# Advancing Wind-Waves Climate Science
## The COWCLIP Project

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Since the Intergovernmental Panel on Climate Change (IPCC) fourth assessment report (AR4), research interest in two key, but independent, roles of wind-waves in climate change science has increased. Greater understanding of wind-waves in the climate system is required as waves can be a key contributor to coastal sea level extremes (through wave setup) and subsequent flooding, cause overtopping of sea defenses with consequent failure and damage to infrastructure or coastal erosion, and drive longshore drift and associated coastal sediment budgets. A comprehensive assessment of potential climate change–driven impacts on the coastal zone must therefore consider potential future changes in wave conditions. In addition, wind-waves are a key process influencing the exchange of momentum, heat, and mass across the air–sea interface. Coupled atmosphere–ocean global climate models (GCMs) do not currently consider the wind-wave–dependent component of these fluxes. A recent workshop[1] held to establish a community working group focused on coordinated ocean-wave climate projections (COWCLIP) created an opportunity to discuss the current status of international activities in wind-wave climate research. Here, we document the community perspective of key scientific questions, challenges, and recommendations relevant to wind-waves in a changing climate. Four themes are addressed: historical wave climate variability and change, global wave climate projections, regional wave climate projections, and coupled wind–wave–climate modeling. The COWCLIP community aims to generate wave climate projections (ultimately of global extent) and aid comprehensive assessments of their uncertainty by: a) providing a systematic community-based framework to support validation, intercomparison, documentation, and data access for wave climate projections; b) describing best practice for regional wave climate projections; and c) engaging the interests of the wind-wave community into the wider climate community and ultimately developing coupled atmosphere–wave–ocean GCMs in order to derive quantitative estimates of wind-wave–driven feedbacks in the coupled climate system.

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**HISTORICAL WIND-WAVE CLIMATE VARIABILITY AND CHANGE.** The key limitation of understanding historical variability of wave climate is length of observational records. The longest in situ observational wave records are approximately 40 years in length. The satellite altimeter record is approximately 25 years in length. Wave reanalyses vary in length up to 45 years (ERA-40), and potentially ~100 years with ERA-CLIM. Wave observations from voluntary observing ships (VOS) extend over longer periods but have limited spatial coverage. Detection

[1] The coordinated ocean wave climate projections (COWCLIP) workshop was supported by the World Climate Research Programme and the Joint Technical Commission for Oceanography and Marine Meteorology of the World Meteorological Organization (WMO) and Intergovernmental Oceanographic Commission (IOC) of UNESCO. The meeting was held in April 2011 at the WMO headquarters in Geneva, Switzerland. Workshop presentations are available at www.jcomm.info/cowclip.

and attribution of variability and change in the wave climate system with respect to natural decadal (or longer) variability is not easily achieved with these short records.

Assessing the historical variability of wave climate has received more research attention than other themes considered within COWCLIP. However, the IPCC AR4 assessed historical variability of wave height only. Wavelength and directional characteristics are equally important components of the wave field, and should receive increased attention in future assessments of wave climate variability and change.

Key science questions leading research of the historical wave record revolved around four themes:

- *Mechanisms of observed changes in wave climate.* How does the power spectrum of wave climate (hourly to centennial time scales) compare to that of other climate variables? What is the relationship between wave climate and existing climate indices? Can we identify suitable proxy records for historical variability of wave climate? Can we define a specific climate index for wave climate applications? Is interannual and interdecadal variability in the present wave climate adequately characterized?
- *Impacts.* What is the relationship between key coastal processes (e.g., shoreline position, coastal sediment budgets) and wave climate?
- *Attribution of change.* How well do climate model-derived wave climates compare to wave reanalyses for present climate conditions (including trends)? Can historical wave climate trends be attributed to human-induced climate change? Given historical wind-wave records provide an integrated indicator of marine winds, what skill do climate models have at representing present climate?
- *Data issues.* What other datasets can be exploited for wave climate studies? Wave climate is presently widely described by integrated wave height, period, and direction parameters. Are there other descriptors more suitable?

## GLOBAL WAVE CLIMATE PROJECTIONS.

Wave climate projection studies to date have had a predominantly regional focus. These studies have typically been carried out in isolation with little to no intercomparison between studies, with forcing conditions derived from a select few greenhouse gas emission scenarios from a select few GCMs. This approach limits the statistical certainty of projected changes in wave climate and leaves major gaps in global coverage. A recent proposal to compile a community ensemble of global wave projections to address these problems formed a basis for workshop discussion.

Both dynamical and statistical methods of deriving wave climate projections are being developed. In the dynamical approach, climate model simulated surface fields (e.g., surface winds) are used to force a spectral wave model. It has been reported that climate model simulations of the current climate (especially surface winds) show biases with respect to the corresponding observed climate. Methods to diminish such biases have been developed to improve representation of the current wave climate. Future projections are determined assuming the bias adjustment is time-invariant. A statistical approach uses reanalyses of the atmosphere and ocean waves to establish a statistical relationship between predictors (e.g., mean sea level pressure, 10-m winds) and the predictand in question (most commonly significant wave height, $H_S$, but joint probability of $H_S$ and peak wave period, $T_P$, energy flux vector, and wave spectrum have also been used). Climate model projections of the predictors are then fed to the statistical relationship to make projections of the predictand. Another approach to derive projections of wave climate, identified as requiring future research effort, is identification and exploitation of useful diagnostics of wave climate and wave-wind feedbacks on the climate system. Statistical projections have the advantage of being less computationally intensive and may be used to sample a larger range of emission and GCM uncertainties when generating projections. However, statistical projections currently have difficulty reproducing the observed wave field in regions where wind and waves are not in equilibrium (i.e., swell-dominated zones), in addition to the underlying assumption that the estimated predictor–predictand relationship will hold under future climate conditions. Dynamical projections provide a physical response to climate model projected changes in surface winds; but the computational resources required limit the ability to sample across several sources of uncertainty. There is consequent need for all approaches, provided that clear knowledge of these advantages/disadvantages, and how each method inter-compares, is available. COWCLIP aims to develop this understanding.

To support intercomparison between multiple datasets, some standardization within the COWCLIP community is required. Datasets representing present wave climate include available waves reanalyses (e.g., ERA-40 and ERA-Interim), altimeter $H_S$ records, and VOS wave datasets. A new wave hindcast that uses surface fields taken from the NCEP Climate Forecast System Reanalysis (CFSR) as forcing to run the WaveWatchIII model is currently underway. The period 1979–2008, which is common to both ERA-Interim and CFSR reanalyses and is also the period of CMIP5 AMIP experiments, was noted as a suitable 30-yr period to represent the present-day climate for ongoing wave studies. For future time-slices, the Coupled Model Intercomparison Project (CMIP5) experiments provide high temporal (and spatial) resolution surface wind outputs for time-slices 2026–2045 and 2080–2100. Future COWCLIP ensembles of dynamical projections will focus on these time slices, although concern was expressed over the short 20-yr period over which high temporal resolution outputs will be available from the CMIP5 midcentury (2026–2045) time-slice experiments (30-yr time slices would be preferred/required to address stakeholder interests).

COWCLIP's initial activities will assess for robustness between wave projection studies that are complete or underway, and are anticipated to provide a contribution to the IPCC AR5. These activities aim to raise the profile of wave climate issues within the climate community, to produce recommendations of how CMIP can support COWCLIP, to compile comprehensive details on CPU and disk space for processing and archive requirements, and to identify how COWCLIP can best support the needs of the coastal impacts community, stakeholders, and policy makers. It is intended that demonstration of COWCLIP within these initial activities will lead to greater community involvement in the ongoing project.

On a longer time frame, COWCLIP aims to routinely generate wave projections from the CMIP simulations, providing an added climate parameter to assess future change. These future experiments will follow a designed approach, aiming to sample evenly over the full sample space (scenarios, climate models) to produce a community ensemble of global wave climate projections, which will enable us to assess robustness of climate change signal and to quantify projection uncertainty of different sources (particularly, uncertainty due to different wave projection approaches). A common set of analyses, procedures, and data policies must therefore be established.

Several key questions relating to development of wave climate projections were identified at the COWCLIP workshop. These can be structured into four key themes:

- *Wave forcing data.* What benefit can be extracted from the current generation of climate models for marine-meteorological applications? Are marine winds derived from higher-resolution climate models any better than those from coarse-resolution models?
- *Models and methodologies to characterize wave climate and changes therein.* How do different wave climate projection methods intercompare? What is the magnitude of uncertainty surrounding the projected wave climate changes, and how are the cascading levels of uncertainty (emission uncertainty, climate model uncertainty, and wave modeling/downscaling uncertainty) best sampled? To what degree are statistical relationships calibrated for present climate valid for the projected future climates? Does potential exist to improve wave climate representations by improving forcing fields or wave model source term parameterizations? What spatial resolution is required to adequately meet expectations of stakeholders?
- *Validation of climate model–derived wave fields.* How well do climate model–derived wave climate fields compare with historical mean and extreme wave records?
- *Robustness of projected changes in wave climate.* What are the projected changes in wave climate, and are these changes robust with respect to the multiple sources of uncertainty introduced in generating these projections? When do projected changes in wave climate emerge from background interannual and decadal variability?

**REGIONAL WAVE CLIMATE PROJECTIONS.** Regional wave climate projection studies provide valuable input to regional coastal impacts and adaptation assessments. But to date, they have typically been carried out in developed regions addressing concerns of local policy makers. As a consequence, regions of greater risk have likely been overlooked.

It is difficult to establish a community ensemble of regional wind-wave projections for any particular region, given the applied localized objectives of existing studies. A global picture of projected wave climate change is emerging, however, from the many existing regional studies. COWCLIP aims to consider the global mosaic of regional projections within the community global ensemble outlined above. This approach will also support intercomparison between the few regional studies that overlap in their domain (e.g., the North Atlantic and adjacent seas).

Questions specific to regional wave projections, in addition to those identified for global studies above, include: 1) To what level do high-resolution regional studies improve the representation of wave climate for these regions? 2) How can the combined influence of sea level rise and projected changes in storm surge and wave climate be best characterized? and 3) What is the added value of coupling a regional climate model with wave and ocean models?

**COUPLED WIND-WAVE CLIMATE MODELING.** Beyond developing wave climate projections in an offline (one-way coupled) sense, COWCLIP's goal is that waves become a standard component of climate modeling systems. Several sea-state–dependent processes are currently parameterized in climate models using wind-dependent parameterizations. An upcoming *BAMS* article by Cavaleri et al. provides a brief review of these processes, which include momentum fluxes (e.g., influence of sea-state–dependent drag on air–sea momentum transfer), energy and heat fluxes (e.g., wave-driven turbulence and approximate Langmuir circulations driving mixing in the surface ocean mixed layer, and wave-dependent variability of sensible and latent heat fluxes into the atmosphere), mass fluxes (e.g., marine aerosol production, and bubble injection into the ocean by breaking waves and associated oceanic uptake of $CO_2$), the radiation budget (e.g., increased albedo by whitecapping waves), and the influence of waves on the marginal ice zone extent (with influence on all above listed processes). Including wave-dependent parameterizations within coupled atmosphere–wave–ocean models provides a more physical-based representation of key processes at the air–sea interface. It also removes the need for uncoupled wave model runs to generate wave information that is needed by the impacts community, and provides additional parameters to assess the coupled climate system. Sea-state dependent parameterizations of the air–sea momentum flux and of surface ocean mixing are currently being investigated within climate models.

Considerable technical computational challenges face the advance of coupling waves into atmosphere–ocean models. Coupling waves into a climate model adds computing overheads. Modeling centers must assess whether there is sufficient benefit to warrant this additional cost. Implementation of wave-dependent parameterizations will potentially lead to climate model stability problems. The time-consuming task of retuning other climate model parameters is expected at all modeling centers after CMIP5, so COWCLIP-planned inclusion of coupling waves in future CMIP experiments is timely.

Stronger communication between wave and climate modeling communities is required to implement these parameterizations. Few researchers have the knowledge required to bridge the gap between these communities. If the select few modeling centers currently implementing wave models into their climate models identify the benefits of wave-dependent parameterizations within their modeling systems, it is anticipated that other climate modeling centers will follow. COWCLIP aims to facilitate the development of research interests in this field.

The primary question to be addressed by the COWCLIP community is: How large are the surface-wave–driven feedbacks associated with each of the above processes on the coupled climate system, and can we identify the relative magnitude of each of these processes? Further questions identified include: Does the inclusion of wave-dependent parameterizations in climate models improve model skill? Which climate model biases are improved? How difficult is it to include wave-dependent parameterizations into climate models? Are present wave-dependent parameterizations of sufficient quality and global applicability to be used in climate models? Are modeled wave fields sufficiently accurate to drive parameterizations and be used as wave climate projections, given that necessary reduction in resolution is required by memory and speed constraints? Are the coupled model's wind and other fields sufficiently accurate to drive an online wave model? Does inclusion of wave-dependent parameterizations in climate models stabilize or destabilize the coupled climate system? Finally, what are the most useful diagnostics to assess the influence of including wave-dependent parameterizations in climate models?

**SUMMARY.** Since the IPCC AR4 reported a need to broaden coastal impact assessments of climate change beyond effects of sea level rise to consider other coastal drivers, interest in how wind-wave properties will respond to the changing climate has increased. Simultaneously, there has been greater interest in the sea-state dependent component of air–sea exchange of momentum, heat, and mass, and the potential consequent feedbacks in the coupled climate system. The COWCLIP community supports development of these research activities by providing a community-based framework to aid intercomparison and quantification with a more complete sample space that cannot be achieved within isolated studies. A pilot phase of COWCLIP research activities is now underway. This phase cannot be expected to address all stakeholder needs, but is a critical step in developing the required infrastructure to support ongoing COWCLIP tasks.

A key recommended objective of COWCLIP is coordination of global wave projections by international research groups, to understand uncertainty within the community ensemble of wave climate projections and to assess robustness of climate change signal. COWCLIP aims for waves to become a standard component of the coupled climate modeling systems, advocating development of coupled atmosphere–wave–ocean models. Such an approach has advantages of more physically representative parameterizations of key processes at the air–sea interface to account for wind-wave–driven feedbacks in the coupled climate system. It also provides additional parameters to assess climate model performance, removing the need for uncoupled wave model runs to generate wave information needed by the impacts community.

The establishment of a COWCLIP community is an important step in advancing wave climate research. However, several challenges remain. Closer links between the COWCLIP community with the global and regional climate modeling communities, and the coastal impacts communities, are necessary to realize the full potential of wave climate research.

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