wave height for 12 hours or more. Averaged over the years 2009-2015, from NZWAVE-12 outputs.

3.2 6.0 m significant wave height threshold

Results for 2016, derived from the NZWAVE-8 forecasts and using H_{thresh} = 6.0 m, and T_{thresh} = 12 hours, are plotted below for the coastal regions (Figure 3-9) and the ocean regions (Figure 3-10). Corresponding results for 2017 are plotted in Figure 3-11 and Figure 3-12.

The spatial patterns of 6.0 m exceedances are broadly similar to those seen for the 4.0 m height threshold, but with reduced numbers. For coastal regions exposed to the Southern Ocean, up to 25 exceedances were found, while the sheltered northeastern regions (Brett, Colville, Plenty) all recorded no more than one event in either year. Compared to 2015 results, both 2016 and 2017 produced generally fewer 6.0 m exceedances, particularly for the east coast.

The interannual variation of these same results over the years 2008-2017 are shown in Figure 3-13, for coastal regions, and Figure 3-14, for ocean regions. By contrast with the results with a 4.0 m threshold, 6.0 m exceedances generally reached a peak in 2015 rather than in 2014 for most regions, and the subsequent decline in exceedances over 2016-2017 is more consistent.

Seasonal variability (Figure 3-15 for coastal regions, and Figure 3-16 for ocean regions) again shows a dual-maximum (winter and spring) cycle for the most energetic regions, and a single winter maximum for regions further north (of course the very low values for the most sheltered regions do not allow a cyclical pattern to be identified).

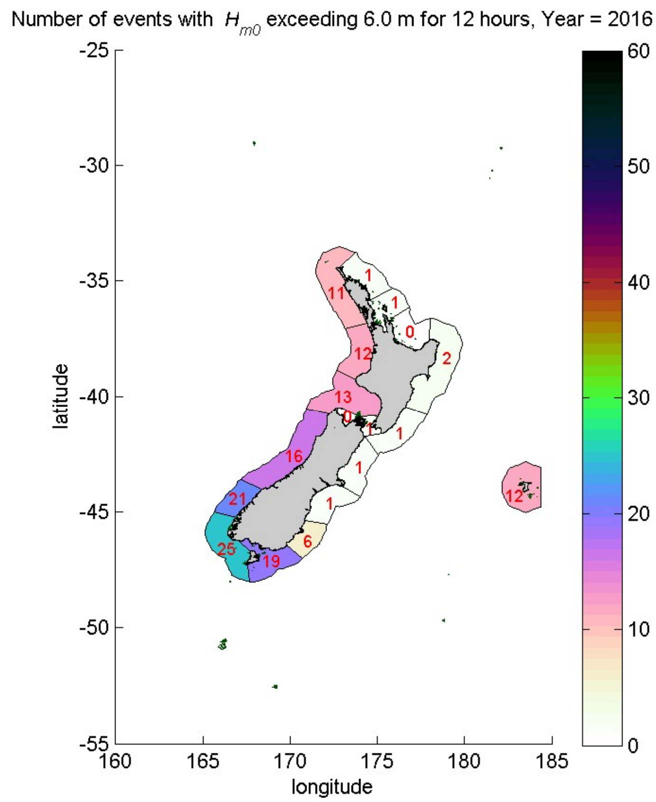

Figure 3-9: Maximum number of storm events in each coastal region exceeding 6.0 m significant wave height for 12 hours or more, for 2016. Computed from NZWAVE-8 forecast outputs.

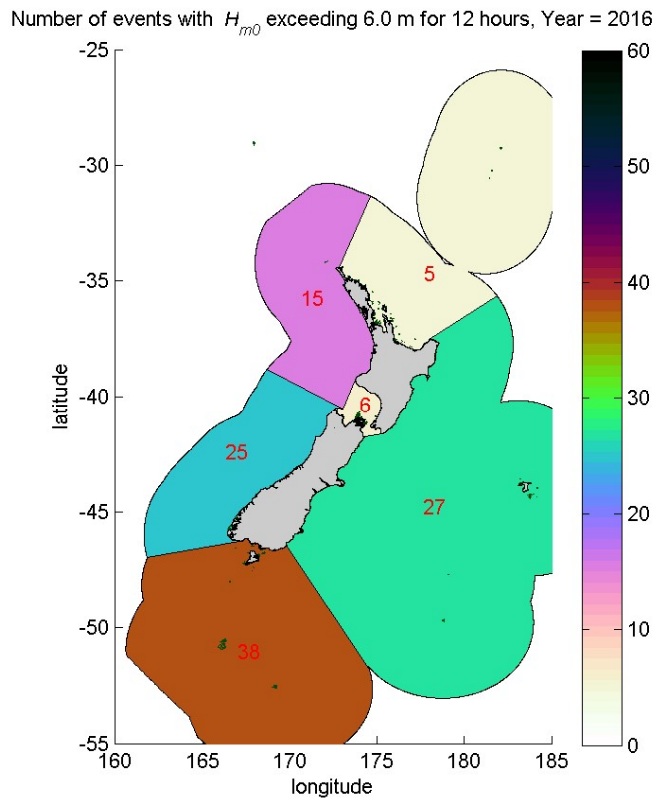

Figure 3-10: Maximum number of storm events in each ocean region exceeding 6.0 m significant wave height for 12 hours or more, for 2016. Computed from NZWAVE-8 forecast outputs.

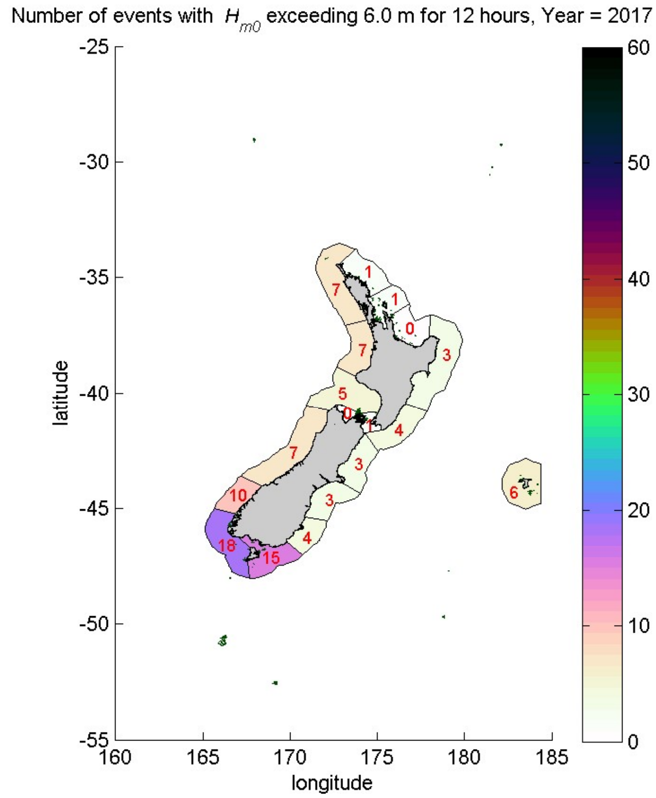

Figure 3-11: Maximum number of storm events in each coastal region exceeding 6.0 m significant wave height for 12 hours or more, for 2017. Computed from NZWAVE-8 forecast outputs.

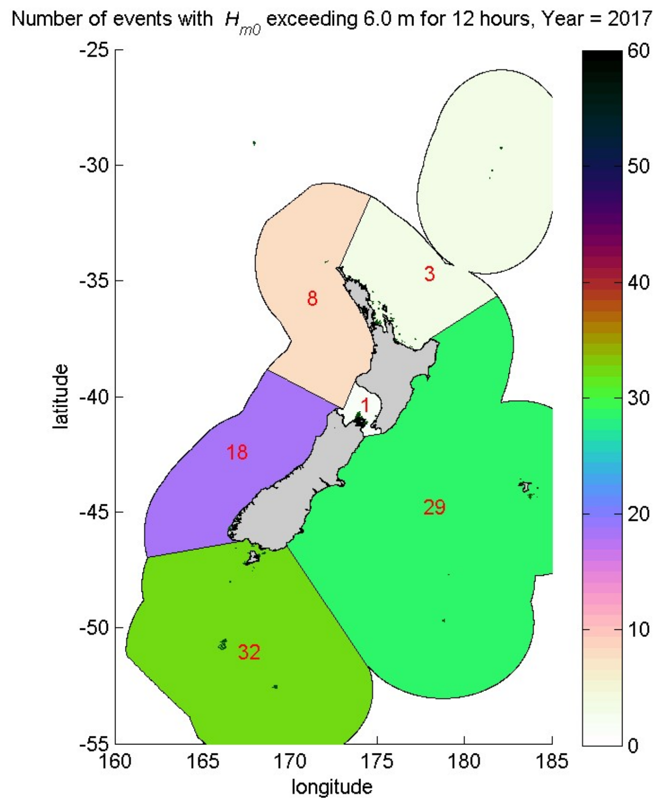

Figure 3-12: Maximum number of storm events in each ocean region exceeding 6.0 m significant wave height for 12 hours or more, for 2017. Computed from NZWAVE-8 forecast outputs.

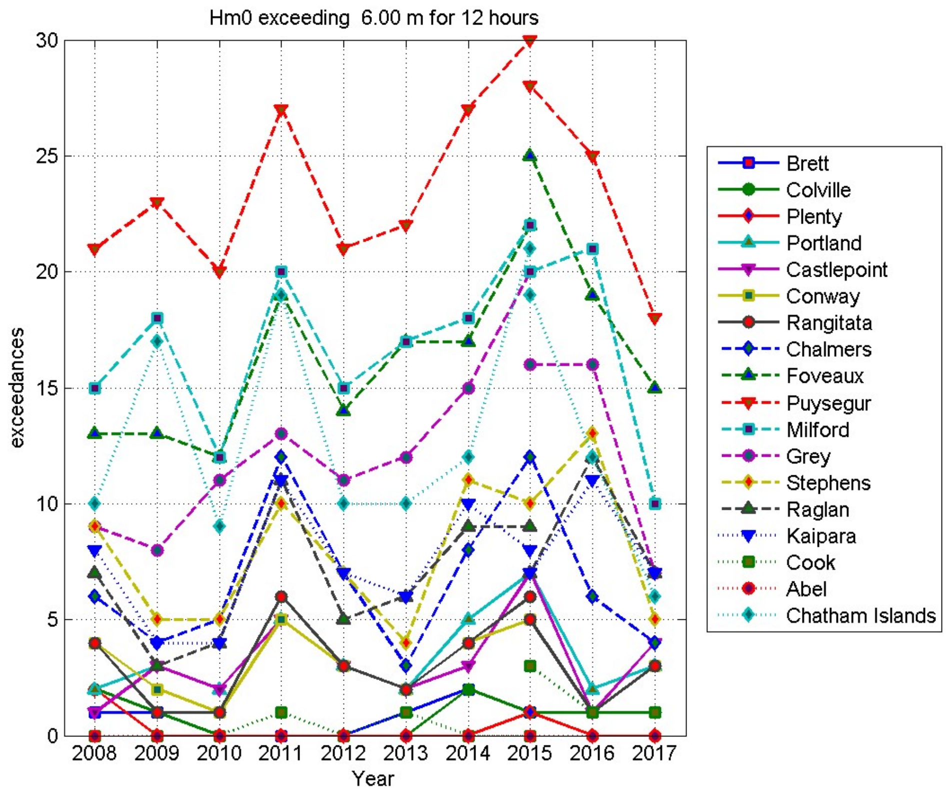

Figure 3-13: Yearly variation in the maximum number of storm events in each coastal region exceeding 6.0 m significant wave height for 12 hours or more. Results for 2008-2015 from the NZWAVE-12 forecast are shown, along with 2015-2017 results from the NZWAVE-8 forecast.

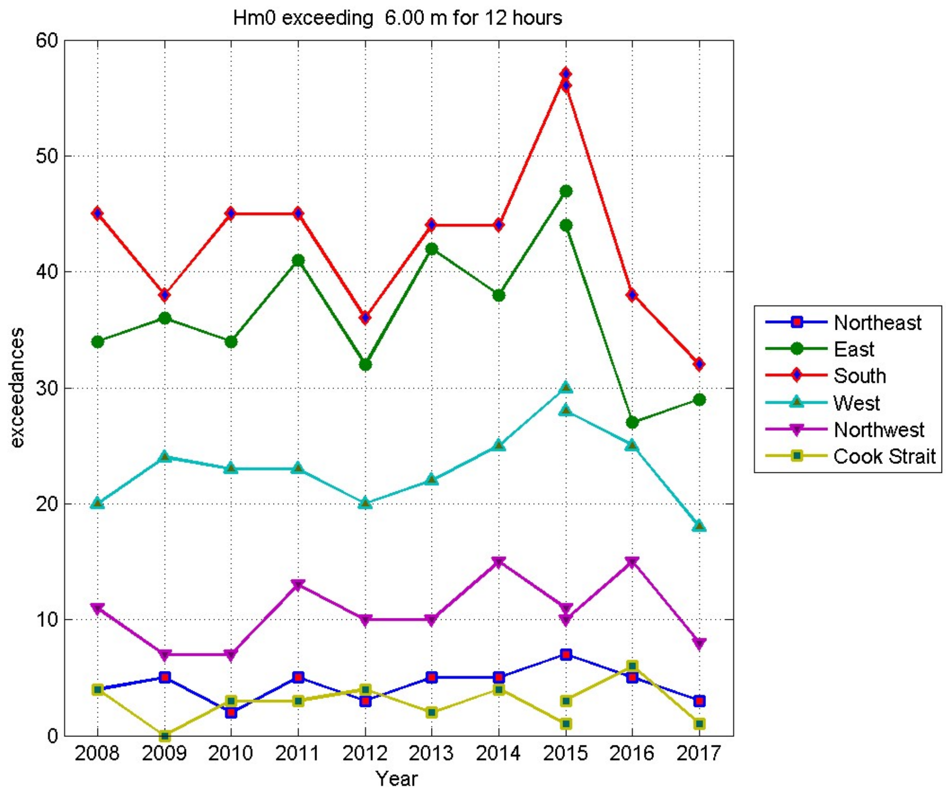

Figure 3-14: Yearly variation in the maximum number of storm events in each ocean region exceeding 6.0 m significant wave height for 12 hours or more. Results for 2008-2015 from the NZWAVE-12 forecast are shown, along with 2015-2017 results from the NZWAVE-8 forecast.

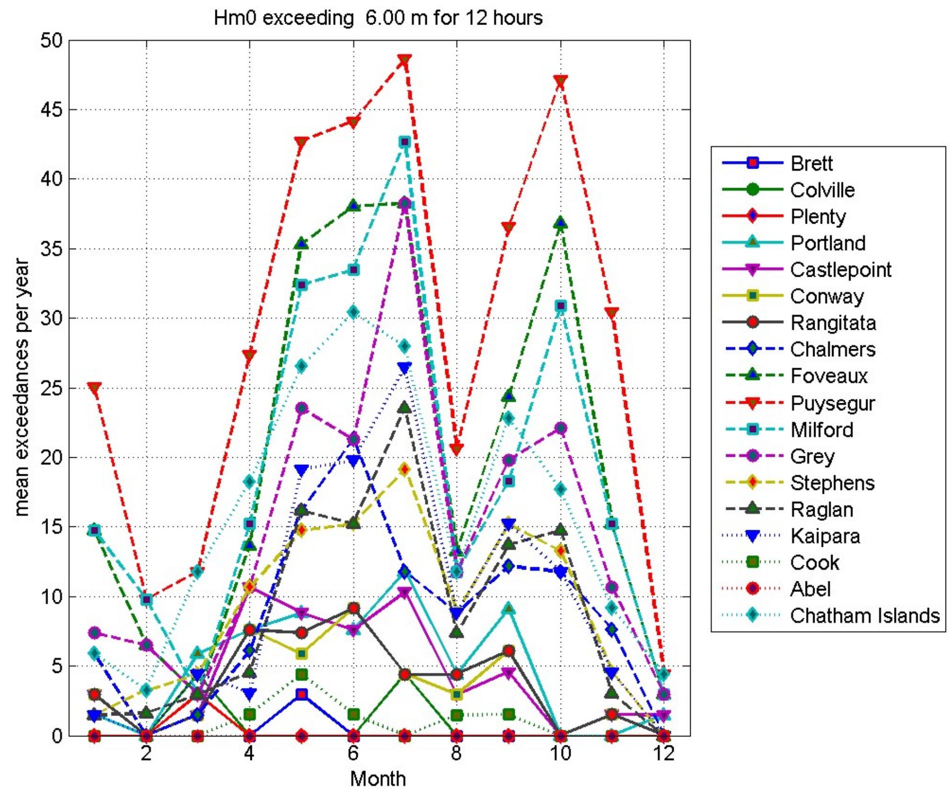

Figure 3-15: Monthly means of the occurrence of storm events in each coastal region exceeding 6.0 m significant wave height for 12 hours or more. Averaged over the years 2009-2015, from NZWAVE-12 outputs.

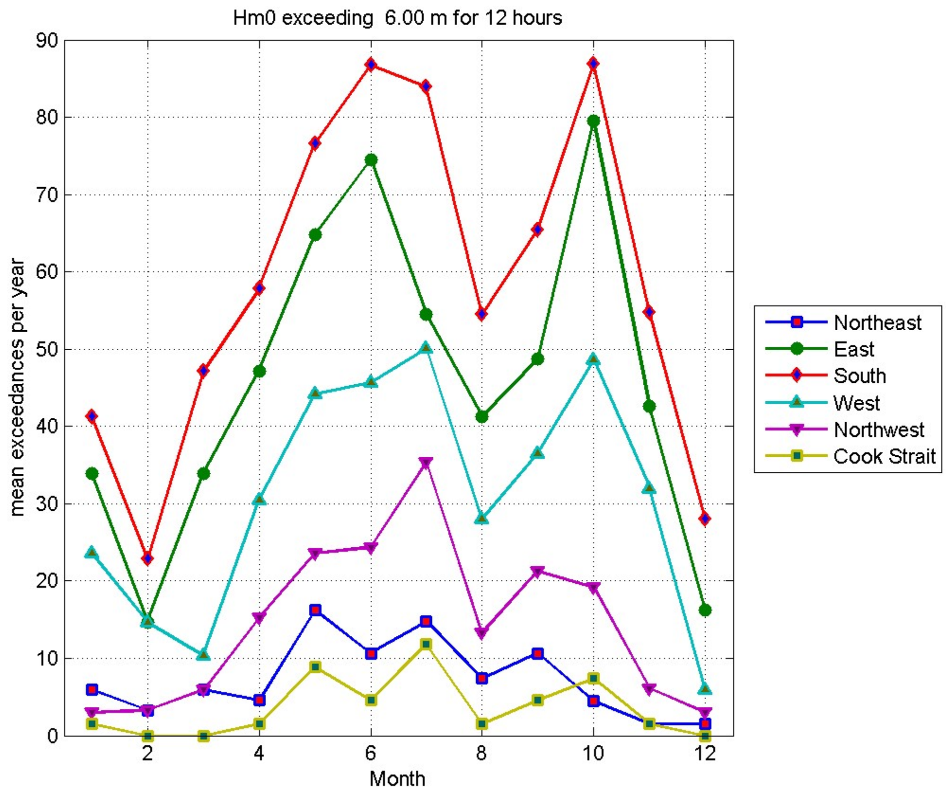

Figure 3-16: Monthly means of the occurrence of storm events in each ocean region exceeding 6.0 m significant wave height for 12 hours or more. Averaged over the years 2009-2015, from NZWAVE-12 outputs.

3.3 8.0 m significant wave height threshold

Results for 2016, derived from the NZWAVE-8 forecasts and using H_{thresh} = 8.0 m, and T_{thresh} = 12 hours, are plotted below for the coastal regions (Figure 3-17) and the ocean regions (Figure 3-18). Corresponding results for 2017 are plotted in Figure 3-19 and Figure 3-20.

For coastal regions the exceedances are all in single figures, and indeed almost entirely zero around the North Island. These values are perhaps too low for the Coastal Extreme Wave Index to be statistically useful with this threshold. This could also be the case for the North and Northwest ocean regions (1 exceedance). But the more energetic East and South ocean region recorded sufficient exceedances for an 8.0 m threshold to be useful in distinguishing “extreme” events in these waters.

The interannual variation of these same results over the years 2008-2015 are shown in Figure 3-21, for coastal regions, and Figure 3-22, for ocean regions. Exceedance numbers for the coastal regions are rather too low to sensibly comment on interannual trends, but we can note a decline in exceedances for the more energetic ocean regions from a peak in 2015.

Seasonal variability (Figure 3-23 for coastal regions, and Figure 3-24 for ocean regions) again shows a dual-maximum (winter and spring) cycle for the most energetic regions. The very low values for the more sheltered regions do not allow patterns to be identified.

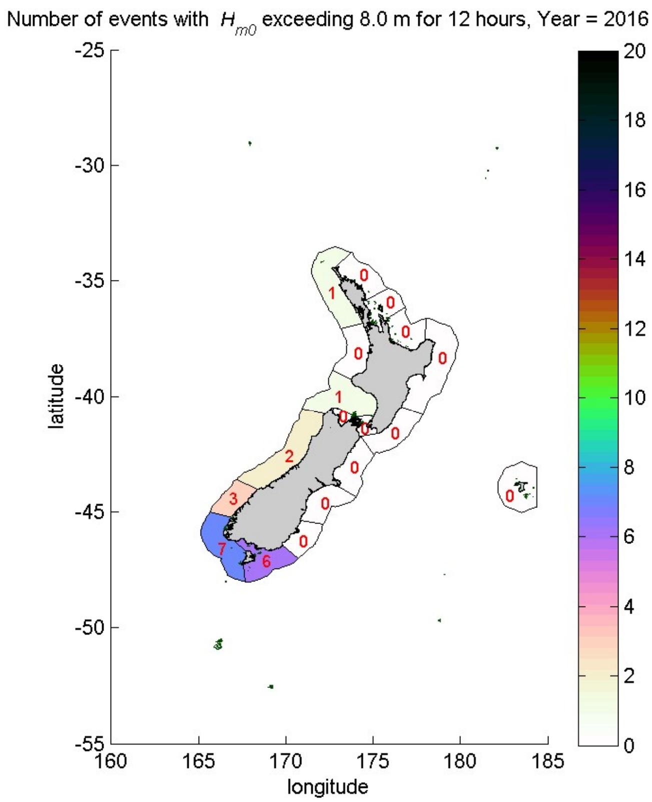

Figure 3-17: Maximum number of storm events in each coastal region exceeding 8.0 m significant wave height for 12 hours or more, for 2016. Computed from NZWAVE-8 forecast outputs.

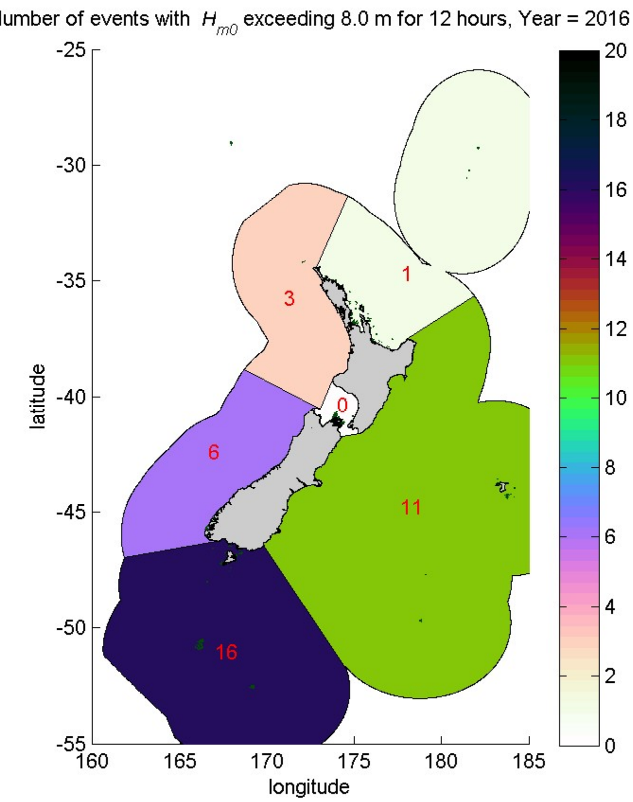

Figure 3-18: Maximum number of storm events in each ocean region exceeding 8.0 m significant wave height for 12 hours or more, for 2016. Computed from NZWAVE-8 forecast outputs.

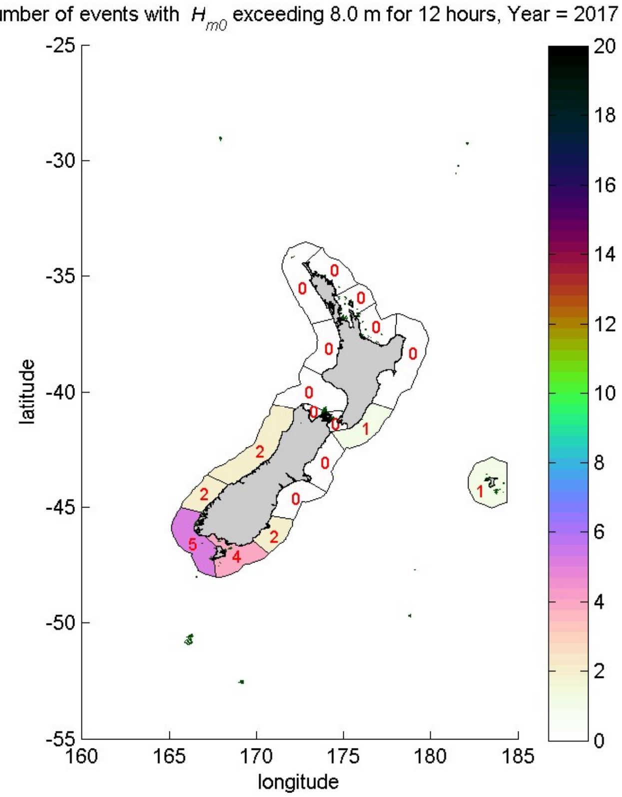

Figure 3-19: Maximum number of storm events in each coastal region exceeding 8.0 m significant wave height for 12 hours or more, for 2017. Computed from NZWAVE-8 forecast outputs.

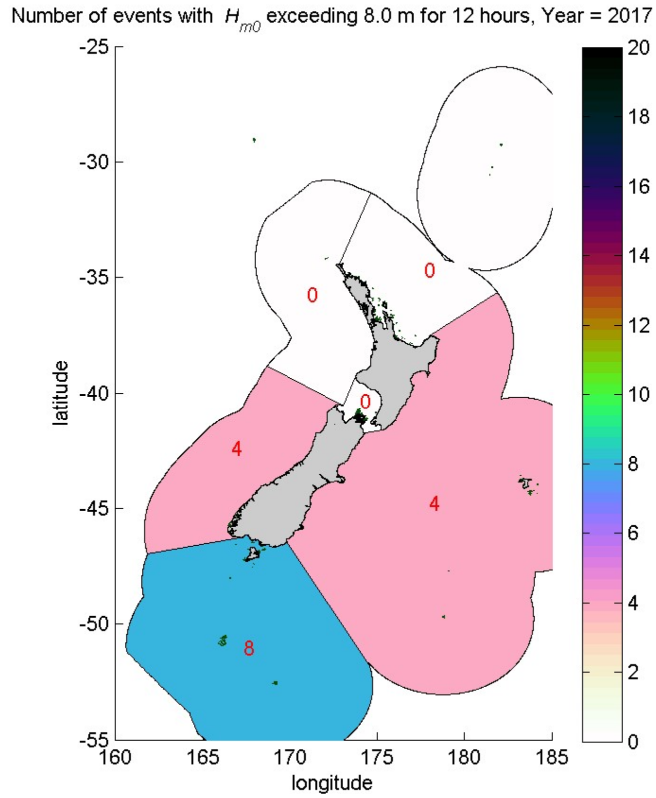

Figure 3-20: Maximum number of storm events in each ocean region exceeding 8.0 m significant wave height for 12 hours or more, for 2017. Computed from NZWAVE-8 forecast outputs.

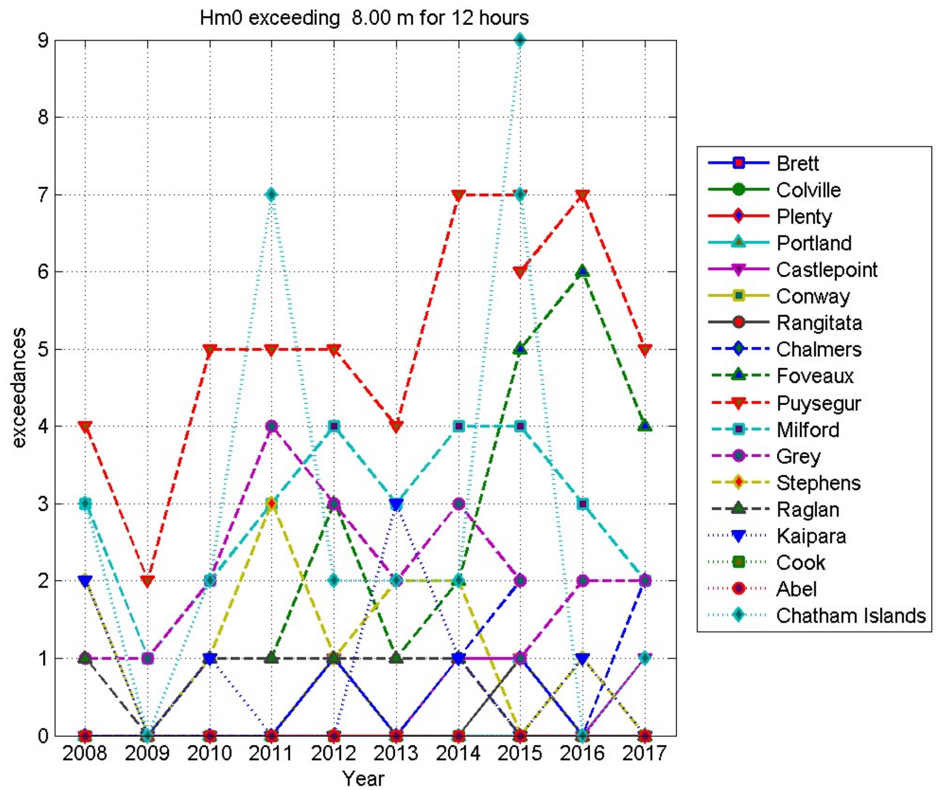

Figure 3-21: Yearly variation in the maximum number of storm events in each coastal region exceeding 8.0 m significant wave height for 12 hours or more. Results for 2008-2015 from the NZWAVE-12 forecast are shown, along with 2015-2017 results from the NZWAVE-8 forecast.

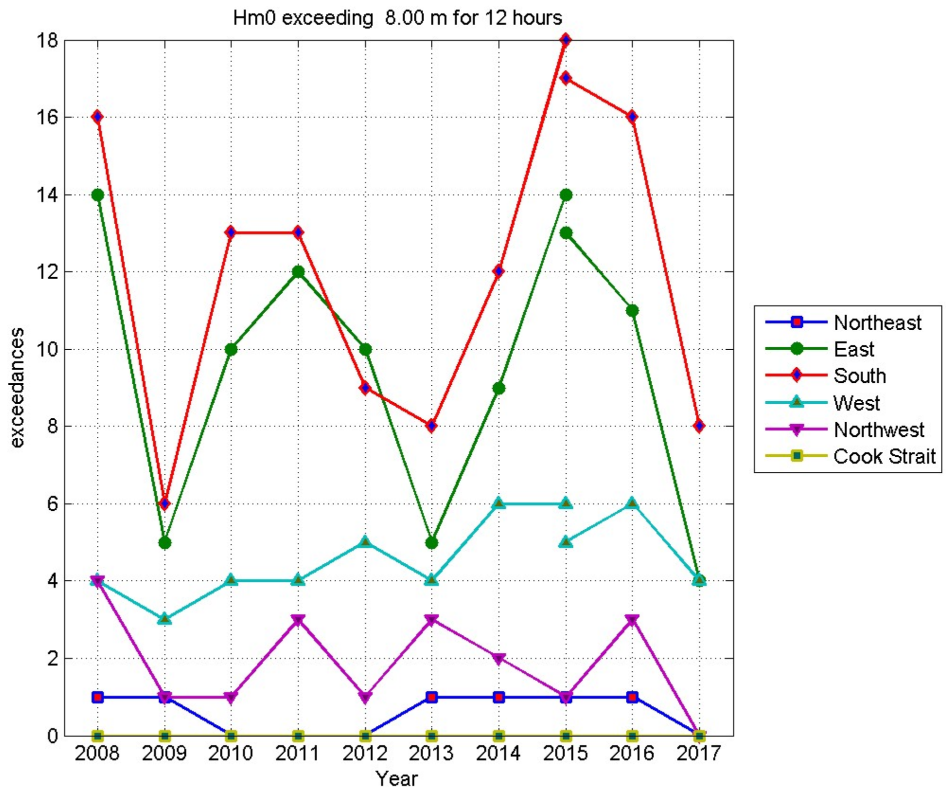

Figure 3-22: Yearly variation in the maximum number of storm events in each ocean region exceeding 8.0 m significant wave height for 12 hours or more. Results for 2008-2015 from the NZWAVE-12 forecast are shown, along with 2015-2017 results from the NZWAVE-8 forecast.

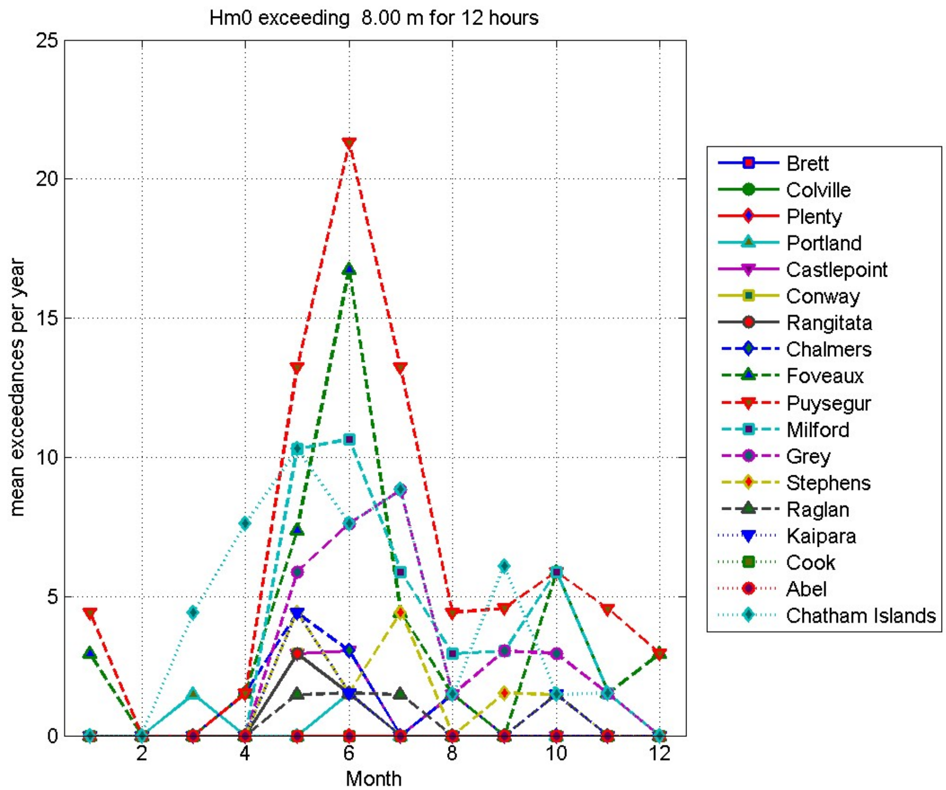

Figure 3-23: Monthly means of the occurrence of storm events in each coastal region exceeding 8.0 m significant wave height for 12 hours or more. Averaged over the years 2009-2015, from NZWAVE-12 outputs.

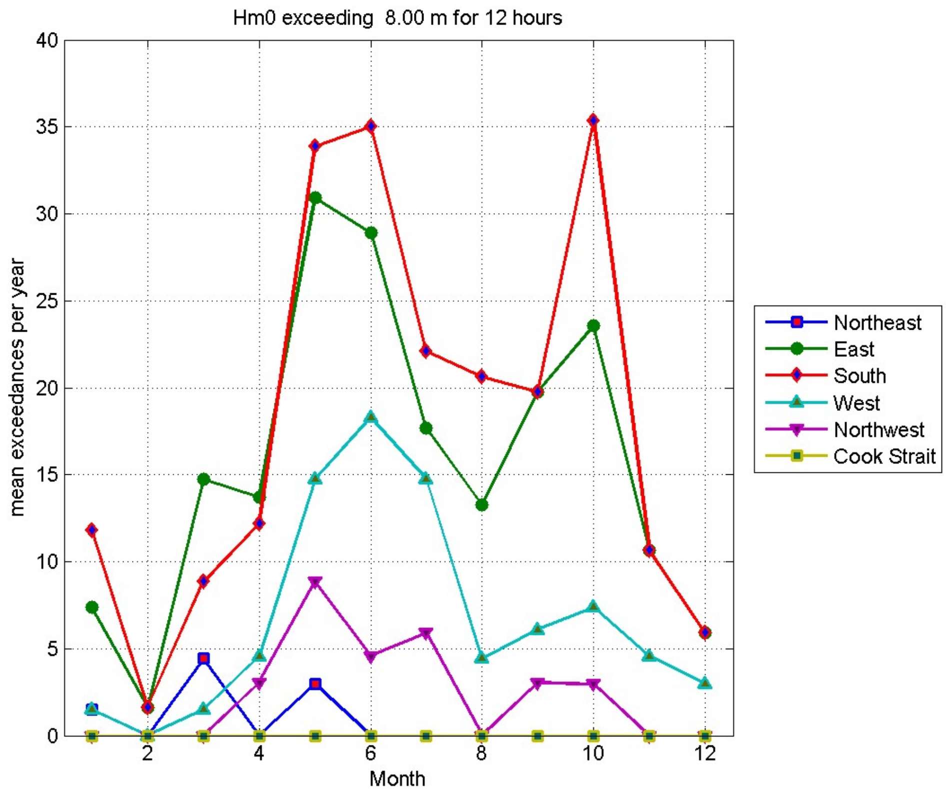

Figure 3-24: Monthly means of the occurrence of storm events in each ocean region exceeding 8.0 m significant wave height for 12 hours or more. Averaged over the years 2009-2015, from NZWAVE-12 outputs.

3.4 Comparison of NZWAVE-12 and NZWAVE-8 outputs

In making a transition from computing wave height exceedances derived from the NZWAVE-12 forecasts to those using NZWAVE-8, it is helpful to use the 2015 overlap period, in which both products could be derived, to quantify differences between results from the two sources.

To do so, we took the exceedance numbers computed as above, summed over the whole of 2015 for each cell of the two model grids. To compare the two, we averaged the respective numbers of exceedances within each 1°×1° grid cell of a common comparison domain covering longitudes 160°E to 183°E (177°W), and latitudes 53°S to 25°S. This was done separately for each of the three threshold criteria considered in the study, i.e., H_{thresh} = 4.0 m, 6.0 m and 8.0 m, using T_{thresh} = 12 hours in each case.

In Figure 3-25 we plot the results from the respective NZWAVE-12 and NZWAVE-8 model outputs, for the H_{thresh} = 4.0 m case. Comparing the two plots we see a broadly consistent spatial distribution of exceedance numbers, but with some small differences. NZWAVE-12 produces slightly higher numbers of exceedances than NZWAVE-8 in much of the domain. An exception is the southernmost waters, below 50°S, where we find that it is NZWAVE-8 that produces the higher exceedance numbers.

The quantitative differences can be more readily visualised in Figure 3-26, which plots the mean exceedance values computed from NZWAVE-12 and NZWAVE-8 for each 1°×1° cell against each other as a scatter plot. Here we have also included results from the 6 m and 8 m threshold cases on the same plot. This illustrates the slightly lower exceedance numbers produced NZWAVE-8 compared to NZWAVE-12, and provides a form of calibration of the number of exceedances produced by one model against the other. We summarise this ‘calibration’ further in Table 3-1, which shows the mean and standard deviation of the ratio of mean exceedance values from NZWAVE-8 and NZWAVE-12, selecting values in several ranges. For example, over the full range, the ratio of annual 12-hour exceedances of the 4 m threshold derived from NZWAVE-8 to those from NZWAVE-12 averages 0.93, with standard deviation 0.19. But restricted to areas where such exceedances lie in the range 40-60, the value from NZWAVE-8 is typically 0.96 ± 0.03 times its equivalent from NZWAVE-12.

We should note that the main difference between the two models is the spatial resolution of the wave model grid. Both use the same input wind fields, which are provided at approximately 12 km resolution. Input wind fields are interpolated to the respective wave model grids. For NZWAVE-12 this is at similar resolution to the wind fields but not identically located, so some spatial smoothing is introduced by the interpolation. NZWAVE-8 is at finer resolution, so slightly less smoothing results from the interpolation. The finer resolution model will allow for variability in the wave field to be propagated with slightly more accuracy, supporting a higher degree of both spatial and temporal variability.

Whether or not a given wave height threshold is exceeded, and particularly whether that exceedance is maintained for 12 hours, can be quite sensitive to such variability. This sensitivity contributes to the relatively high degree of scatter in exceedance values from the two models (Figure 3-26).

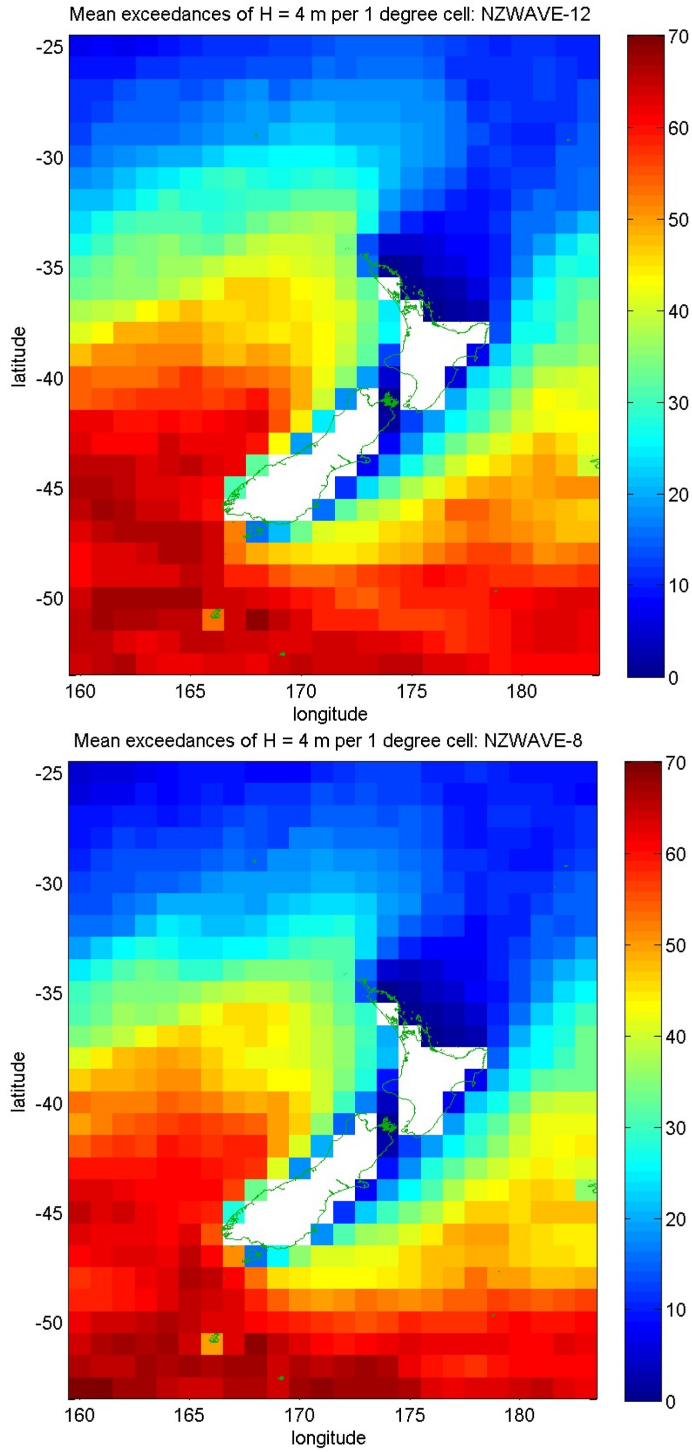

Figure 3-25: Number of exceedances of a 4 m significant wave height threshold for 12 hours or more in 2015 from NZWAVE-12 (top) and NZWAVE-8 (bottom). Exceedances are averaged over cells of a common grid at 1-degree spatial resolution.

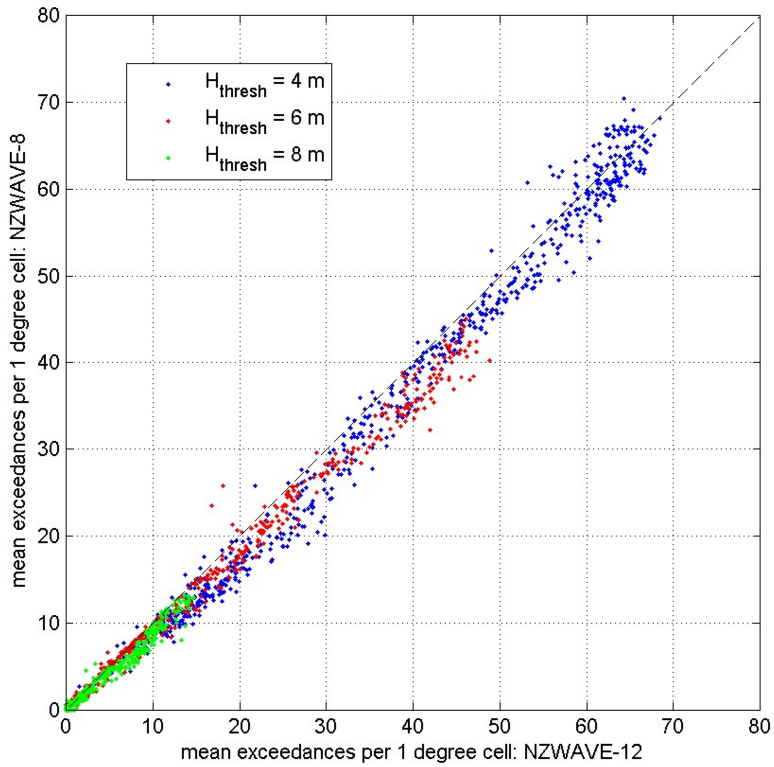

Figure 3-26: Scatter plot comparing annual mean exceedances for 2015 derived from NZWAVE-12 and NZWAVE-8 outputs. Each point represents values averaged over a common 1-degree cell, of 12-hour exceedances of 4 m, 6 m and 8 m significant wave height thresholds The dashed black line represents exact agreement.

Table 3-1: Statistics for the ratio of the number of exceedances predicted by NZWAVE-8 to the corresponding number predicted by NZWAVE-12. Values show the mean (±1 standard deviation) of the ratios of exceedance numbers, binned by exceedance number ranges, derived from the data plotted in Figure 3-26.

	Significant height threshold (m)		
Range of exceedance numbers	**4 m**	**6 m**	**8 m**
all	0.93 ± 0.19	0.97 ± 0.48	0.94 ± 0.55
0-20	0.88 ± 0.31	0.98 ± 0.56	0.93 ± 0.55
10-30	0.85 ± 0.09	0.91 ± 0.08	0.89 ± 0.08
20-40	0.89 ± 0.08	0.90 ± 0.05	-
30-50	0.94 ± 0.05	0.90 ± 0.04	-
40-60	0.96 ± 0.03	0.90 ± 0.05	-
50-70	0.98 ± 0.05	-	-

4 Discussion

We have presented Extreme Wave Indices for Oceanic and Coastal regions of New Zealand. These are based on counting events in which significant wave height output by an operational wave forecasting system exceeds selected threshold levels (4.0, 6.0 and 8.0 m) for sustained periods exceeding 12 hours, and determining the maximum such counts within the prescribed Oceanic and Coastal regions.

The extended spatial coverage of the forecasts used, and their ongoing maintenance with an operational forecasting system means that there are no gaps in the spatial or temporal coverage of these indices from 2008 through 2017, and nor should there be coverage gaps in future updates of the indices, as long as the wave forecast system is maintained.

NIWA's operational wave forecast system is, however, subject to modification from time to time, as modifications are introduced intended to improve the performance of the forecasts. In particular, the NZWAVE-12 model introduced in 2007 has now been replaced by the higher-resolution NZWAVE-8 model. An overlap period including the whole of 2015 has allowed us to quantify systematic differences in the indices associated with this changeover. We have identified a tendency for indices derived from NZWAVE-8 to be lower than corresponding values from NZWAVE-12, and have derived some scaling factors to quantify this change, along with measures of associated uncertainty. It would be possible to apply these scaling factors, e.g., to adjust indices derived from NZWAVE-12 to be more consistent with those from NZWAVE-8 (or vice-versa).

It should be noted that further modifications to NIWA's forecast system have occurred in 2018 (with a 16 week overlap period for inter-comparisons, that may be extended if required). In this case, the same NZWAVE-8 spatial grid, and the same input wind fields (from the NZLAM model) are still used, but significant changes have been made to representations of physical processes within the wave model. The impact of these changes, and any further modifications yet to come, will need to be considered in future updates of the Extreme Wave Indices.

An associated issue is that, as discussed in Section 2.3, we have computed extreme wave indices for each region as a maximum value of exceedances counted for each grid cell within that region. This choice returns an integer value that also reflects the intention that the index represent "extreme" events. An alternative definition using a spatial average over each region would return non-integer values, and would also be more statistically robust.

A rescaling procedure to reconcile indices computed from different forecast models, as outlined in Section 3.4, would also return non-integer values from integer-valued "raw" computed indices, meaning that any perceived advantage in preferring an integer-valued index would be lost. Also, if we use a nonlinear scaling procedure, it would be best applied to exceedance numbers in each grid cell before deriving a bulk statistic (whether maximum or mean) for each spatial domain.

The need for rescaling may, therefore, provide further motivation to reconsider the definition of the indices to use a spatial mean rather than maximum.

At this stage, however, we have simply reported the unadjusted indices as computed from either source, considering that such a step would be better taken in the light of further comparisons of forecast outputs with measurements from wave buoy or satellite records. Such work is in progress for the present version of the operational forecast system, but is beyond the scope of the present study.

5 References

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