MARINE CLIMATE CHANGE IMPACTS PARTNERSHIP: SCIENCE REVIEW
MCCIP Science Review 2013: 295-301

Submitted June 2013
Published online 28 November 2013
doi:10.14465/2013.arc31.295-301

Impacts of climate change on built structures (offshore)

Jon Side [a], Rob Harris [a], David Woolf [a], Mike Bell [a] and Anthony Brooks [b]

[a] *Heriot-Watt University, Orkney Campus, Stromness, KW16 3AW, UK*
[b] *ABP Marine Environmental Research Ltd., Southampton, SO14 2AQ, UK*

EXECUTIVE SUMMARY

It is clear that all industry sectors deploying, operating and maintaining offshore structures (and their insurers) are aware of the possible impacts of climate change. However, at the present time, particularly given the range of uncertainties inherent in future prediction and the range of variability apparent in historical data, it tends to be more of a watching brief rather than a call for specific actions, and changes in operational practices, to be adopted.

For significant wave height and storminess it is possible that the coming decades may see increasing trends in mean and extreme values. These short term trends, are observable in historical datasets and in future may be a result of changing climate, but equally may be explained by the natural variability that is so apparent within the historical data. The safeguard to ensure the adequate protection of offshore structures is the awareness of the variability and the short term fluctuations (pseudo-trends) that can be found in time series data for these parameters.

Protection for offshore structures is also provided by designs to meet extreme criteria (e.g. the 100 year wave in combination with associated wind and current criteria). In the absence of evidence to the contrary it would seem inappropriate at this time to insist on more stringent thresholds given the variability in data and uncertainty in predictions. Once they are operational, additional protection to offshore structures is afforded not only by remote condition monitoring systems but also by regular inspection and maintenance. In this regard any short term trends in the frequency and severity of storms and associated wave heights (whether the result of climate change or not) may have implications for the weather windows in which such marine operations can be safely conducted. This in turn may result in delays before any necessary remedial measures can be undertaken.

1. WHAT IS ALREADY HAPPENING?

Significant Wave Height

There have been ongoing studies undertaken by the offshore petroleum industry to analyse data on wave height that have been recorded at a number of offshore installations since the early 1970s. In particular Leggett (2007) has investigated the link between regional scale variability in the wind field and changes in wave height. The annual mean significant wave height shows an increase since 1973 into the first half of the 1990s after which a decrease is apparent. The apparent seasonal trends, however, are different for autumn and winter periods suggesting that significant wave heights have been reducing in the autumn (October – December) since a peak in 1980-1985, but in winter (January-March) have increased since 1990-1995. Both seasons, however, also show a strong relationship to the North Atlantic Oscillation (NAO) index using 5 year running means. It is recognised, however, that much longer time series of data are required for robust statistical analysis, particularly for the determination of the extreme 50 and 100 year significant wave heights used frequently as one of the design criteria for offshore structures, and most particularly for fixed and permanent floating structures in the offshore petroleum industry. Leggett (2007) used the 1988 to 1996 years time series data, when the recorded significant wave heights were at their greatest, to calculate a 100 year significant wave height of 17.5m, contrasting this with the 15.6m now used as the basis for design criteria in the northern North Sea.

A related modeling study for the Bay of Bengal and Arabian Sea used a general circulation model, for various scenarios of global warming, downscaling this to project wave conditions for a 30 year future (Radhika *et al.*, 2012). The authors found that for three specified locations the resulting calculations of the 100 year significant wave height were between 8% and 44% greater than those specified for design purposes, they conclude, however, "the assessment of climate change and its impact is fraught with numerous uncertainties and much more consideration of appropriate analysis and experimental

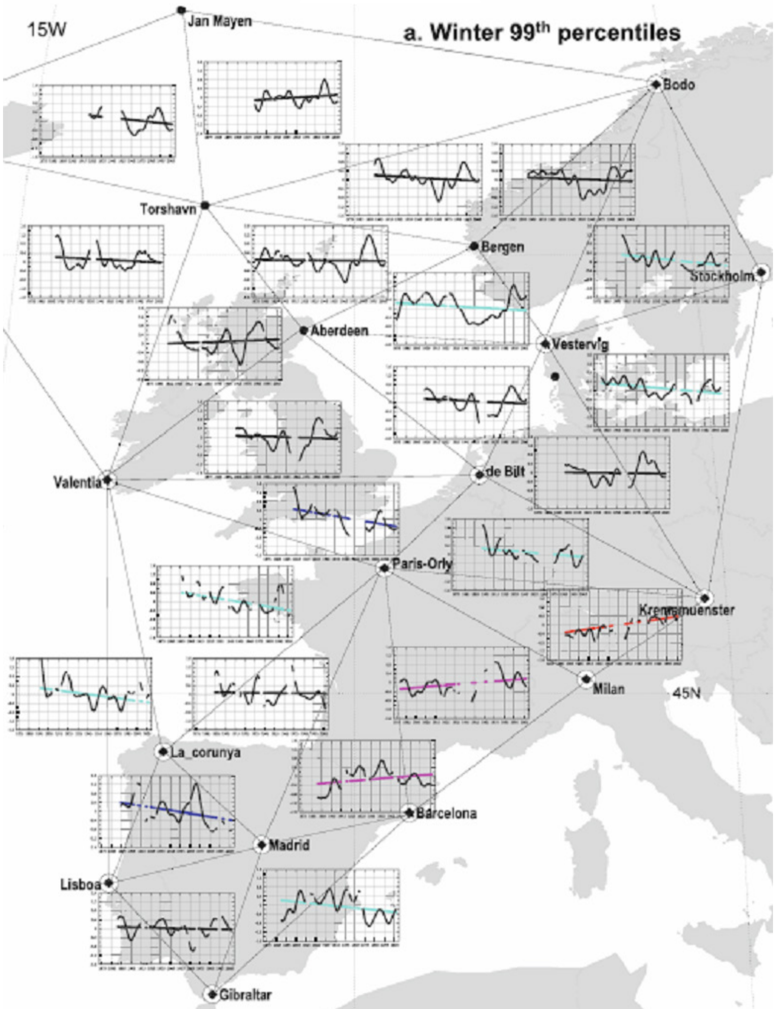


Figure 1: Estimated linear trends in the 1978-2007storm index series used by Wang et al. *(2011) with red and magenta indicating increasing trends, and blue and cyan indicating downward trends, of at least 5% and 20% significance respectively [source: Wang* et al.*, 2011)].*

procedures is needed before any firm recommendation can be made to designers".

Taylor *et al*. (2009) used NAO records to infer extreme wave events in the North Atlantic off Norway and concluded that extreme wave events before 1960 were likely to have been more severe than those experienced since. In summary we can note three important features:

• The difficulty in attributing trends in wave climate to anthropogenic climate change.

• Reliable future prediction of extreme significant wave height, particularly for the design of offshore structures, depends on data sets covering a long time series, and a high degree of confidence in the models used.

• That the wave climate presently recorded cannot be considered a true "baseline" given the variability recorded in recent decades and the known decadal scale variations found for example in the NAO.

Storminess

Similar features also hinder predictions of increased storminess. In a study investigating trends and variability of storminess over Western Europe and the North Atlantic (using a times series from 1878 to 2007) Wang *et al*. (2011) also find interesting and regionally varying relationships between storminess and the NAO and note that for the North Sea area in winter (here December to February) the 1960s–1970s was the calmest period, while the 1990s was the roughest period in the record, which corresponds with the significant wave height findings described by Leggett (2007). They note also the very large seasonal and regional differences in trends and variability during this period. Their analysis suggests a significant trend of reduction in storminess for the English Channel region but no statistically significant trends elsewhere in the North Sea or the North Atlantic region west of Scotland. Figure 1 shows some of the findings of this work which is subtly different from projections made by UK climate change modelling. The most salient feature is perhaps the fact that within each of the times series shown in Figure 1 pseudo-trends of both increase and decrease can be observed over several consecutive years and decades, which if viewed in isolation could result in serious misinterpretation.

The ability of the NAO to act as a proxy or predictor for the incidence of severe storms is uncertain and appears to vary with location and historically (Allan *et al*., 2009). Furthermore, whilst the NAO is highly correlated with wind direction frequency, evidence for connections between the NAO and wind speed or storminess measures is less clear, particularly in terms of the frequency of extreme wind speed events (Burningham and French, 2012). It is therefore evident that this one single index does not capture all atmospheric variability.

Sea-level rise and storm surges

Predictions of sea-level rise depend less on historical data but rely on models of sea temperature change and ice melt. Both the European Union and UK rely principally on the IPCC predictions for these, but these predictions are supported by the long term data on sea-level rise from tide gauges. Surge events in the waters around Britain are caused by extra-tropical weather patterns, which produce a wide variety of dynamic responses. When considering tidal surges, attention is usually given to the extreme high water levels generated at the coast. However, fast flowing offshore currents are also generated during both positive (high coastal water levels) and negative (lowered coastal water levels) surge events that may have a significant impact on offshore structures as well as on sediment transport (e.g. Burlace, 1986; HR Wallingford *et al.*, 2002).

Industry responses

It is clear that the offshore petroleum and other industry sectors deploying, operating and maintaining offshore structures (and their insurers) are aware of the possible impacts of climate change described above. Even in the newly emerging marine renewable sector it is apparent that wave and tidal developers are considering the potential impacts of climate change on their structures (S. Couch, personal communication). However, at the present time, particularly given the range of uncertainties inherent in future prediction and the range of variability apparent in historical data, it tends to be more of a watching brief rather than a call for specific actions, and changes in operational practices, to be adopted. Often one thinks only of the increased forces that structures might have to withstand in the future, but importantly many aspects of the deployment, operation and maintenance of these will depend on "weather windows" for at sea working to be conducted safely, and there is a long history of time series data being used to evaluate these.

2. WHAT COULD HAPPEN?

Average UK land temperature has risen since the mid 20th century, as have average sea level, and sea surface temperature around the UK coast. As discussed above over the same time period, trends in storminess and storm surges are more difficult to identify and the use of these data and those on wave height to make predictions of future changes throughout the 21st century can only be done with far less confidence. UKCP09, nonetheless suggests:-

• Projections of UK coastal absolute sea-level rise (allowing for the mostly upward land movement) for 2095 are in the range from approximately 12–76 cm. To allow for uncertainties, a low probability, High++ absolute sea-level rise estimate is 93 cm to 1.9 m by 2100. (The H++ scenario is presented within the UKCP09 marine report to provide users with estimates of sea-level rise increase beyond the likely range but within physical plausibility.)

• Around the UK the size of storm surge expected to occur on average about once in 50 years is projected to increase by less than 0.9 mm per year (not including relative mean sea-level change) over the 21st century. In most locations this trend cannot be clearly distinguished from natural variability. This component of extreme sea level is thus far less important than was implied by UKCIP02, where corresponding values exceeded 5 mm per year in places.

• The HadAM3H (the climate model used in UKCIP02) suggested, albeit with low confidence, that winter storms and mild, wet and windy winter weather were expected to become more frequent. In HadCM3 (the climate model used in UKCP09) there is little change in the frequency of storms over the UK in winter. Although there is a southward shift in the North Atlantic storm track in this model the increase in frequency occurs to the south-west of the UK giving little change over the UK as a whole. There is also little change in the intensity of UK storms in this more recent model.

• As a consequence, using this climate model input, the wave model suggests seasonal mean and extreme waves are generally expected to increase slightly to the SW of the UK, reduce to the north of the UK and experience little change in the North Sea. There are large uncertainties associated with this, especially with the estimation of projected extreme values. Nonetheless changes in the winter mean significant wave height are projected to be between −35 cm and + 5 cm by 2100. Changes in the mean annual maxima are projected to be between −1.5 m and +1 m with the lowered wave heights in Regions 1 and 7 and the increases in Regions 2, 3 and 5.

For offshore structures and the operations associated with their deployment and maintenance there are not only implications from each of the above predictions, but also more particularly where combinations of extreme events occur. For example storm surges and extreme waves may often be generated by the same storm event. Overall, however, the prediction of increased winter storminess is no longer suggested by UKCP09, and in general terms the predicted changes in parameters associated with storminess, storm surges and wave heights, if increasing, are rather modest. That is not to say, given the high degree of uncertainty associated with these specific predictions that this will remain the case (and there are other outcomes observed from the ensemble models considered by the IPCC). Thus the following review looks more generally at the concerns raised for offshore structures were increases in storminess, storm surge and significant wave height to occur.

Fixed petroleum industry structures

The IPCC have considered possible impacts of climate change for offshore structures in the Polar Regions, but there appears to be no similar review for the North Sea and North Atlantic region. Fixed oil and gas industry structures are found predominantly in Regions 1, 2 and 5 but recent activity has led to the development of petroleum resources in Region 7. For many of these structures design has taken into account tidal ranges with storm surge, and thus gradual increases in sea level (mean still water level) are not likely to be of significant concern. A pattern of increase in significant wave height will place greater stresses on these structures where design considerations focus also on extreme events (e.g. the 100 year significant wave height). Unlike the Gulf of Mexico where Hurricanes Hilda and Betsy resulted in the destruction of a number of fixed offshore structures in 1964 and 1965 there are no known examples of major storm damage affecting the structural integrity of fixed platforms in the North Sea. Since a revision of the design code, to reflect a longer time series of data (CASOCA, 1981) there have been no recorded platform losses due to storms. UKPC09 predictions suggest either no change or a slight decreasing trend in significant wave height in Regions 1 and 7 where the significant wave heights are greater, but a slight increase in Regions 2 and 5. Given the variability associated with the time series data and uncertainties with prediction it is difficult to suggest that design practices should be changed.

Sub-sea structures are mostly in deep water and with increasing water depth such structures are less prone to influence from waves. Storm surges, however, may result in increases in seabed currents and thus enhanced scour around structures at the seabed. For piled structures this is of less concern and regular monitoring and maintenance programmes would readily highlight such occurrences for remediation. For large gravity based structures problems associated with scour have been well studied (e.g. Whitehouse *et al*., 2011) but there are no predictions for how scour may be exacerbated by climate change. Remedial measures are always available, but may be costly and depend on regular inspection, which appears to be a robust safeguard.

Floating petroleum industry structures

Increases in sea level are similarly not likely to be of concern for floating offshore structures used either in exploration drilling or also, more widely in recent years, in production operations. While there are recorded incidences of mooring failure and damage, there has been only one major floating offshore platform disaster associated with a storm event in the North Sea (the Alexander Kielland in March 1980). A subsequent inquiry concluded, however, that the structural weakness which led to the initial failure during the storm was already present prior to the incident. Were reliable predictions to be available of increased storminess and increases in extreme wave events mobile floating structures could be modified or replaced, albeit at a cost.

In most cases the design lifetime of oil and gas installations is limited to perhaps 25-50 years and with declining production many of these structures are approaching decommissioning and removal. Older platforms of course may be more vulnerable owing to their history of prolonged exposure to dynamic forces.

Pipelines

In the surf zone and near-shore waters, pipelines are vulnerable to forces from waves, particularly in storm events, and as a consequence a high level of protection is provided in such zones, mostly by burial and rock dumping. Once again routine inspection would reveal any exposure of the pipeline with remedial measures available.

By far the greatest length of pipeline on the UKCS is in deeper waters where currents close to the seabed, rather than wave action, are more influential on the status of the pipeline. In many areas prone to scour, pipelines are trenched and may be backfilled or may backfill naturally. Other pipelines are laid on the seabed without such protection. Scouring occurs naturally and continually, but may be exacerbated by increased seabed currents during storm surges. In extreme cases sediment scour may leave stretches of the pipeline unsupported, resulting in spanning. Continued exposure to current around the pipe section can result in vortex shedding induced vibrations with stresses that in theory could be sufficient to result in a fracture. For operational pipelines routine inspection along the pipeline length and subsequent remedial actions (sand bagging and rock dumping) keep such processes in check.

The situation regarding mothballed and decommissioned pipelines that are not completely removed at the cessation of oil and gas production operations is less clear. While these obviously do not represent a hazard in terms of the risk of a gas leak or oil spill they may, if not maintained, develop spanning sections which may lead to break up of the pipeline posing a risk to demersal fishing gears. The Westhaven tragedy in March 1997 was a result of its trawl doors coming jammed under a spanning section of mothballed pipeline, aggravated by the skipper not following the usual precautions once his gear had become fast (Side, 1999).

Unlike most oil industry structures, decommissioned pipelines left *in-situ* on the seabed will thus no longer be limited to life-spans of 25-50 years but instead would remain in perpetuity. The extent to which ongoing surveys will be required is not certain and thus changes in the condition of these may not be monitored. Similar concerns arise with regard to some gravity base structures for which complete removal may prove impractical.

Offshore operations

Many aspects of offshore operations are weather constrained and thus limited to weather windows within which they can be safely conducted. This applies obviously to installation of structures (and also their decommissioning and removal) but also applies to many of the inspection and maintenance activities that are undertaken. The analysis of data for these windows looks specifically for the likely time duration of conditions below the threshold deemed safe for the operation, and thus is subtly different from the analyses described above. No studies appear to have been conducted that review historical or modelled data with regard to this specific aspect of operations, but would be as constrained by the lack of historical data and its variability as those analyses already discussed. Reduction in weather window occurrence, however, could have significant implications for many of the monitoring and maintenance activities that are currently carried out for oil and gas industry structures including pipelines.

Offshore wind generation

Wind farms are now installed or planned in the licensing rounds for Regions 1, 2, 3, 4, 5 and 6. In all cases initial development has been in shallower waters and concentrated in the southern regions of the UKCS. These structures are prone to similar impacts from storm surges and extreme waves to those described for fixed oil and gas industry structures. During extreme events generation may cease thus reducing the effect of wind stresses in combination with waves on the structure. UKCP09 suggests a slight increase in annual mean and extreme significant wave height in Regions 2 and 5 where the greatest concentration of wind farm projects is found.

Wave energy convertors

Wave energy convertors are designed not only to withstand high energy wave environments but also to capture energy from these. The sector is in its infancy with prototype designs being tested at EMEC (European Marine Energy Centre) in Orkney and with lease rights now issued for 600MW of installed capacity by the Crown Estate (either off the west coast of the Orkney Islands or Lewis). It is in these regions, however, that UKCP09 predicts a reduction in annual significant wave height. In many cases and for a variety of different designs wave energy devices can stop generating during extreme events operating in a safe mode, and thus as a consequence of good design considerations are capable of reducing the wave generated forces on the structure. Suitable sites tend to be those less affected by tidal currents but may be found in shallow waters for some devices fixed to the seabed and further offshore in waters greater than 50m for others. In the deeper waters increased scouring (wave and storm surge induced) may affect mooring systems and seabed fixtures. In near-shore zones wave devices may be subject to currents from long-shore drift.

Tidal energy convertors

Tidal energy can be harnessed from those areas which are characterised by either a large tidal range and/or fast tidal streams. Tidal stream energy converters and tidal lagoons (which may be used to capture energy in areas with large tidal ranges) are considered here. Tidal barrages are described separately in the Coastal Structures Report Card.

As with their counterparts designed for the extraction of wave energy, tidal stream energy convertors are relatively new with prototype designs under test at EMEC and lease rights issued for 1GW of installed capacity mostly in the Pentland Firth and Orkney Waters and the west coast of Scotland. A number of additional tidal stream resource sites have also been identified in English and Welsh waters (TCE, 2012). While ideal tidal energy sites will be sheltered and protected from storm waves, many of the areas of greatest tidal flow (e.g. the Pentland Firth) are exposed to Atlantic storm events and hence extreme waves. Such areas are characterised by no or only thin sediment veneers over the seabed and thus scour is likely to be less of a problem. The extreme combinations of storm surge induced currents with strong tidal currents and extreme waves (not an unlikely combination), has been less studied and many aspects of their interaction are not fully understood. All tidal stream energy convertors are also capable of ceasing generation during extreme events which affords some protection from the combined forces exerted.

There are a small number of tidal lagoon projects currently in the project planning stage, however, there are currently no operational developments.

Marine renewable operations

For wind farms and wave energy devices weather window considerations for installation and removal, inspection and maintenance are likely to be similar to those described for the offshore petroleum industry. (Except that for manned petroleum installations a helipad may still enable access to the facility even in extreme weather, thus only at-sea or sub-sea maintenance is affected.) For tidal devices, however, the situation is further complicated by the requirement that many operations may only be safely conducted during brief periods at or around slack water. While tidal velocities may be perfectly predictable this nonetheless adds a further complication to the already complicated analysis of data for weather windows for this marine renewable sector.

Unlike oil and gas developments marine renewable energy sites (wave, wind and tide) could potentially be operated in perpetuity. The technologies used, however, are likely to have finite lifetimes being replaced at intervals, rather more frequently than the 25-50 year lifespan of offshore petroleum structures. Unlike fixed offshore platforms for the oil and gas industry wave and tidal energy convertors are mechanical devices, which will be replaced from time to time, and are certain to be upgraded as more efficient designs become available. Climate change concerns for this sector, however, will extend well beyond those timescales being presently considered.

Differentiating impacts from climate change from energy extraction

It is recognised that climate change will have many effects on the biology and ecology of the marine environment in UK waters (reference to the relevant MCCIP report). Changes in sea temperature are already affecting the distribution of pelagic species and other subtle changes in biodiversity are anticipated. In some cases it is relatively easy to differentiate the effects of other sources of anthropogenic change (e.g. industrial pollution) from the changes arising from climatic factors. However, in the case of marine renewable development this may prove more problematic. For example, some species and indeed biotopes can only be found in extreme high energy environments. Where these are at the southern limit of their geographical range, increasing sea temperatures may result in their disappearance. Equally, removal of energy may have the same effect. Differentiating between these may prove very difficult indeed and developing a clearer understanding of the effects of energy extraction on the physical and biological environment must be a priority for the regulatory authorities responsible for the licensing of marine renewable projects.

Cables

Telecommunication cables have a long operational history and can be found in all Regions. Faults in operational cables are immediately detected and rapidly remedied with the authorities maintaining an analysis of likely causes of failure, distinguishing particularly between third party damage (fishing gear and dragging anchors) and mechanical failures particularly those associated with storm events. Power cables tend to be better protected and are usually trenched on areas of the continental shelf, mostly to afford protection from third party damage. The International Cable Protection Committee (ICPC) estimates that less than 10% of the recorded faults to power cables are caused by natural hazards, the vast majority is as a consequence of third party damage. Wave action and currents close to the seabed where cables are exposed rather than buried can cause abrasion, stress and fatigue which armouring may not be sufficient to resist. Once again regular inspection is able to highlight areas of concern for remedial action for operational cables, but there are additionally many kilometres of decommissioned telephone cables.

For all cables as with pipelines additional protection is provide at landfall points and in the surf zone.

Some conclusions

For significant wave height and storminess it is possible that the coming decades may see increasing trends in mean and extreme values. Short term trends, are observable in historic datasets and may occur in future as a result of changing climate. However, such changes may occur anyway due to the natural variability that is so apparent within the historical data. The safeguard to ensure the adequate protection of offshore structures is the awareness of the variability and the short term fluctuations (pseudo-trends) that can be found in time series data for these parameters.

Protection for offshore structures is also provided by designs to meet extreme criteria (e.g. the 100 year wave in combination with associated wind and current criteria). In the absence of evidence to the contrary it would seem inappropriate at this time to insist on more stringent thresholds given the variability in data and uncertainty in predictions. Once they are operational, additional protection to offshore structures is afforded not only by remote condition monitoring systems but also by regular inspection and maintenance. In this regard any short term trends in the frequency and severity of storms and associated wave heights (whether the result of climate change or not) may have implications for the weather windows in which such marine operations can be safely conducted. This in turn may result in delays before any necessary remedial measures can be undertaken.

3. KNOWLEDGE GAPS

a. *Physical modelling*: There is a need for a better understanding and representation of the dynamics of external forcing on the ocean-atmosphere system.

b. *Historical data*: There is scope for careful collation and analysis of historical datasets, particularly addressing missing data and inconsistencies, and relationships between those data for wind and significant wave height. Specifically with respect to Weather windowing, routinely undertaken by many offshore industries for various activities, a consideration of the effect of differing climate change scenarios on these outcomes would be of particular value.

c. *Wave, tide and storm surge interactions*: a better understanding of extreme combinations of storm surge induced currents, with strong tidal currents and extreme waves are also a priority for the tidal stream energy sector.

4. SOCIO-ECONOMIC IMPACTS

The principal impacts that are foreseen would arise where changes in the design criteria for offshore structures are adopted (e.g. an increase in the design threshold for the 100 year wave). Many existing structures would not be able to satisfy these, and for petroleum developments that are marginal this may result in the premature decommissioning and abandonment of the field. In other cases the replacement of existing structures would involve substantial costs.

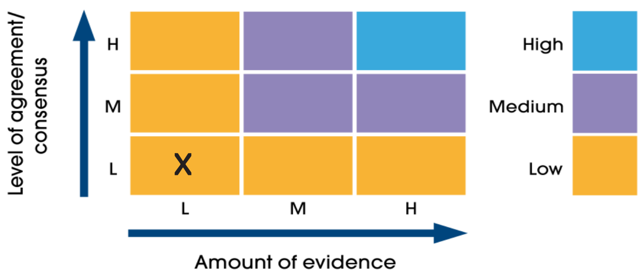
Counter-posed to this of course, for manned offshore oil and gas installations, are the losses of life and costs that would be associated with major structural failures during an extreme weather event. Such an event, although unlikely, is possible (e.g. the 10,000 year wave might occur) but to conclude its occurrence was the result of climate change given our present understanding of data and modelling would be foolhardy.

Any reduction in the availability of weather windows would also impose additional operating costs on all sectors using offshore structures.

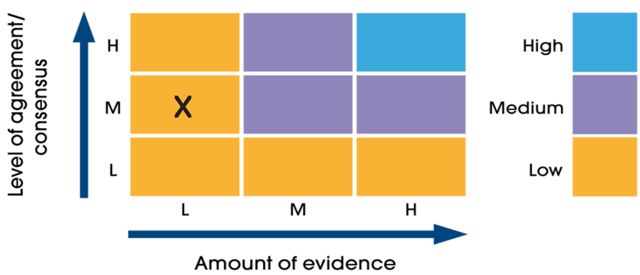
5. CONFIDENCE ASSESSMENT

These are unchanged from the previous review. Importantly, though, the variability in both historical data and ensemble projections is greater than any predicted trends.

What is already happening?



What could happen?



CITATION

Please cite this document as:
Side, J., Harris, R., Woolf, D., Bell, M. and Brooks, A. (2013) Impacts of climate change on built structures (offshore). *MCCIP Science Review 2013*, 295-301, doi:10.14465/2013.arc31.295-301

ACKNOWLEDGMENTS

With thanks to the previous Built Structures Report (Authors: Jon Rees and Steven Hunt).

REFERENCES

Allan, R.J., Tett, S. and Alexander, L. (2009). Fluctuations in autumn-winter severe storms over the British Isles: 1920 to present. *Int. J. Climatology*, **29**, 357-371.

Burlace, M.I. (1986) The negative North Sea surge of the 19th December 1982. *Hydrographic J.*, **39**, 11-15.

Burningham, H. and French, J. (2012) Is the NAO winter index a reliable proxy for wind climate and storminess in northwest Europe? *Int. J. Climatology*, doi:10.1002/joc.3571

CASOCA ~ Committee on Assessment of Safety of Outer Continental Shelf Activities (1981). *Safety and Offshore Oil.* National Academy Press, Washington, USA

HR Wallingford, Posford Haskoning, Cefas, D'Olier, B. (2002). *Southern North Sea Sediment Transport Study Phase 2: Sediment Transport Report.* Report No. EX4526, August 2002.

Leggett, I. (2007) *Impacts of Climate Change on Marine Environment – Oil and Gas Industry.* Defra Conference, 12th July 2007

Radhika S., Deo, M.C. and Latha, G. (2012) *Evaluation of the wave height used in the design of offshore structures considering the effects of climate change.* Proc. IMechE, Part M (published on line 23rd April 2012)

Side, J. (1999) Issues arising from the Westhaven tragedy concerning fishing gear and pipeline interactions. *Underwater Technology,* **24**(1), 3-10.

Taylor, P.H., Barker, V. E., Bishop, D. and Eatock-Taylor, R. (2009) *100 year waves, teleconnections and wave climate variability.* 17th International Workshop on Wave Hindcasting and Forecasting, Halifax, Canada.

TCE ~ The Crown Estate. (2012) *UK Wave and Tidal Key Resource Areas Project.* Summary Report, October 2012. http://www.thecrownestate.co.uk/media/355255/uk-wave-and-tidal-key-resource-areas-project.pdf. Accessed on 22/10/2012.

Wang, X.L., Wan H., Zwiers, F.W., Swail, V.R., Compo, G.P., Allan, R J., Vose, R.S., Jourdain, S. and Yin X. (2011) Trends and low-frequency variability of storminess over Western Europe, 1878-2007. *Clim.Dyn.*, **37**, 2355-2371.

Whitehouse R., Sutherland, J. and Harris, J. (2011). *Evaluating Scour at Marine Gravity Structures.* Maritime Eng., 164(MA4), 143-157.