# Predictions of Climate Change Impact on Fatigue Assessment of Offshore Floating Structures

*Tao Zou, Miroslaw Lech Kaminski*

Department of Maritime and Transport technology, Delft University of Technology

Delft, the Netherlands

## ABSTRACT

Climate change is a long-term phenomenon, and fatigue is also a long-term cumulative process. In the design of floating structures, design wave data are measured in the past and believed to be representative of sea states in the future. However, this kind of design does not consider the effect of climate change on wave conditions and consequently on fatigue consumptions. The aim of this paper is to outline a predictive methodology to estimate the effect of climate change on fatigue assessment of offshore floating structures. There are three steps in the methodology: data preprocessing, wave simulations and fatigue analysis. In data reprocessing, RCP scenarios are used to predict the Green House Gases (GHGs) concentration in the future. Wind field data are simulated by the atmospheric models in CMIP5. Bathymetry and vessel property data are also prepared. At the second step, the third generation wind-driven wave models are applied to simulate the growth, propagation and dissipation of waves based on the energy (or action) balance equation. Then, fatigue calculations are carried out with Miner's rule and S-N curves. In order to clarify the methodology, this paper presents a case study for the fatigue assessment of FPSO- Glas Dowr at Sable Field, offshore South Africa. Sea states at Sable Field from 2007 to 2020 are simulated by the numerical wave model- WaveWatch III. Fatigue consumptions are calculated for two hotspots at midship of the vessel. In order to evaluate the quality of this fatigue assessment, wind data from ERA-interim are also used as the environmental loadings to simulate wave conditions and calculate fatigue damage at the same hotspots. The comparison of these fatigue calculations shows that the atmospheric model in CMIP5 underestimate wind speed, and result in a much underestimated fatigue damage. It is concluded that RCP scenarios, atmospheric and wave models provide a promising solution to predicting the effect of climate change on wave conditions and consequently on fatigue consumptions of floating structures. However, both GHGs scenarios and atmospheric models still require further improvement, because they all underestimate the environmental loadings and lead to an underestimation of fatigue assessment.

KEY WORDS: Climate change, fatigue assessment, offshore floating structures.

## INTRODUCTION

Structural safety is always the main requirement for ships and offshore platforms design. Offshore structures are supposed to be designed with adequate strength to resist environmental loadings. Fatigue is one of the governing failure modes for ships and offshore structures. Ocean waves are considered as the main source of fatigue damage. Fatigue is a long-term cumulative process and all sea states have to be taken into account. These sea states data are obtained by past measurements and are assumed to be representative. However, the effect of climate change has been observed in many aspects, such as temperature, extreme weather events or wave conditions. In order to ensure the safety of offshore structures, the effect of climate change on wave conditions should be considered in design stage.

The prediction of wave conditions is a challenge and there is still no widely accepted solution. Young et al. (2011) analyzed a 23-year database of satellite altimeter measurements, and investigated the global trends of annual wind speed and wave height by linear interpolation. Their conclusion indicated that the trend of either wind speed or wave height is region-dependent. The global wind speed was increasing consistently (1991-2008); whereas the global wave height did not show any consistent trend. Bitner-Gregersen and Skjong (2011) predicted the climate change impact on tanker design. The extreme significant wave height (Hs) was assumed to have 0.5-2.0 meters increase by $21^{st}$ century. It is concluded that the rise of significant wave height by 2.0 meters would result in a 10%-15% increase of deck steel weight in the midship region in order to maintain the safety level. However, both of these two predictions on wave height change did not reflect the inner mechanics of wave generations and the predicted results are not suitable for fatigue analysis, because fatigue assessments require more detailed information of sea states.

Most ocean waves are generated by wind. They are classified into wind sea waves and swells. Wind sea waves are generated by local wind and swells are waves propagating from remote sea areas. Wind is the flow of air in a large scale and caused by differences in the atmospheric pressure. The driving forces of wind are the non-uniform distribution of solar radiation and the rotation of the earth. Climate change is influenced by both natural variation and human activities. With the emission of GHGs, human activities are regarded with high confidence as the primary reason of climate change during the recent decades (IPCC, 2007). In order to predict the effect of climate change, many GHGs scenarios are presented, which describe greenhouse gas concentration (or emissions) trajectories in the future. Grabemann and Weisse (2008) simulated the sea state in the North Sea for the 30-year period 2071–2100 using the wave model WAM. Their wind data were obtained from the simulation results of two Global Climate Models (GCMs: HadAM3H and ECHAM4/OPYC3) with two different emission scenarios of GHGs. They found a moderate increased frequency of the most severe wave condition occurrences in the North Sea and concluded that extreme wave heights may increase by up to 0.35 m in the Southern and Eastern North Sea at the end of the century.

This paper is to outline a predictive methodology to estimate the effect of climate change on fatigue assessment of offshore floating structures. In the first part of this paper, environmental data sources and wave models are introduced. Then, the procedure of this methodology is discussed. In the third part, a case study is presented in order to clarify the methodology. The prediction of fatigue consumption of FPSO –Glas Dowr is demonstrated. The wind data is predicted by CMIP5 and RCP8.5 scenario. Sea states at Sable Field, offshore South Africa from 2007 to 2020 are simulated by the numerical wave model- WaveWatch III (WW3). Fatigue consumptions are calculated for two hotspots at midship of the vessel. In order to evaluate the quality of this fatigue assessment, wind data from ERA-interim are used as the environmental loadings to simulate wave conditions and calculate fatigue damage at the same hotspots. Finally, the conclusions are given.

## DATA DESCRIPTIONS AND WAVE MODELS

Representative Concentration Pathways (RCPs) are four greenhouse gas concentration scenarios adopted by the Intergovernmental Panel on Climate Change (IPCC). As requested by IPCC, the RCPs should be compatible with the full range of stabilization, mitigation and baseline emission scenarios available in the current scientific literature. These four RCPs were selected based primarily on their emissions, associated concentration outcomes, and net radiative forcing as shown in Figure 1. They include information about concentrations and emissions of GHGs, emissions of other radiatively active gases and aerosols, land use and land cover up to the year 2100 (Moss et al., 2008). The RCP 2.6 is representative for scenarios with low greenhouse gas concentration levels. The peak radiative forcing level reaches 3.1 $W/m^2$ around 2050, and falls back to 2.6 $W/m^2$ by 2100. The corresponding greenhouse gas emissions are decreasing substantially over time. The GHGs emission of RCP 4.5 is increasing slowly until 2060 and keeps stable before 2100. This stabilization scenario considers the employment of green technologies and policies for reducing GHGs emissions. The RCP 6.0 is also a stabilization scenario, but the employment of green technologies and policies does not receive attentions as much as RCP 2.6 and 4.5. The emission of GHGs is not stabilized until 2100. The RCP 8.5 represents those scenarios with increasing greenhouse gas emissions. The GHGs concentration is rising sharply and the radiative forcing level reaches 8.5 $W/m^2$ in 2100.

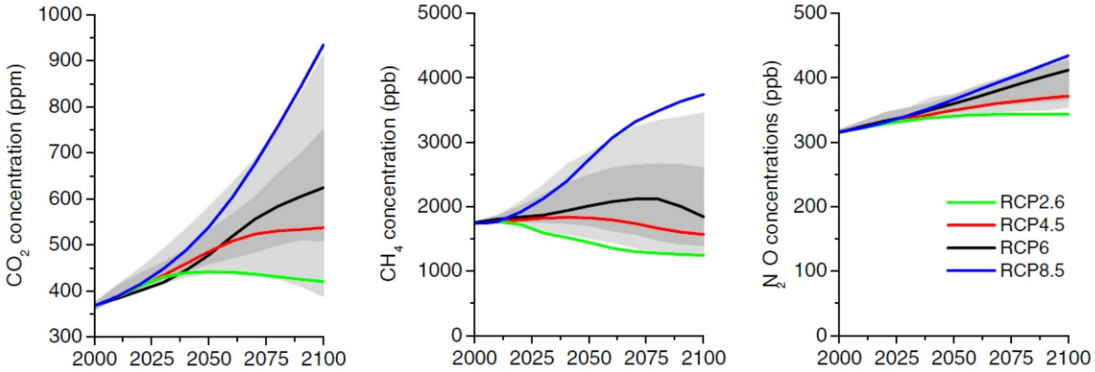


Figure 1. Trends in concentrations of greenhouse gases. Grey area indicates the 98th and 90th percentiles (van Vuuren et al. 2011)

The fifth phase of the Coupled Model Intercomparison Project (CMIP5) is considered as the combination and comparison of different global coupled ocean-atmosphere general circulation models. One of its main purposes is to examine climate “predictability” and to explore the ability of models to predict climate on decadal time scales. By adopting radiative forcing data from RCPs, atmospheric models of CMIP5 would output the corresponding atmospheric data including wind fields data from 2000 to 2100. Then, WaveWatch III (WW3) is applied to simulate the global wave conditions. WW3 is the third generation wind-wave modeling framework. It has been developed at the Marine Modeling and Analysis Branch of the National Centers for Environmental Prediction’s Environmental Modeling Center (Tolman, 2014). As the driving force, wind fields data are requested by WW3. The spectral action balance equation is used to simulate atmospheric wind forcing, nonlinear wave-wave interactions, and dissipation, and to output statistical wave parameters (Janssen, 2008).

ERA-Interim is a global atmospheric reanalysis project covering the period from 1979 to the present. Observations are assimilated to correct bias and output consistent environmental data. Environmental observations are by voluntary observing ships (VOS), buoys, and satellites (Semedo et al., 2011). Considering the large amount of observations, ERA-interim’s wave data are widely used for metocean analysis.

## METHODOLOGY

This paper is to outline a predictive methodology to analyze the effect of climate change on fatigue assessment of offshore floating structures. There are three steps: data preprocessing, wave simulations, and fatigue analysis; see Figure 2.

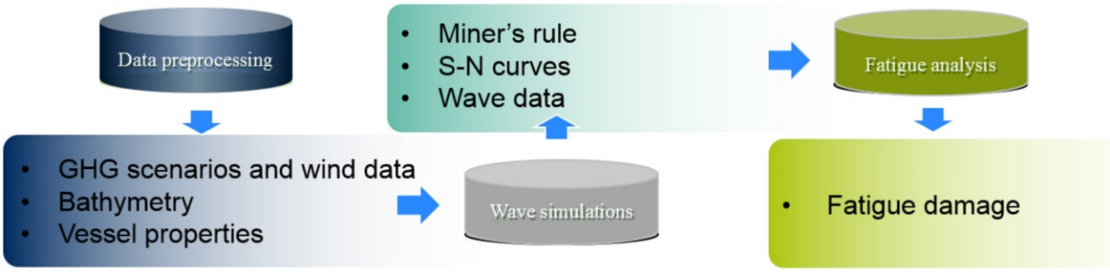


Figure 2. Data flow of the calculation methodology

At first, one of the four RCPs should be chosen depending on the future GHGs emission expectation. Then, an atmospheric simulation is made to predict the wind fields. The simulation of atmosphere is complicated and is not discussed in this paper. More details about atmospheric models can be found in Taylor et al. (2012). Water depth is another important element, because the physics and numerical formulations in shallow water are not identical to those in deep water. Each FPSO or other floating platform has its own structural properties, which may result in different stress responses. Hence, bathymetry and structural properties of vessels should also be prepared.

Secondly, the wind-driven wave model WaveWatch III is used to simulate ocean waves on the specific sea areas. As known, most ocean waves are generated by wind. But their wave properties are quite different from each other. Wind sea waves are generated by local wind with relative high frequencies and swells are generated at remote sea areas with low frequencies. The shapes of their spectra also differ. Swell spectra have narrower frequency and directional range than wind sea spectra. All these differences should be taken into account in fatigue damage calculations. A wave partitioning method is utilized to identify wind sea waves and swells (Hanson, Phillips, 2001).

Swells are propagating over long distance from remote sea areas. Hence, a large spatial scale or even a global scale wave simulation is needed. The requirement of simulating spatial scale is depending on the target sea area. For instance, sea states at Sable Field are highly dependent on waves form both Atlantic and Indian Ocean. In addition, the selection of wave physical formulation approaches is also important for wave simulations. There is a variety of physical approaches for wave growth, dissipation, non-linear wave interactions, wave-ice interactions, shallow water effect, etc. An appropriate physical formulation approach can make wave simulations more reliable or less time-consuming.

Two methods of fatigue calculations are recommended in fatigue assessment (Det Norske Veritas, 2010). One is simplified by postulating the long-term stress range distribution without specifying wave conditions encountered by FPSOs; another is using spectral method for the estimation of long-term stress range. In the spectral method, the long-term stress distribution is considered as a summation of short-term stress distributions and represented by scatter diagrams. By the stress transfer functions, the relation between wave spectra and stress responses is described as Equation [1]. Stresses in each short-term sea state is fitted by Rayleigh distribution. The corresponding fatigue damage in each short-term sea states is calculated based on S-N curves as Equation [2]. According to Miner's rule, long-term fatigue damage is accumulated by linear summation of fatigue damage from each sea state in the wave scatter diagram as equation [3].

$$S_\sigma(\sigma|H_s,T_z,\theta) = |H_\sigma(\sigma|\theta)|^2 \cdot S_\eta(\sigma|H_s,T_z,\theta) \quad [1]$$

$$\log N = \mathrm{C} - \mathrm{m} \cdot \log \Delta\sigma \quad [2]$$

$$\mathrm{D} = \sum_{i=1}^{j} \frac{n_i}{N_i} \quad [3]$$

where

$S_\sigma(\sigma|H_s, T_z, \theta)$= response spectrum of the ship

$H_\sigma(\sigma|\theta)$= stress transfer function

$S_\eta(\sigma|H_s, T_z, \theta)$=wave spectrum

N=predicted number of cycles to failure for stress range $\Delta\sigma$

$\Delta\sigma$=stress range

C, m=S-N curve parameters

D=accumulated fatigue damage

j=number of stress blocks

$n_i$=number of stress cycles in stress block j

$N_i$=number of cycles to failure at constant stress range $\Delta\sigma$

## CASE STUDY

In this case study, the fatigue consumptions on FPSO-Glas Dowr from 2007 to 2020 are predicted. Glas Dowr is a converted FPSO owned by Bluewater. It was operating at Sable Field, offshore South Africa. The main dimensions of Glas Dowr are listed in Table 1. It is assumed that Glas Dowr is working at Sable Field during 2007-2020.

Table 1 Main dimensions of Glas Dowr

| | |
|---|---|
| **Displacement** | 121400 metric tons |
| **Length** | 232m |
| **Breadth** | 42m |
| **Depth** | 21.2m |
| **Actual Midship Draft** | 12.99m |
| **Water Depth** | 103m |

RCP 8.5 is chosen to predict the GHGs concentration from 2007 to 2020. RCP 8.5 examines the uncertainties on the world population, income, resource use efficiency, energy technology and urbanization, and predicts a high GHGs concentration which results in a high radiative forcing level 8.5 W/m$^2$ in the year 2100 (Riahi et al. 2007). The corresponding wind fields are simulated by Beijing Climate Center Climate System Model (BCC-CSM) (Wu et al., 2008). Wave conditions are obtained from WW3 and bathymetry data are provided by ETOPO1 model developed by the National Oceanic and Atmospheric Administration (NOAA).

In WW3, the numerical formulations, including the third propagation scheme, discrete interaction approximation and the Ardhuin et al's source term package (2010) for input and dissipation, are selected to make wave simulations. Wave spectra of all the sea states are generated by simulations of WW3. The wave spectrum is defined with 25 frequencies (range 0.042-0.414Hz, frequency increment factor 1.1) and 24 equally spaced directions. A global simulation is carried out to consider swells propagated from both Atlantic and Indian Ocean.

In each sea state, one wind sea system and several swell systems are partitioned based on the partitioning method presented by Hanson and Phillips (2001). In order to simplify the calculation of fatigue damage, all these swell systems are combined into one based on the conservation balance of wave energy. Each wave system is represented by wave height, wave period and wave direction.

Wave direction is an important element for fatigue assessment of vessels. Wave directions relative to vessel headings are dependent on the mooring system of FPSOs. The turret mooring system can adjust the vessel heading according to the directions of wind, wave and current in order to reduce stresses. Spread moored FPSOs are fixed with mooring lines and cannot change vessel headings, and relative wave directions equal absolute wave directions. Glas Dowr is a turret mooring FPSO. Because environmental loadings from wind and current are not taken into account in this case study, the direction of vessel heading is defined as the average direction of total waves at each sea state.

Fatigue damages are calculated with the spectral method. A fatigue calculation program –Bluefat, developed by Bluewater, is used to calculate external wave pressures, internal tank pressures and global horizontal and vertical bending moments, and estimate fatigue damage. The fatigue life of Glas Dowr is estimated based on S-N curves and Miner's rule. In order to evaluate the quality of fatigue assessment with the predicted wave data, another fatigue assessments are carried out with ERA-interim wind data.

Hot spots are defined as points in structure where a fatigue crack may initiate due to the combined effect of structural stress fluctuation and the weld geometry or a similar notch (Det Norske Veritas, 2010). The most critical hot-spots are expected to be in the longitudinal-web frame connections (Aalberts et al, 2010). The hot spots selected in this case study are located at midship section as listed in Table 2. One hotspot is at the main deck and another is near the neutral axis.

Table 2 Selected locations for fatigue calculations (Aalberts et al., 2010)

| **Location ID** | **Description** |
|---|---|
| PS22D | Main deck frame $66\frac{1}{2}$ SB |
| PS34W | on web of stiffener 34, 50mm from ship's side at frame $66\frac{1}{2}$ SB. |

## RESULTS AND DISCUSSION

The annual fatigue consumptions from 2007 to 2020 are predicted as shown in Figure 3. The wind data is predicted by the BCC-CSM model from CMIP5 with RCP8.5 scenario. The wave conditions are simulated with WW3. All wave systems are descried by Jonswap spectra with parameters Hs, Tz, mean wave directions and peakedness factor. An one-slope S-N curve with m=3 and log(C)=5.75 is used in all cases to calculate fatigue damages.

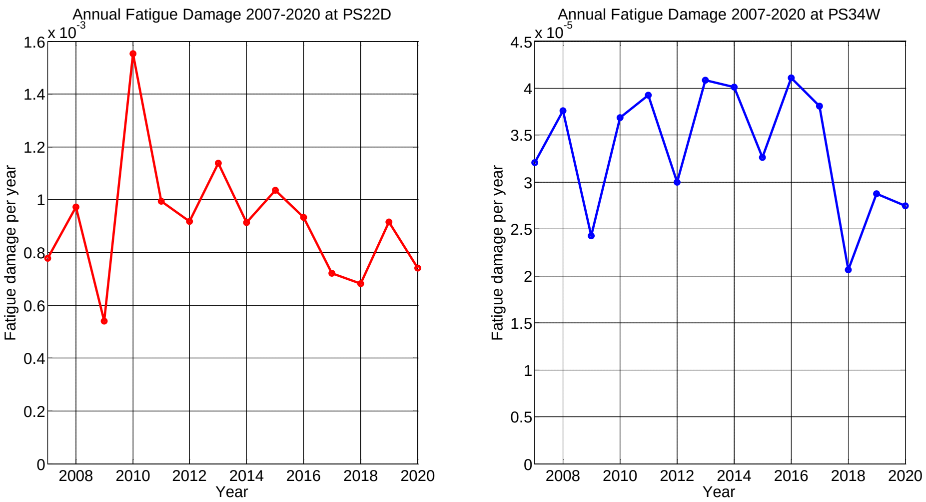


Figure 3. The annual fatigue consumptions from 2007 to 2020 at PS22D and PS34W

The peak damage at PS22D hotspot appears in 2010, and the maximum damage at PS34W is in 2016; the lowest damage is found in 2009 and 2018 respectively. The peak values at these two hotspots do not appear at the same year. That's because there are more head sea waves (180 degree off stern) in 2010 and more waves propagating from vessel side directions in 2018. The directional distributions of waves in these two years are shown in Figure 4. PS22D is located at the main deck and very sensitive to head sea waves; whereas PS34W is near the neutral axis and the main damage source is the wave pressure at the portside.

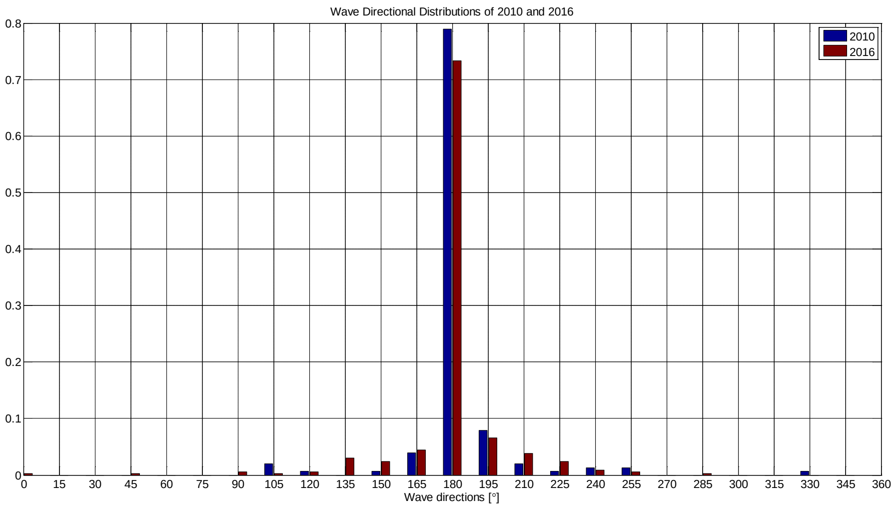


Figure 4. The directional distributions of waves in 2010 and 2016

In order to evaluate the fatigue prediction with wind data from CMIP5, another fatigue assessment for 2007 to 2009 is made with wind data from ERA-interim. The annual fatigue consumptions are calculated and compared with the predicted fatigue damages by CMIP5 wind data. The comparison is shown in Table 3. The fatigue damage with ERA-interim is 7 times as high as fatigue of CMIP5 at PS22D and 4.45 times as high as fatigue at PS34W. As wave loading is the only fatigue source, this gap is induce by the differences of sea states in these two fatigue assessments. As shown in Figure 5, from 2007 to 2009, the sea states simulated with ERA-interim wind data have higher significant wave height. The significant wave height in most CMIP5 sea states is lower than 3.5 meters; while there are many tough sea states of ERA-interim with Hs higher than 3.5 meters. The average Hs of ERA-interim is 64% higher than Hs of CMIP5. All the sea states are simulated by wind-driven wave model-WW3. Hence, the lower Hs is due to the slower wind speed in CMIP5 As shown in Figure 6, latitudinal component U of wind speed in ERA-interim is 52% higher than the speed of CMIP5 on average. The difference of longitudinal component V is less than 5%. In total, the wind speed of ERA-interim is 1.29 times as high as the wind speed of CMIP5.

Table 3 Annual fatigue damage from 2007 to 2009

| | | 2007 | 2008 | 2009 |
|---|---|---|---|---|
| PS22D | CMIP5 | 7.8E-4 | 9.7E-4 | 5.4E-4 |
| | ERA-interim | 6.2E-3 | 4.7E-3 | 5.2E-3 |
| PS34W | CMIP5 | 3.2E-5 | 3.8E-5 | 2.4E-5 |
| | ERA-interim | 1.5E-4 | 1.3E-4 | 1.4E-4 |

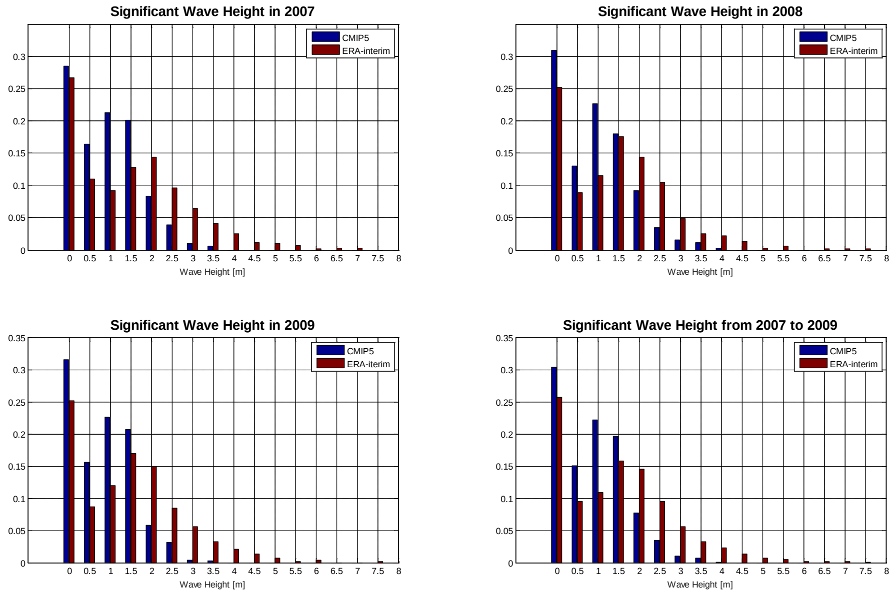


Figure 5. Distribution of significant wave height from 2007 to 2009

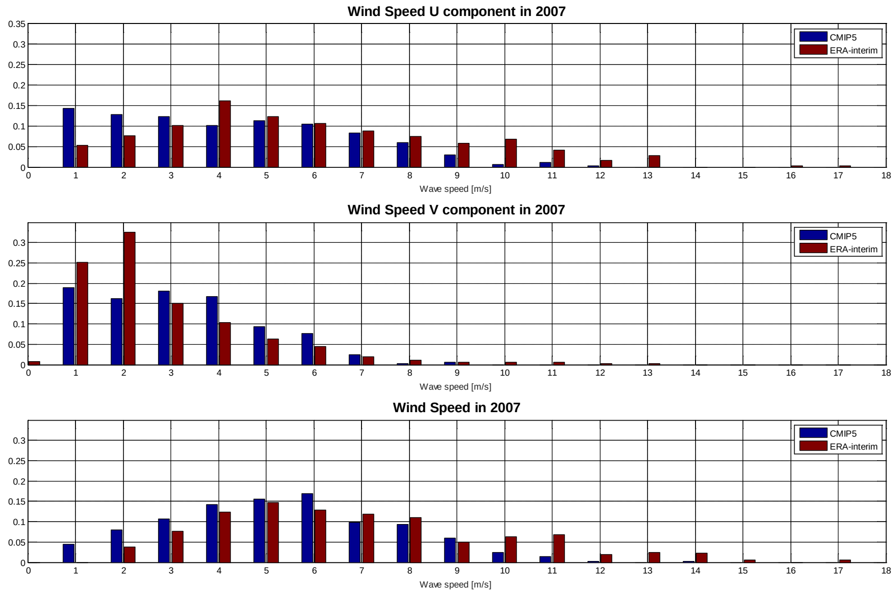


Figure 6. Distribution of wind speed in 2007

## CONCLUSIONS

This paper outlined the methodology of predicting the climate change impact on fatigue consumptions of offshore floating structures. The effect of climate change is taken into account by predicting the trajectory of GHGs concentration. RCP scenarios are used to describe the trajectory of GHGs concentration by examining the uncertainties on the world population, income, resource use efficiency, energy technology, and urbanization. The atmospheric circulation is simulated with the atmospheric models in CMIP5 and the global wind field data are obtained. The third generation wave models are used to simulate wave conditions based on the energy (or action) balance equation with wind fields as driving forces. With the wave scatter diagram obtained from wave models, fatigue assessment is carried out. In the case study, the calculation procedure is demonstrated to predict the annual fatigue damage of Glas Dowr from 2007 to 2020. RCP 8.5, BCC-CSM atmospheric model and WaveWatch III are utilized to simulate the wind fields and wave conditions. With those predicted wave data, the fatigue assessment of Glas Dowr is made. In order to validate the quality of this fatigue analysis, another fatigue assessment is carried out with wind data from ERA-interim project.

Annual fatigue consumptions from 2007 to 2009 calculated with these two different datasets (CMIP5, ERA-interim) are compared. Annual fatigue damage calculated with ERA-interim is 7 times higher than fatigue of CMIP5 at PS22D and 4.45 times higher at PS34W. This big gap is due to the underestimation of environmental loadings from BCC-CSM. The peak fatigue consumptions of these two hotspots are not at the same year, because of the wave directional distributions. In 2009, there are more head sea waves. Stress at the main deck is mainly dominated by bending moment induced by head sea waves. In contrast, hotspots near the neutral axis are hardly influenced by bending moment. Instead, they are more sensitive to wave pressure caused by waves propagated from the vessel's sides. The comparison of the wind and wave statistical parameters from these two datasets shows that BCC-CSM underestimates wind speed, and lead to the lower fatigue damage at Sable Field.

Although the predicted fatigue consumption is underestimated, the application of GHGs scenarios and numerical atmospheric-wave models provides a promising solution to predicting the effect of climate change on wave conditions and consequently on fatigue consumptions of floating structures. The comparison indicated that both GHGs scenarios and models still require further improvement and validation, because they all underestimate the environmental loadings and result in an underestimation of fatigue assessment at Sable Field. In addition, the effect of climate change is region-dependent. A multi-region prediction of climate change impact on fatigue assessment is also needed.

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