PROJECTION OF FUTURE WAVE CLIMATE FOR MARINE RENEWABLE ENERGY

Nobuhito Mori[1], Li Erikson[2], Mark A. Hemer[3], Piero Lionello[4], Fernando Mendez[5],
Alvaro Semedo[6], Xiaolan Wang[7] and Judith Wolf[8]

[1] Disaster Prevention Research Institute, Kyoto University, Japan
[2] Pacific Coastal & Marine Science Center, USGS, USA
[3] The Centre for Australian Weather and Climate Research, CSIRO, Australia
[4] DiSTeBA, University of Salento and CMCC,Italy
[5] IH Cantabria, Universidad de Cantabria, Spain
[6] Escola Naval, CINAV, Portugal
[7] Climate Research Division, Environment Canada, Canada
[8] National Oceanography Centre, UK

Future changes in wind-wave climate have broad implications for operation and design of coastal, near- and off-shore industries, ecosystems and wave energy resources. However, wind-waves have received little attention in global assessments of projected long-term range of future climate change. We present strategies and results from the community derived multi-model ensemble of wave climate projections (COWCLIP). The COWCLIP project has been active since 2011 and includes global and regional wave climate projections. Results show that the area of projected significant wave height H_s decrease is greater during boreal winter (January-March) than boreal summer (July-September) in the northern Hemisphere. A projected increase in annual mean H_s is found over 7.1% of the global ocean, predominantly in the Southern Ocean, and is larger during austral winter. Increased Southern Ocean wave activity influences a larger proportion of the global ocean as swell propagates northwards into the other ocean basins.

Keywords: global warming, climate change, wave climate projections, wave energy

INTRODUCTION

The importance of the global wave energy resource has increased as different types of wave energy converters (e.g., point absorbers and attenuators, oscillating wave surge converters and oscillating water columns, amongst others) have been proposed and tested as a means to provide renewable energy (e.g. Pelamis [1] and Oyster [2]). Long-term future projections of available wave energy will aid developers and decision makers locate appropriate sites for wave energy device deployments as demand for access to the wave energy resources increase [3].

Understanding of wave climate is taken from long-term observational data. There is increasing evidence for climate driven historical wind-wave variability climate over at least the satellite altimeter era with trends in wave height seen in observing ship records over the past half century. Observed variability in wave climate is attributable to changes in global marine wind fields and with projected future changes in these winds, climate driven changes in wave climate are anticipated (see Figure 1). However, the observational wave climate record is limited and a long-term projection based on the historical record is not appropriate without understanding the relationships between atmospheric climatology and the consequent wave fields. General circulation models are now routinely used to develop future long-term projections of climate, under assumed future greenhouse gas (or radiative) forcing scenarios. However, these models generally do not yet include wind-wave dependent parameterizations, and wave parameters are therefore not available amongst the standard suite of climate variables used to characterize the climate system. As a result, understanding of long-term changes in wave climate is limited relative to other climatological parameters such as temperature, precipitation or sea-level.

A growing number of studies have considered how global wave climate may respond to projected future climate scenarios with increased greenhouse gas concentrations. These studies have been carried out independently, using different methods to investigate projected future wave climate changes [4-8]. Within each individual study, only a limited number of climate model simulations were investigated due to limited study scope and/or availability of suitable climate model data. Individual studies are therefore unable to fully quantify the uncertainty of projected changes in wave climate. Here, our primary aim is to use results contributed to the

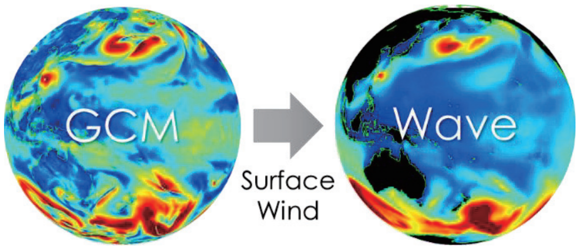

Figure 1. Methodology of wave climate projection based on general circulation model (GCM) output

Coordinated Ocean Wave Climate Project (COWCLIP [9]) to quantitatively compare the magnitude of projected changes derived from several independent studies and to determine the level of agreement which surround available projections of wave climate since 2011.

We summarize current activities of COWCLIP in this article. First, an outline of the project and methodology of wave climate projection are presented. Second, the results of wave climate projection for the late 21st century are summarized in a global scale.

OUTLINE OF COWCLIP PROJECT

Surface wind waves were identified in the Intergovernmental Panel for Climate Change (IPCC) Fourth Assessment Report (AR4) as one of the key drivers in the coastal zone, but little information was available on projected changes under future climate scenarios. The Coordinated Ocean Wave Climate Project (COWCLIP) aims to raise the profile of wind-waves as a variable in the global climate system – both to foster and support determination of the:

- Effects of climate variability and change on the wave climate, and

- Feedback influences of waves on the coupled ocean-atmosphere climate system.

Phase 1 of COWCLIP was conducted in 2011-2012 using a multi-model and multi-scenario ensemble based on the CMIP3 products. Phase 2, commenced in late 2013, will summarize a designed ensemble of wave projections based on CMIP5 simulations for different emission scenarios. The first part of the phase 2 product is expected to be released in 2015 (Figure 2). COWCLIP phase 2 also plans to examine regional wave climate change. Five regional wave projections, Europe, Mediterranean Sea, North America coasts, East Asia and Oceania, are planned to be conducted at a scale of order 100kms. These data sets will be free and openly available to the academic community.

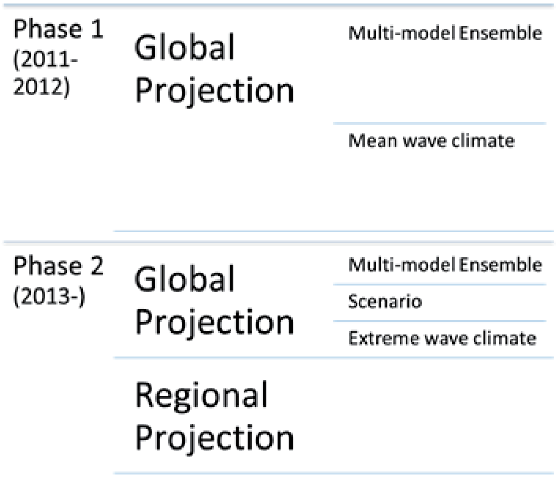

Figure 2. Outline of COWCLIP project.

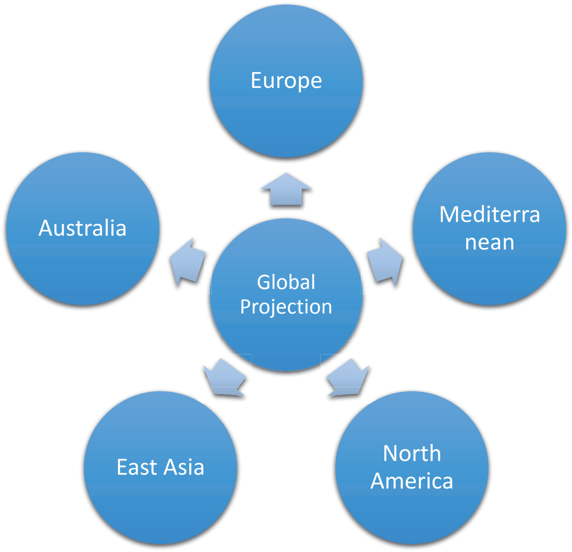

Figure 3. Phase 2 COWCLIP for regional wave projections

METHODOLOGY

The wave projections can be classified into two methods: dynamical projections using a spectral wave model, and statistical projections using some empirical relations between atmospheric field and wave field. One of the goals of COWCLIP is to determine the uncertainties introduced into wave projections of future mean wave height and monthly or annual mean fields given different wave projection methods and different forcing scenarios.

Dynamical wave projections were conducted using different spectral wave models (WAM, WaveWatchIII and SWAN) driven by sea surface winds (U_{10}) from GCM or RCM outputs. Dynamical wave projections provide several different wave fields such as wave height (H_s), period and direction. Dynamical wave projections are also suitable to discuss how wind sea and swell will respond to projected forcing conditions. Statistical wave projections consist of empirical relations of H_s and atmospheric parameters (e.g. U_{10}, sea level pressure, SLP, etc.). Although the calibration and validation are required before being used for providing projections, the statistical wave projections are relatively computationally in-expensive. Statistical wave projections thus provide advantages for assessing future changes of H_s for a large ensemble of future scenarios (e.g., [*8*]).

COWCLIP Phase 1 has collected an ensemble of opportunity, including wave climate projections derived from different scenarios, wave models and forcing (SLP or U_{10}). Its contributing studies [4-7] have assessed the performance of each model to represent the historical wave climate on an individual basis.

RESULTS OF WAVE CLIMATE CHANGE

Here we present major results from the COWCLIP phase 1. Signals of projected change in significant wave height, H_S, by late 21st century show agreement between models over considerable portions of the global ocean (Figure 4). Changes in the multi-model annual mean H_S show consistent projected decrease among models over a larger area and consistent increases over a smaller area. Projected increases in H_S are generally limited to the Southern Ocean, associated with a projected strengthening of the westerlies. Small areas of projected increase in the tropical eastern Pacific Ocean are associated with an increasing southern ocean swell component. Agreed decrease across all models is projected in all other ocean basins, particularly in the subtropics. In the North Atlantic, this decrease spans all seasons, generally consistent with projected wind changes in the CMIP3 multi-model dataset. In the boreal winter (January, February and March, JFM; Figure 4c), the relative area of projected decrease is enhanced. In the austral winter however (July, August and September, JAS; Figure 4d), regions of projected decrease and increase are comparable at about 8 % of the global ocean. A notable region of agreed projected increase is observed in the southern Pacific trade wind zone, consistent with projected strengthening of easterly trade winds in the winter subtropics seen in the CMIP3 multi-model dataset.

The changes of wave climate depend on wave models, atmospheric conditions, and greenhouse gas emission scenarios. The effects of future emission scenarios on wave climate become larger as the projection range becomes longer. Figure 5 shows an example of future change of mean H_s driven by different SSTs with the same wave model and the same greenhouse gas emission scenario (SRES A1B). Although the wave model is primarily forced using sea surface winds, the mean H_s is sensitive to different SST forcing. Therefore, reduction and estimation of uncertainty of wave climate projections is an important consideration for the phase 2 of COWCLIP project.

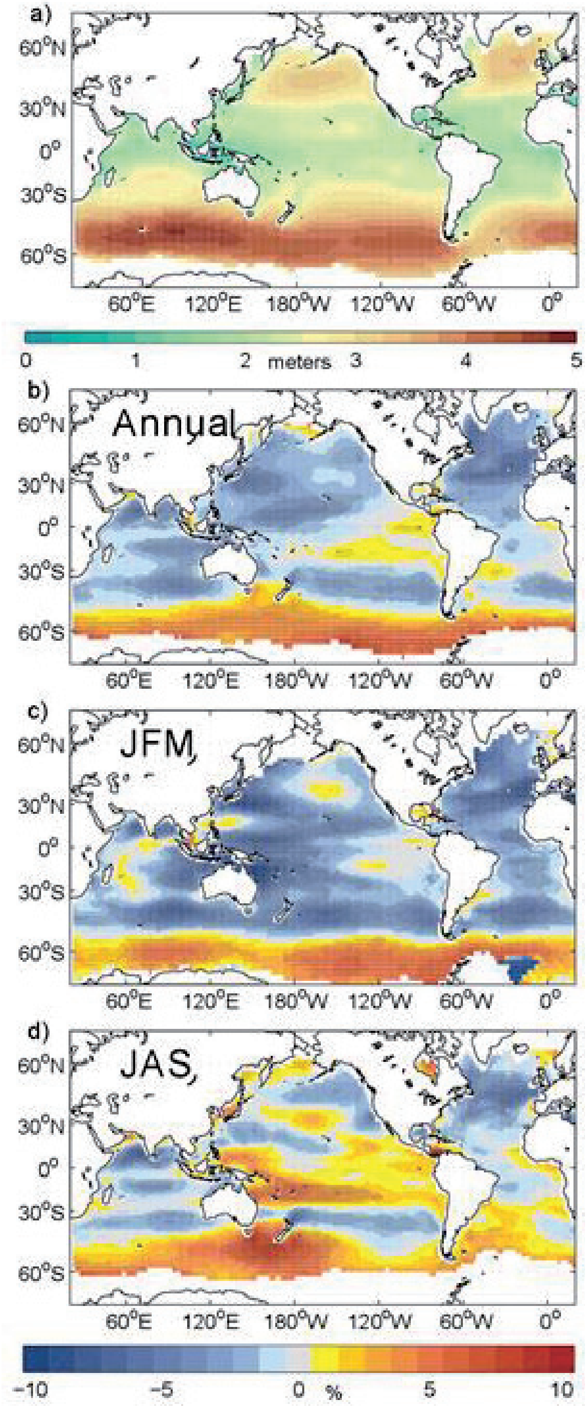

Figure 4. Future change of mean H_s at the end of 21st century in comparison with present climate condition (a: present climate, b: future change of annual mean, c and d: future change in JFM and JAS) [9]

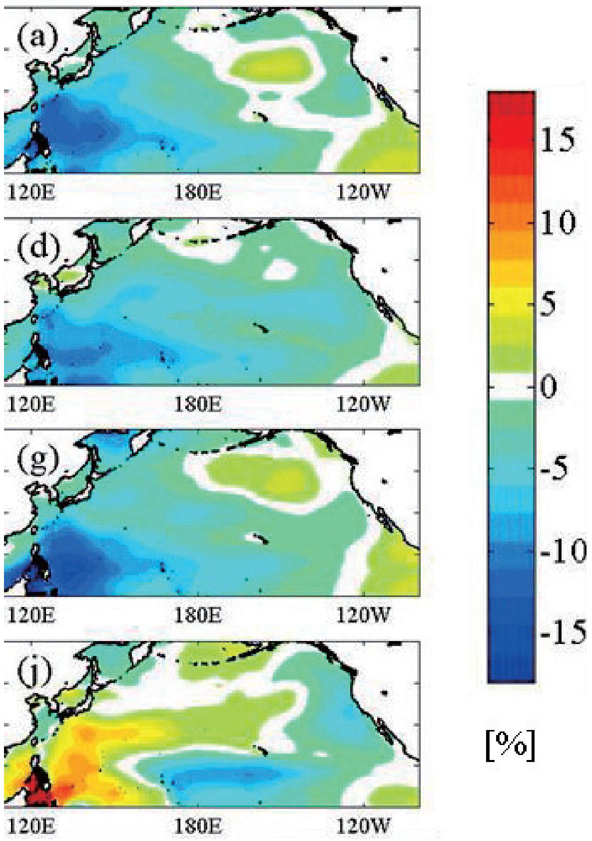

Figure 5. Future change of mean H_s depend on different SST (a, d, g, j) driven GCM winds.

ON GOING STUDY

The COWCLIP products can be used for long-term impact assessment of marine renewable design for available energy resource, fatigue and extreme design, etc. COWCLIP is planning to produce a next generation wave projection products based on CMIP5 simulations this year.

As the wave power is proportional to H_s^2T (T is wave period), the future changes of wave height and period are important for long-term assessment of wave energy converters. COWCLIP Phase 2 will be able to distribute this information to the public in the near future.

ACKNOWLEDGMENT

This article is a part of Coordinated Ocean Wave Climate Project (COWCLIP) supported by JCOMM, WMO-IOC.

REFERENCES

[1] R. Henderson, “Design, simulation, and testing of a novel hydraulic power take-off system for the Pelamis wave energy converter”, *Renewable Energy*. Volume 31, Issue 2, 2006, pp.271–283.

[2] T. Whittaker, D. Collier, M. Folley, M. Osterried, A. Henry, M. Crowley, “The development of Oyster – A shallow water surging wave energy converter”, *Proceedings of the 7th European Wave and Tidal Energy Conference*. 2007, 6p.

[3] A.D. de Andrés, R. Guanche, L. Meneses, C. Vidal, I.J. Losada, “Factors that influence array layout on wave energy farms”, *Ocean Engineering*. Volume 82, 2014, pp. 32–41

[4] X.L. Wang, and V. R. Swail, “Climate change signal and uncertainty in projections of ocean wave heights”, *Climate Dynamics*. Volume 26, 2006, pp.109–126.

[5] N. Mori, Yasuda, T., Mase, H., Tom, T. and Oku, Y., “Projection of extreme wave climate change under the global warming”, *Hydrological Research Letters*. Volume 4, 2010, pp.15-19. doi:10.3178/hrl.4.15.

[6] Y. Fan, I.M. Held, S.J. Lin, X.L. Wang, “Ocean warming effect on surface gravity wave climate change for the end of the Twenty-First century”, *Journal of Climate*. Volume 26, 2013, pp.6046–6066.

[7] M.A. Hemer, Katzfey, J. and Trenham, C., “Global dynamical projections of surface ocean wave climate for a future high greenhouse gas emission scenario”, *Ocean Modelling*. Volume 70, 2013, pp. 221–245.

[8] X.L. Wang, Y. Feng, and V. R. Swail, “Changes in global ocean wave heights as projected using multimodel CMIP5 simulations”, *Geophysical. Research Letters,* 41, 2014, 1026-1034.

[9] M.A. Hemer, Y. Fan, N. Mori, A. Semedo and X.L. Wang, “Projected changes in wave climate from a multi-model ensemble”, *Nature Climate Change*. 2013, 6p., doi:10.1038/nclimate1791.