Proceedings of the ASME 2021
Asset Integrity Management - Ageing and Life Extension Conference
AIM-ALE 2021
November 30 – December 2, 2021

AIM-ALE2021-77749

IMPLICATIONS OF THE LOADS JIP ON EXTREME WAVE CONDITIONS IN THE NORTH SEA

Graham Feld[1], David Randell[2], Phillip Jonathan[1,3]

[1]Shell Research Ltd, UK
[2]Shell Global Solutions, NL
[3]Lancaster University, UK

ABSTRACT

Extreme value analysis is used to assess the impact of the new approaches described in the LOADS JIP on the development of metocean wave criteria in the Central North Sea. The use of the Forristall distributions for determining crest and wave heights is well established but this paper compares inferences using those short-term probability distributions with those from the new approaches in LOADS which better reflect wave non-linearity and the effects of wave breaking in intermediate and deep waters. The new distributions also indicate some sensitivity to wave spreading and JONSWAP peakedness and the sensitivity of extreme wave conditions to these sea-state descriptors is examined. For crest heights, the analysis covered both point and area statistics for nominal deck sizes up to 50m x 50m.

In the presence of uncertainty, there is also potential ambiguity surrounding the precise definition of return value. The quantitative effect of uncertainty is dependent upon the definition used and the impact of three different definitions is compared with the traditional approach of effectively ignoring uncertainty in the extrapolation process.

The analysis was carried out using the NORA10 WAM hindcast developed by the Norwegian Met Office which covered approximately 60 years of historical atmospheric and sea-state conditions. The paper presents quantitative comparisons between return values derived using the different approaches concentrating on return periods of 100 and 10,000 years.

Keywords: Extreme environmental loading assessment

NOMENCLATURE

C	Individual crest height above mean sea level
CDF	Cumulative distribution function
CEVA	Covariate extreme value analysis (Shell software package)
EVA	Extreme value analysis
GP	generalised Pareto
H	Individual crest-to-trough wave height, m
Hs	Significant wave height, m
γ	JONSWAP spectrum peak-enhancement factor
σ	spreading of the wave spectrum expressed as the wrapped normal rms of the spectral peak
σ_{GP}	scale parameter of generalised Pareto distribution
ξ_{GP}	scale parameter of generalised Pareto distribution

1 INTRODUCTION

The LOADS JIP has proposed a new approach to the determination of the reliability of fixed jacket structures. There are many elements of the new approach, but a key component is the method by which the return values of metocean conditions are derived. The LOADS approach is essentially probabilistic and tries to capture the real variability that is seen in individual waves and sea-states offshore including capturing non-linear effects and breaking wave probabilities.

The analysis described here focuses on three parameters:

- Significant wave height, *Hs*
- Maximum individual crest-to-trough wave height, *H*
- Maximum crest height above mean sea level, *C*

The paper does not focus on the mathematical details of the LOADS JIP approach itself but, rather, it presents an illustration of the effect of the proposed methods on the extreme wave and crest heights in the Central North Sea. The return values of these parameters have some sensitivity to a variety of inputs and the degree of sensitivity was assessed for a typical Central North Sea location. The variants of inputs that were examined are given in Table 1-1. For simplicity, only the omni-directional extremes of each parameter have been examined are reported here.

Table 1-1 Sensitivities associated with LOADS JIP

Sensitivity	*Hs*	*H*	*C*
Return value definition	X	X	X
Short-term probability distribution		X	X
JONSWAP peak-enhancement factor, γ		X	X
Wave spreading, σ			X
Deck size			X

For the first of these, the return value definition [2] that is selected has not in the past been that critical because the commonly-used alternatives are equivalent in the absence of uncertainty. However, where uncertainty is taken into account the situation changes and there can be significant differences in the return values generated depending on which approach is used. Since the LOADS JIP explicitly includes the effects of uncertainty, the impact of the choices made was examined.

In the context of short-term probability distributions for *H* and *C*, the Forristall distribution incorporating second-order effects has been used for many years. However, more recent evidence has indicated that higher-order effects can also be important for crest heights, particularly for steeper sea states. The LOADS JIP has developed three different distributions for crest height to reflect this, whilst adopting the Boccotti distribution [1] for wave heights. These distributions have sensitivities to the wave spectral shape (peak rms spreading, σ, and JONSWAP peak-enhancement factor, γ) and the effects of both of these are examined.

Finally, there has been a long-standing requirement in ISO 19901-1 that the plan area of structural components should be taken into account when determining the extreme crest heights but in practice this has rarely been captured in metocean criteria. The effect of deck area has also been examined here by application to square decks from a point case up to a 50m x 50m plan area.

Since the paper concentrates on the effect of the changes proposed by the LOADS JIP on the wave extremes, the effects of tide and surge are not included in the analysis and it is carried out without reference to any particular structure type. Instead, the paper focusses on the progressive impact of each of the elements described in Table 1-1 on *Hs, H* and *C* as would be presented in metocean criteria documents.

All analyses for this paper were carried out using a grid point from the NORA10-WAM hindcast model which was calibrated using measurements in the Central North Sea.

The paper is laid out as follows:

- Section 2 gives a brief overview of the LOADS JIP. At the time of writing, the details of the JIP are still confidential to the Participants so only a high-level description is given.
- Section 3 presents the metocean data set that was used for the sensitivity analysis.
- Section 4 describes the analysis that was carried out for this study which follows the overall LOADS JIP methodology.
- Section 5 presents the results from the analyses by providing a quantitative indication of the impact of the various sensitivities that were examined.
- Section 6 lays out some overall conclusions of the work.

It should be emphasised that the results presented here can only be considered indicative for the Central North Sea. For other regions of the North Sea and elsewhere in the world, the results would be affected by the severity and nature of the local climate and so whilst might be expected to be qualitatively similar, the degree of impact would differ.

2 LOADS JIP

The LOADS JIP focuses on a re-examination of the structural reliability of offshore jacket structures in the light of recent developments in our understanding of wave physics and the resultant impact on structural loading. In order to properly capture these, a probabilistic analysis of extremes is essential to capture the variability in wave shapes that can be experienced and the variety of impact points on real structures. The main elements that are described in the JIP are:

1. Increases in crest heights as a result of effects above second order.
2. The effects of wave breaking on crest height distributions.
3. The explicit inclusion of the area of a deck over which waves can develop.
4. The kinematics of breaking and non-breaking waves.
5. The loading on jackets and decks associated with the new LOADS crest height distributions and kinematic models.
6. A re-examination of the return value definition in order to ensure a robust inclusion of statistical uncertainties in determination of extreme waves and loads.

The context of this paper, however, is an examination of the impact of the new approaches on the determination of extreme metocean wave and crest heights divorced from any particular structural form. To address that component of the JIP study only items 1,2, 3 and 6 from the above list are relevant. All of these items represent a change to the traditional way of deriving the metocean criteria which has focused on the use of the Forristall wave and Forristall 3-D crest height distributions for a single point and no explicit quantitative inclusion of uncertainty in the extrapolation process.
The sections below give a brief overview of the theory behind the return period definition, the wave and crest height probability distributions, and the deck area as they effect return values of wave and crest height.

2.1 Return Value Definition

The traditional approach to determining return values or of parameters of interest is by applying one of two definitions of the *N*-return period which are equivalent in the absence of uncertainty:

- Definition A: 1-1/*N* quantile of the 1-year maximum
- Definition B: exp(-1) quantile of the *N*-year maximum

In reality, however, there is always some sampling or epistemic uncertainty in any modelling and extrapolation process because it is inevitably based on a finite data sample. One way of estimating the uncertainty is to perform bootstrapping on the underlying data sample, derive the extreme value distribution for each bootstrap and then statistically combine the distributions. However, there are many different ways they could be combined and each method will, in general, produce a different estimate of the return values. As a result, Definitions A and B are no longer equivalent.

Some of the most likely ways of combining the data are described in great detail in [2] where a toy case was created to illustrate a variety of different definitions and to provide some indication of the sensitivity of the results.

To illustrate the effect of uncertainty on return value, a generalised Pareto (GP) distribution with a known scale, σ_{GP}, and shape, ξ_{GP} parameter was set up and then 50 bootstraps of the original data were sampled. The top panel of Figure 2-1 shows the collection of CDFs of the annual maximum for each bootstrap as a tail plot on log scale and the middle panel shows the CDFs of the 1,000-year maximum in its usual form. Each coloured line in the two panels represents a GP model fitted to a particular bootstrap resample, with different σ_{GP}, and ξ_{GP} in general. The bottom plot shows the spread of these combinations of GP parameters. The actual "true" parameters (used to simulate the original sample) are given as a black dot. The bootstraps with the largest shape parameters are shown in colours towards the yellow end of the spectrum and the most negative shape parameters are at the purple end of the spectrum. These colours are echoed in the cumulative distribution functions (CDF) plots.

There are now many ways the CDFs can be handled to produce a predictive estimate for an extreme chosen quantile corresponding to a particular return period. Three of the most likely were presented in [2] and are described below using the same notation as in that paper and this is also used to identify the return value definitions in subsequent discussion.

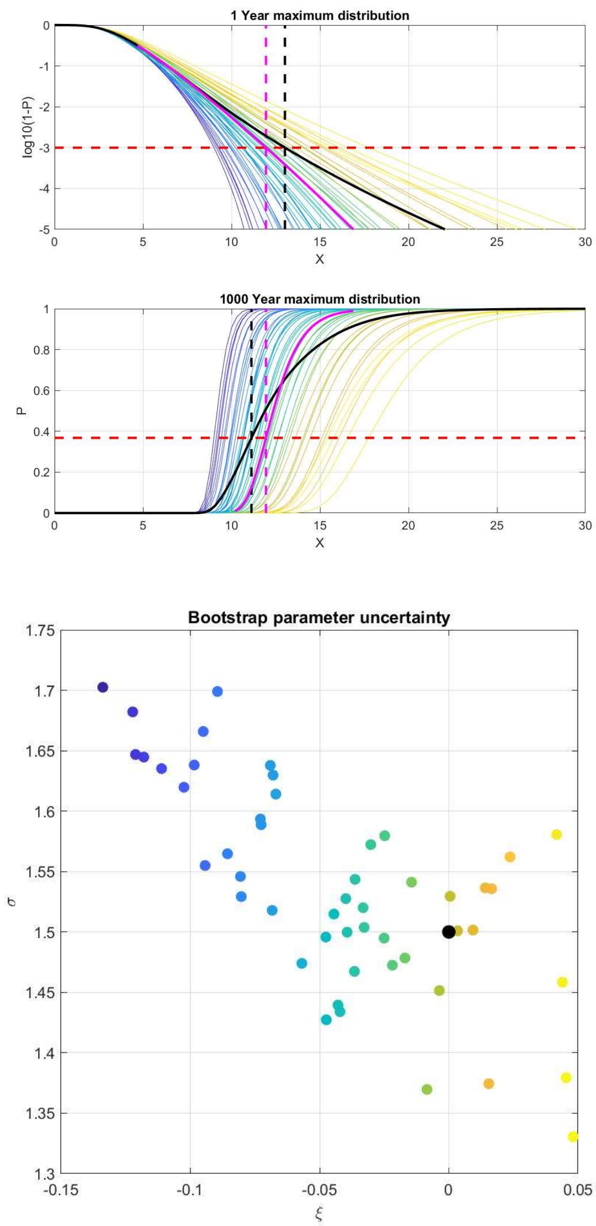

Figure 2-1 Illustration of the effect of different return period definitions

1) **q3: 1-1/N quantile of predictive annual maximum distribution:** Taking return value definition A, we focus on the quantile of the 1-year maximum with non-exceedance probability 1-1/N in the top plot of Figure 2-1.

This probability level is shown as the horizontal red dashed line. The black solid curve in the top panel represents the average probability of exceedance curve, i.e. it is derived via "vertical" integration over the individual coloured bootstrap CDFs. For the higher X values the lower bootstrap curves start to drop out of the averaging calculation completely because their exceedance probabilities are very close to zero and the solid black line therefore starts to move towards the most extreme bootstrap. This produces the highest return value estimate of the options.

2) **q4: exp(-1) quantile of predictive N-year maximum distribution:** Using return value definition B and the centre panel, we again take the "vertical" mean of the bootstrap CDFs but this time for the *N*-year maximum distribution. The result is shown as the solid black line. The return value could then be read off at the "most-probable" exp(-1)=0.3679 quantile (shown are a red dashed line) of the black curve. This produces the lowest return values of the three options.

3) **q2: mean quantile**: A third approach is to select a given quantile from each bootstrap CDF and take the mean value of that quantile across all the bootstraps. That produces the pink lines in the plots. This is a "horizontal integration". In this approach it doesn't matter if you use 1-1/*N* quantile of 1-year maximum, or exp(-1) quantile of *N*-year maximum. This is intermediate between approaches 1 and 2 in terms of severity.

If the critical issue for a structure is the probability of exceeding a certain level of a parameter, e.g. a wave crest touching a deck beam, then the vertical integration method is more appropriate because it tells you the probability of exceeding the level of interest rather than focusing on the average value of the parameter X itself.

It is worth emphasising that the differences between the three approaches described here relate only to the way that the CFDs from each bootstrap are statistically combined. In the absence of uncertainty therefore, all definitions are equivalent as there is just a single CFD. Further, as the size of the data set available for analysis increases, the uncertainties in GP parameters reduce, and hence the definitions again converge.

2.2 Crest height distributions

There are three versions of the crest height distributions that have been presented in the LOADS JIP. These are described below only in an illustrative sense due to the confidentiality that currently pertains to the results from the JIP.

2.3 LOADS 1 Distribution

The initial crest distribution in the LOADS JIP was for deep and intermediate water, and it was a development of the work carried out in the ShortCrest JIP which is now in the public domain [3]. There, the distribution was defined as:

$$\eta_c^{(NL)} = \eta^{(1)}[1 + \beta\{c_1(c_3Ak_c) + c_1c_2(c_3Ak_c)^2\}]$$

where:

$\eta^{(1)}$	linearly predicted crest elevation
A	linear wave amplitude
Ak_c	wave steepness
c_1, c_2	coefficients describing the non-linear amplification at 2nd order and above
c_3	coefficient for correction to wave steepness as a function of wave spreading
β	wave breaking dissipation term

Within the LOADS JIP, some modifications to the coefficients in this formula were made in order to improve the representation of the effects of wave breaking and spreading but essentially the form of the equation remains unchanged.

2.4 LOADS 2 Distribution

A simplified version of the LOADS 1 distribution was also developed in the JIP which removed the dependence of spreading and also enabled a single crest height distribution to be used for all water depths. The motivation of this was that the observed impact of the wave spreading on crest height distributions was hard to distinguish from statistical noise.

The formulation was of a similar nature to the ShortCrest approach described above in that it reflected linear, second order and higher order terms which were then modified by the degree of breaking which was heavily dependent upon the steepness of the sea state.

2.5 LOADS 3 Distribution

A third crest height distribution was also developed within the JIP which incorporated a 2-part distribution where the tail was modelled by a GP distribution to produce an asymptotic upper limit on crest heights in any given sea state. This formulation still included wave spreading in the tuning of the empirical coefficients.

2.6 Boccotti wave height distribution

The ShortCrest JIP [3] recommended the use of the Boccotti distribution [1] following the observation that the Forristall distribution appears to under-estimate wave heights for non-broad-banded sea states. The Boccotti distribution is relatively easy to apply and does take spectral bandwidth into account in its formula and appears to work somewhat better than Forristall for a larger range of realistic sea states.

2.7 Deck Area

The ISO 19901-1 Standard [5] states:

> *"The statistics of wave crest elevation may be determined for a single point in space (i.e. point statistics). However, the elevations within finite areas (e.g. platform deck area) are exceeded at higher probability than provided by the point statistics. For structures which are sensitive to exceedance of airgap, consideration should be given to this increased probability of exceedance in assessing the structural reliability to be achieved or implied by the relevant code. "*

Despite this, it is not normal to apply this requirement in the derivation of metocean extremes. The LOADS JIP proposes a method by which initially the linear dispersion equation is applied to the directional wave spectrum from which a large wave is simulated. The non-linear effects are then simulated by a non-linear adjustment to the resultant linear sea surface. As previously indicated, the exact method by which this is done is still bound by Confidentiality.

3 DATA SET

A sensitivity analysis was carried out on a calibrated version of the NORA10-WAM data set [6] for a Central North Sea (CNS) location. This is a 3-hourly data set covering the period 1957-2018. The parameters from the model that were used were:

- Significant wave height, *Hs*
- Peak spectral wave period, *Tp*
- Mean spectral wave period, T_{02}
- Mean spectral wave period, T_{01}
- Mean wave direction, Wvd

For the analysis, the JONSWAP peak-enhancement factor (γ) and rms peak spreading (σ) were taken as fixed in each run rather than determining these values from the model spectra on a sea-state by sea-state basis. This was due to the fact that hindcast models do not tend to represent these parameters accurately and also to allow an assessment to be made of the sensitivity of the results to these parameters.

The actual spreading values that were used for the analysis were based on an analysis of wave buoy data in the North Sea. The results of analysis of data from Wavec and DWR buoys shown in Figure 3-1 indicate that a peak spreading value of around 20 – 25 degrees is typical for large storms, although anything from 10 – 40 degrees was observed.

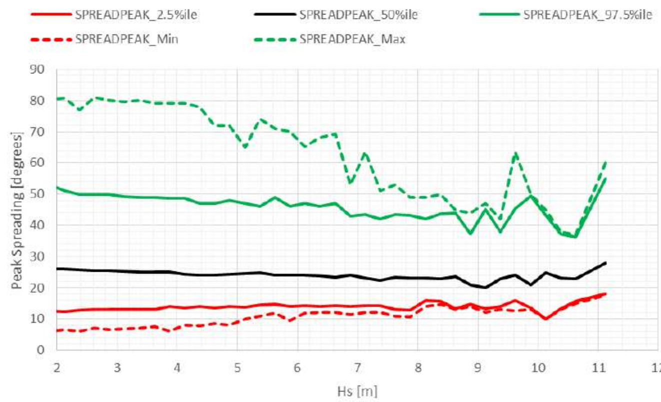

Figure 3-1 Range of peak spreading values form measured wave buoy data in the Central North Sea

4 ANALYSIS

The analysis itself was carried out using the Covariate Extreme Value Analysis (CEVA) methodology [4] which has several key steps:

1. Fitting a Generalised Pareto (GP) distribution and rate of occurrence model to storm peak *Hs* values by direction and/or season.
2. Simulating long return periods of storm peaks and associating a storm history with each one.
3. Sampling maximum wave and crest heights from each sea state within each storm according to a defined probability distribution.
4. Evolving individual waves across a plan area taking account of non-linear effects to enable a maximum crest over an area to be determined for each wave.
5. Repeating the process for multiple bootstraps of the original data.
6. Determining a statistical summary of the bootstraps to determine the return values.

Each of these CEVA stages is described briefly below but a fuller description can also be found in [4].

4.1 Fitting GP Model

Storm events and their storm peak values are identified by exceedance of a storm threshold value which varies by season and direction. Using this approach, storm events are not just confined to the more severe season-direction combinations. The GP model is then fitted to all season-direction subsets using a penalisation method to determine an appropriate degree of smoothing. The parameters of the resultant fitted model will include the local quantile thresholds and the GP parameters as well a Poisson rate of occurrence which will also vary with season and direction.

The omni-directional case is not fitted explicitly in this process but arises naturally from the aggregation of the statistical characteristics of the season-direction subsets. This ensures that the complexity of the environment is captured and that the omni-directional model is statistically consistent with the season-direction subsets.

4.2 Monte Carlo Simulation of Storms

Once the GP model has been fitted, a Monte Carlo approach is used to simulate storm events. Each simulated storm has a peak magnitude and direction that are selected at random from their distributions. A storm history is then associated with the peak by a re-scaling of a similar randomly selected storm event that has been observed in the data set. The storm history includes:

- varying *Hs* – the storm history is linearly re-scaled to match the simulated storm peak
- mean wave periods T_{01} and T_{02} – the steepness of the original sea states are maintained when the *Hs* values are re-scaled
- mean wave direction – the directional variation is shifted so that the peak direction matches the direction of the randomly selected storm peak event

In this analysis, importance sampling is used to ensure a good description of the full distribution is achieved efficiently.

4.3 Short-Term Distributions of Wave and Crest Heights

In order to determine return values of individual wave and crest heights, probability distributions for each are applied to all of the storm histories. This allows for maximum individual wave and crest heights to be simulated as part of the Monte Carlo analysis. In this analysis, the following distributions were assessed with the indicated sensitivities:

- Wave heights:
  - Forristall
  - Boccotti – for various γ
- Crest heights:
  - Forristall 3-D
  - LOADS 1 – for various γ and σ
  - LOADS 2
  - LOADS 3 – for various σ

4.4 Evolving Waves over an Area

The probability distributions described above all relate to waves and crests that occur at a point. Over the plan area of a platform, though, any observed crest will continue to develop as the various frequency components progress. The LOADS JIP approach models this progression initially using the linear dispersion equation and then by using a transformation to incorporate non-linear and breaking effects. This results in some waves producing larger crests at some point over any defined area than would occur at any single point. The maximum crests both at a point and over an area are determined.

4.5 Bootstrapping

The whole process described above was repeated for 200 different bootstraps of the original data in order to estimate the uncertainty associated with the extrapolation process. For each bootstrap, the CDF of omni-directional maximum storm peaks was determined such that return values could be estimated by applying a variety of statistical approaches as discussed in the next section.

4.6 Determination of Return Values

As described in Section 2.1, there are numerous ways that the return period values could be derived and the three described in that section were compared in this study. The baseline analysis was based on bootstrap average of return value definition q3 (exp(-1) quantile of predictive N-year maximum distribution), taken as an unbiased estimate of the traditionally-derived approach.

5 RESULTS

The analysis was carried out to determine the impact of applying the various elements of the LOADS JIP methodology compared to the traditional approach of using the Forristall second-order approach for a single point based on fitting to a single bootstrap. The analysis examined results based on the sensitivities as were listed in **Table *1-1***. Section 5.1 presents the baseline return values based on this traditional approach and subsequent sections then present the incremental effect of applying the various sensitivities listed in the table.

5.1 Baseline Analysis

Figure 5-1 shows the extreme value analysis (EVA) for the baseline case which best reflects the traditional analysis approach. The plot shows the return values from the following analysis approach:

- Return value defined using q4 (exp(-1) quantile of predictive N-year maximum distribution)
- Forristall wave height distribution
- Forristall 3-D crest distribution
- Point crest height statistics

This plot is reflective of the values for *Hs, H* and *C* that would typically be presented in a metocean criteria document for this central North Sea location. Subsequent plots provide incremental effects over and above these values in order to give an indication of the impact of each of the various modifications suggested by the LOADS JIP methods.

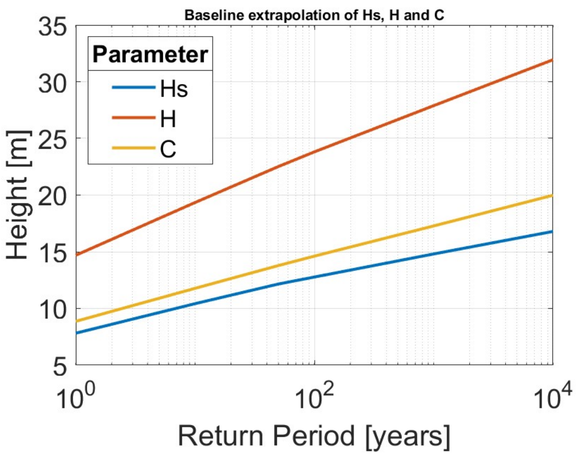

Figure 5-1 Baseline EVA of Hs, H and C at a point without uncertainty

5.2 Return Value Definition

The EVA curves for different return period definitions for *Hs*, *H* and *C* are shown in **Figure *5-2*** for return periods between 1 and 10,000 years. The wave and crest height calculations are based on the use of Forristall and Forristall 3-D distributions, respectively. The absolute increase for the return value definition q4 (1-1/N quantile of predictive annual maximum distribution) over the baseline approach (return value definition q3) is shown for each return period. This difference is around 3.0m for *Hs* and *C* and around 4.7m for *H* for the 10,000-year case but only about 0.5m for all three parameters at 100 years.

The mean quantile approach q2 shows a significantly smaller impact with an increase of around 0.8m, 1.2m and 1.0m for *Hs,* H and *C* at 10,000 years and only about 0.2m at 100 years for all parameters.

A similar analysis was carried out on the impact of the different return period definitions for the Boccotti wave height distribution with a γ of 2.0 (Figure 5-3), and the three candidate LOADS crest height distributions for representative value for the sea-state spectrum of γ of 2.0 and σ of 22º (Figure 5-4).

The impact on the return values for each of these is broadly similar at just above 4m for *H* and just above 3m for *C* for the 10,000-year case which are very comparable with the impact on the Forristall-based extremes.

An indicative summary of the impact of the return period definition is given in Table 5-1.

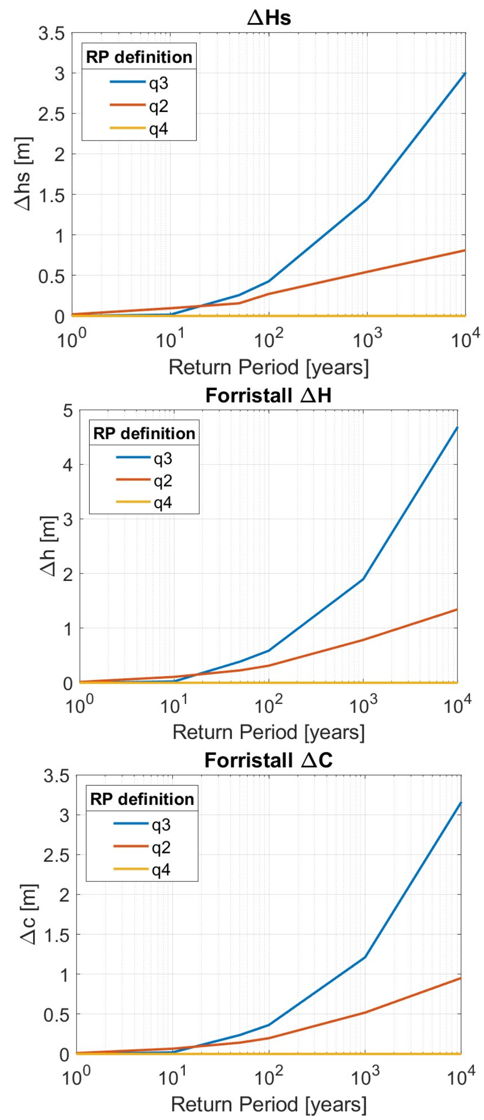

Figure 5-2 Impact of different return period definitions on baseline EVA for Hs (top), H (middle) and C (bottom)

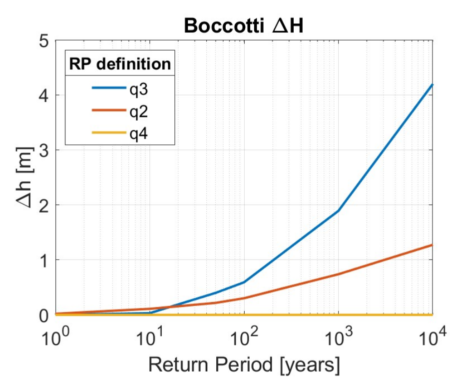

Figure 5-3 Impact of different return period definitions on EVA of Boccotti H (γ = 2.0)

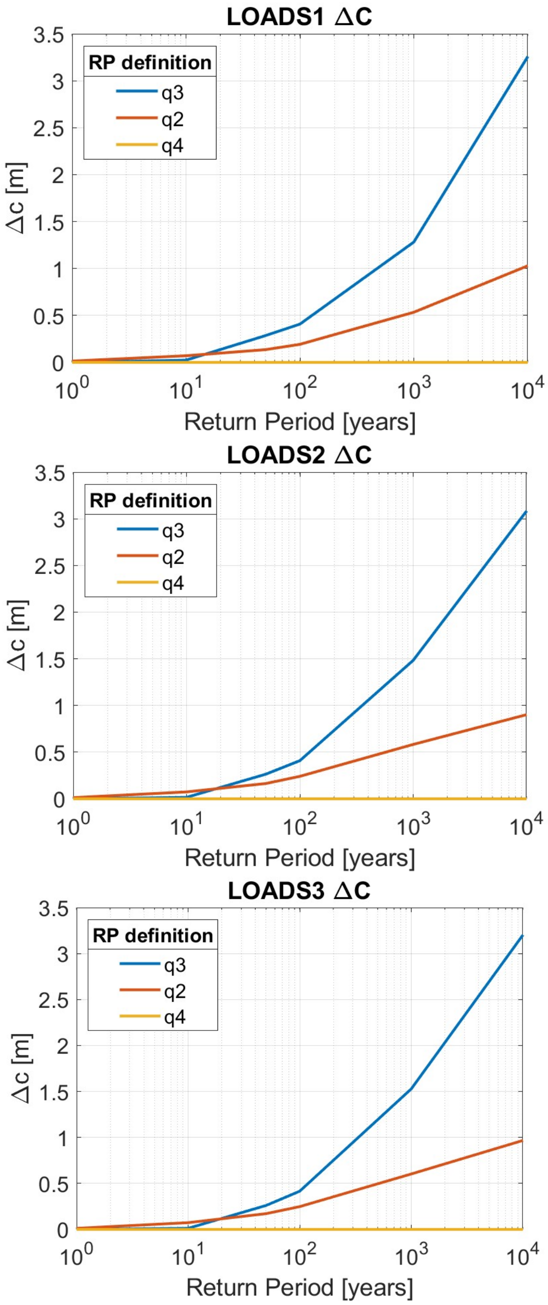

Figure 5-4 Impact of different return period definitions on EVA for the LOADS C distributions (γ = 2.0, σ=22⁰)

Table 5-1 Indicative impact of return period definition on Hs, H and C

[m]	q2-q4		q3-q4	
	100 years	10,000 years	100 years	10,000 years
Hs	0.2	0.8	0.5	3.0
H	0.2	1.2	0.5	4.7
C	0.2	1.0	0.5	3.0

5.3 Short-Term Wave Height Distribution

The differences between the Boccotti *H* distribution and the Forristall distribution for increasing return period for each of the return period definitions are shown in Figure 5-5. The plots show the impact as a function of γ on the x-axis and RP on the y-axis. These indicate a consistency of impact across the definitions and also that although the Boccotti distribution is dependent on the spectral bandwidth γ, the impact in the range of 2 – 4 is very small. For all return period definitions at 100 years, the impact is around 0.9m and around 1.0 - 1.2m at 10,000 years. A summary of the impact across all return period definitions is given in Table 5-2.

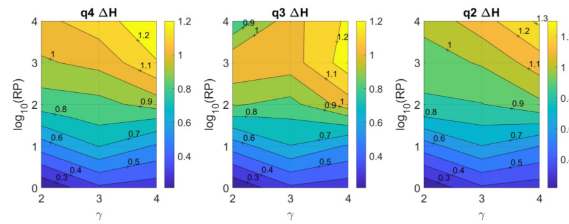

Figure 5-5 Difference between the Boccotti and Forristall H distributions for each return period definition

Table 5-2 Indicative impact of Boccotti H over Forristall

[m]	100 years	10,000 years
H	0.9	1.1

5.4 Short-Term Crest Height Distribution

The impacts over the Forristall distribution of the different crest height distributions are shown in Figure 5-6, Figure 5-9 and Figure 5-10 for the LOADS 1 crest distributions for each return period definition which varies with *γ* and σ. The equivalent for LOADS 2 and LOADS 3 (varying with σ) distributions are given in Figure 5-9 and Figure 5-10, respectively. Across the plots it is clear that once again the return value definition does not really play a role in the impact from the different distributions.

With respect to LOADS 1 and LOADS 3, there is some variation with spreading, σ, with larger spreading values having a smaller impact over Forristall but the effect of changes of γ are very small indeed across all return periods. Indicative impacts from the various distributions are summarised in Table 5-3.

A direct comparison of the impact of the three LOADS crest distributions for the full range of σ and γ values is shown in Figure 5-11. The plot indicates that the LOADS 2 distribution is aligned for most return periods with the most conservative of the LOADS 1 variants with eth LAODS 3 distributions tend to progressively under-estimate compared to eth other two dsitributions.

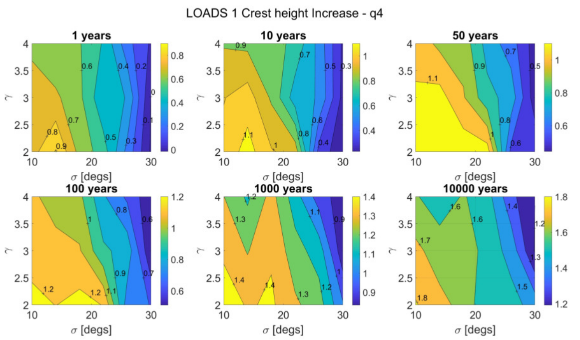

Figure 5-6 Impact of use of LOADS1 crest distribution above Forristall (q4)

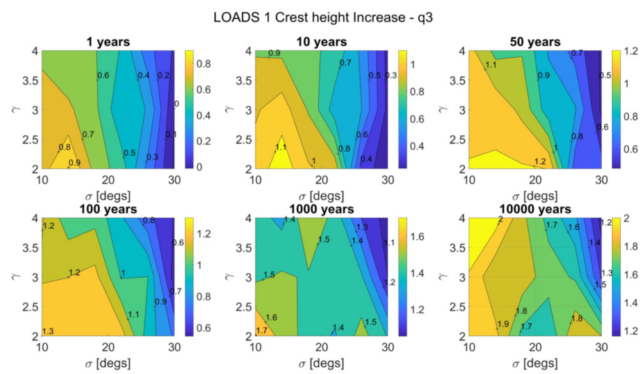

Figure 5-7 Impact of use of LOADS1 crest distribution above Forristall (q3)

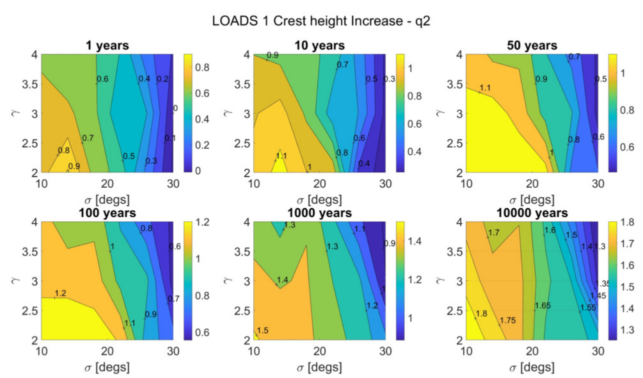

Figure 5-8 Impact of use of LOADS 1 crest distribution above Forristall (q2)

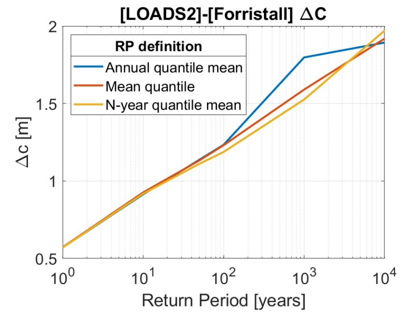

Figure 5-9 Impact of use of LOADS 2 crest distribution above Forristall

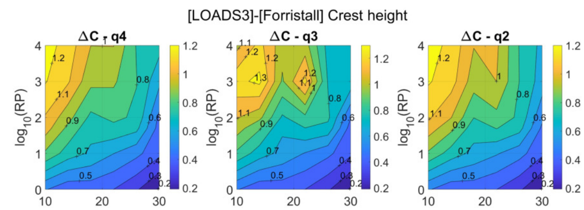

Figure 5-10 Impact of use of LOADS 3 crest distribution above Forristall

Table 5-3 Indicative impact of LOADS crest height distributions over Forristall

[m]	100 years	10,000 years
LOADS1	1.0	1.8
LOADS 2	1.3	1.9
LOADS 3	0.8	1.0

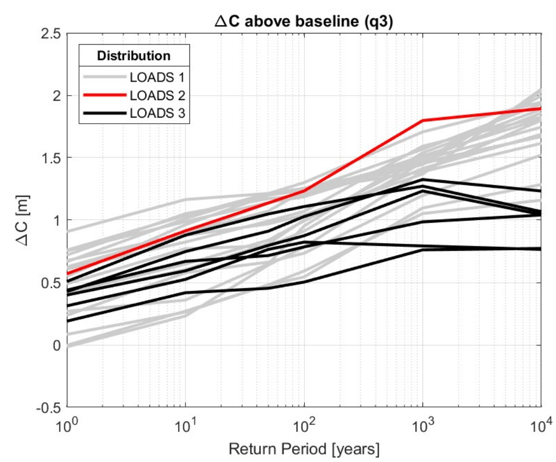

Figure 5-11 Comparison of impact of LOADS crest distributions compared to the baseline (q3)

5.5 Deck Size

The effect of deck size on the extreme crest heights is examined in Figure 5-12 to Figure 5-15 for hypothetical deck areas of 5mx5m up to 50m x 50m for the LOADS 1 distribution which is the only one of the three LOADS distributions which includes the area effect. The results are only shown for return value definition q3 with a summary in Table 5-4. Results for other return value definitions are similar.

Table 5-4 Indicative impact of deck area over a point case for LOADS 1 distribution

[m]	100 years	10,000 years
5m x 5m	0.3	0.6
10m x 10m	0.5	0.8
25m x 25m	1.1	1.3
50m x 50m	1.6	2.3

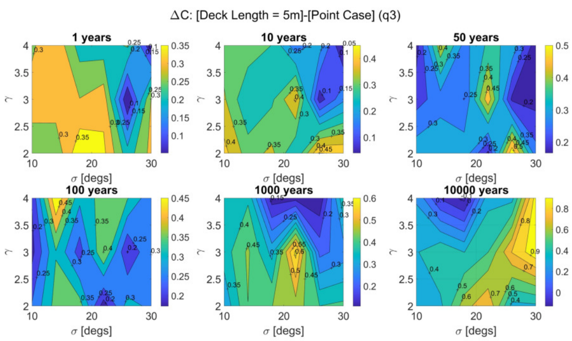

Figure 5-12 Impact of 5m x 5m deck area over point extremes for LOADS 1 C distribution (q2)

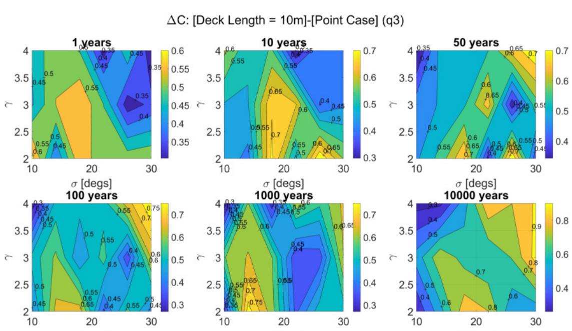

Figure 5-13 Impact of 10m x 10m deck area over point extremes for LOADS 1 C distribution (q2)

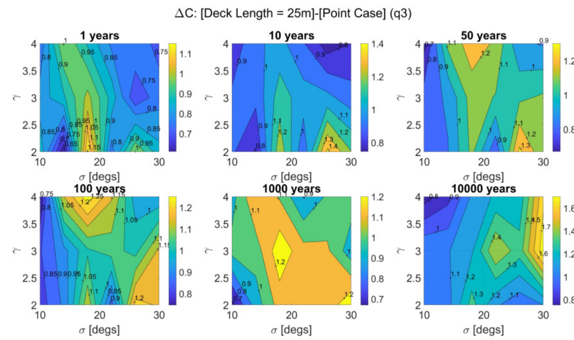

Figure 5-14 Impact of 25m x 25m deck area over point extremes for LOADS 1 C distribution (q2)

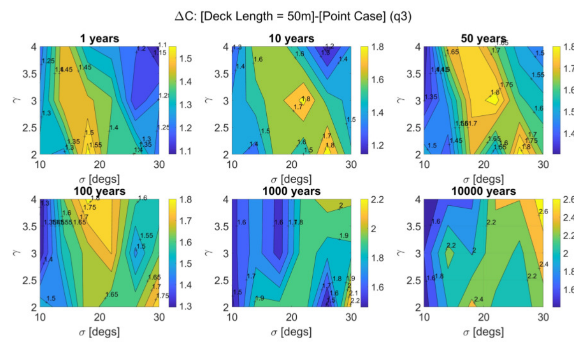

Figure 5-15 Impact of 50m x 50m deck area over point extremes for LOADS 1 C distribution (q2)

5.6 Overall

For the point case, the impact of the LOADS JIP methods and the q3 return value definition (as opposed to q4) is summarised in Table 5-5. It is clear from the table that for all of *Hs, H* and *C* there is a significant contribution from the explicit inclusion of uncertainty in the derivation of return values, particularly for the return periods above 100 years. Indeed, the adoption of this statistical approach is actually the biggest contributor to the increase in all parameters for the 10,000-year case. The results are also summarised pictorially for crests in Figure 5-16 for increasing return periods for the three LOADS crest distributions and these plots also show the sensitivity to spectral shape γ and σ for LOADS 1 (top) and to σ for the LOADS 3 distribution. It is clear from these last two plots that the effect of the spectral shape itself is relatively small compared to the other sources of change. The LOADS 3 crest distribution has a somewhat smaller impact than the other two crest distributions particularly at 10,000 years. Figure 5-17 shows a similarly small impact on wave heights from JONSWAP γ when using the Boccotti distribution.

Table 5-5 Overall indicative impact of application of LOADS JIP methods over Forristall distribution, and return value definition for a point case

[m]	100 years			10,000 years		
RP [yrs]	q3-q4	LOADS JIP distrib-ution	**Overall**	q3-q4	LOADS JIP distrib-ution	**Overall**
LOADS 1 *C*	0.5	1.0	**1.5**	3.0	1.8	**4.9**
LOADS 2 *C*	0.5	1.3	**1.8**	3.0	1.9	**4.9**
LOADS 3 *C*	0.5	0.8	**1.3**	3.0	1.0	**4.0**
Boccotti *H*	0.5	0.9	**1.4**	4.7	1.1	**5.8**
Hs	0.5	-	**0.5**	3.0	-	**3.0**

For the area case, Table 5-6 and Table 5-7 summarise the overall effects of using the LOADS 1 crest height distribution for the area case on the 100-year and 10,000-year return values and also the contributing elements from each of the analysis method modifications. Figure 5-18 to Figure 5-21 also depict the effect for increasing deck size as a function of γ and σ. As the return period increases, the effect of changes in spreading on return values reduces. In practical terms, this implies that it is only necessary to have an approximate knowledge of a likely range of γ and σ in order to estimate crest heights reliably.

Even for the area case, the return period definition still has the largest single impact at 10,000 years with the choice of wave crest distribution being the second-most significant except for very large deck areas. At the 100-year return period, the effect of using the LOADS 1 crest distribution is the most significant one apart from large deck areas for which the area effect is most significant.

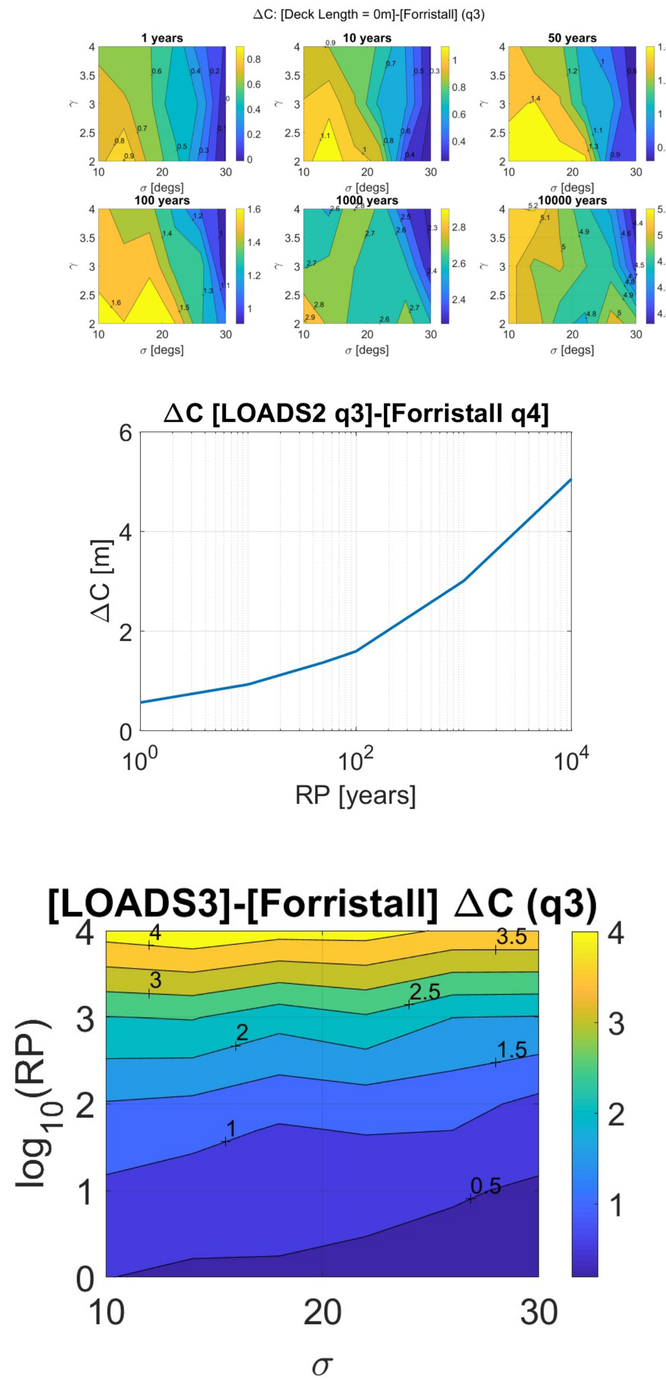

Figure 5-16 Overall effect of LOADS JIP on return values of point crests. LOADS 1 (top), LOADS 2 (middle) and LOADS 3 (bottom)

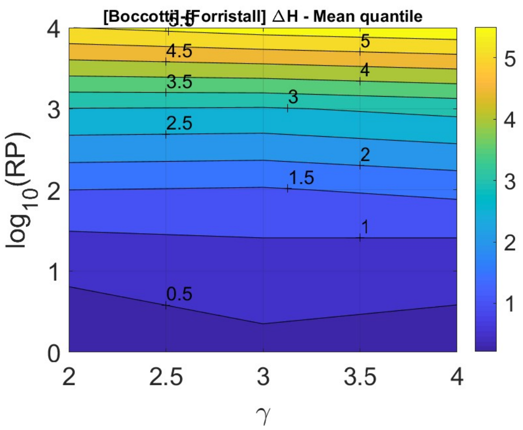

Figure 5-17 Overall effect of LOADS JIP approach on return values of wave heights

Table 5-6 Overall indicative impact of application of LOADS JIP methods over Forristall distribution for 100-year RP

[m]	100 years			
RP [yrs]	q3-q4	*C* Distbn	Area	Overall
Point case	0.5	1.0	0.0	1.5
5m x 5m	0.5	1.0	0.3	1.8
10m x 10m	0.5	1.0	0.5	2.0
25m x 25m	0.5	1.0	1.1	2.6
50m x 50m	0.5	1.0	1.6	3.1

Table 5-7 Overall indicative impact of application of LOADS JIP methods over Forristall distribution for 10,000-year RP

[m]	10,000 years			
RP [yrs]	q3-q4	*C* Distbn	Area	Overall
Point case	3.0	1.8	0.0	4.8
5m x 5m	3.0	1.8	0.6	5.4
10m x 10m	3.0	1.8	0.8	5.6
25m x 25m	3.0	1.8	1.3	6.1
50m x 50m	3.0	1.8	2.3	7.1

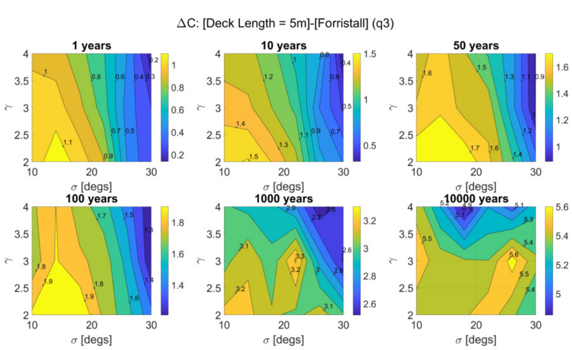

Figure 5-18 Overall effect of LOADS JIP approach on return values of crest heights for a 5m x 5m deck area

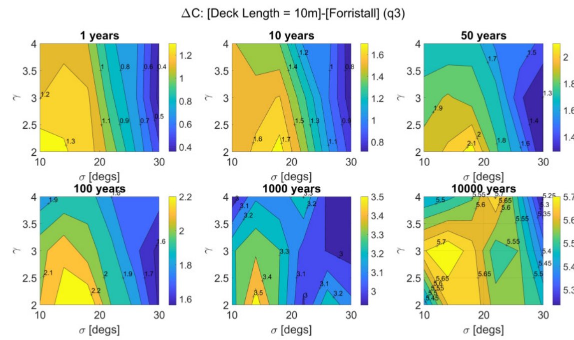

Figure 5-19 Overall effect of LOADS JIP approach on return values of crest heights for a 10m x 10m deck area

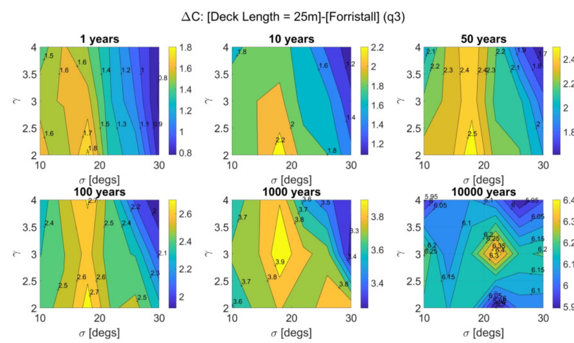

Figure 5-20 Overall effect of LOADS JIP approach on return values of crest heights for a 25m x 25m deck area

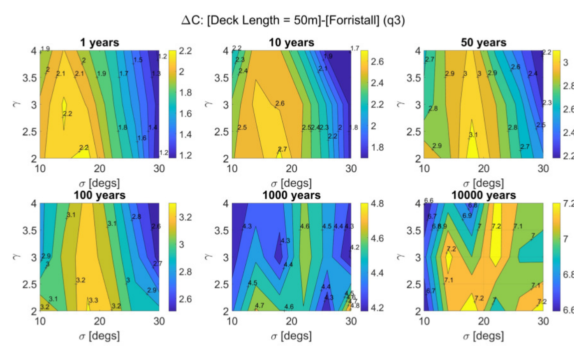

Figure 5-21 Overall effect of LOADS JIP approach on return values of crest heights for a 50m x 50m deck area

6 CONCLUSIONS

The impact of the LOADS JIP methods on return values of *Hs*, *H* and *C* at a point are considerable. The explicit inclusion of uncertainty is the most significant change for return periods above 100 years but for lower return periods the new short-term distributions are more significant - LOADS 2 tends to be the most conservative option. The magnitude of the area effect is smaller than the other two contributors except for large decks.

For both wave and crest heights, the effect of spectral shape is small implying that only an approximate knowledge of γ and σ is sufficient.

REFERENCES

[1] P. Boccotti. *Some new results on statistical properties of wind waves.* Applied Ocean Research, 1983.

[2] P. Jonathan, D. Randell, J. Wadsworth and J. Tawn. *On return values for extreme seas*. Ocean Eng. 220 107725.

[3] J. Hennig, J. Scharnke, C. Swan, Ø. Hagen, K. Ewans, P. Tromans, G. Forristall *Effect of Short-Crestedness on Extreme Wave Impact: A Summary of Findings From the Joint Industry Project "ShorTCresT",* OMAE2015-41167, 2015

[4] G. Feld, D. Randell, E. Ross, P. Jonathan, *Design conditions for waves and water levels using extreme value analysis with covariates*, Ocean Engineering 173, 2019, 851-866

[5] ISO19901-1, 2015. *Petroleum and natural gas industries. Specific requirements for offshore structures. Part 1: Metocean design and operating considerations.* First edition. International Standards Organization.

[6] M. Reistad, Ø. Breivik, H. Haakenstad, O.J. Aarnes, B.R. Furevik, J. Bidlot, *A high-resolution hindcast of wind and waves for the North Sea, the Norwegian Sea, and the Barents Sea*, Journal of Geophysical Research, Volume 116, Issue C5, 2011