Sea level rise (SLR) projections are one of the more contentious issues within the Intergovernmental Panel on Climate Change (IPCC) Assessment Report 4 (AR4) and receive considerable attention because of the high coastal population at risk of inundation from SLR (particularly during extreme sea level events). However, inundation is not the only process of concern to coastal communities. At least 70% of Earth’s sandy beaches are presently eroding, yet to date the IPCC has not attempted to address the impacts SLR and shifting storm patterns will have on future erosion of the world’s coasts. The IPCC Working Group (WG-1) indicates that the limiting factor in making assessments of the effects of climate change on coastal erosion is insufficient information on changes in surface ocean waves.

Changes in the ocean wave climate received minimal attention in the IPCC AR4, despite WG-2’s recognition that waves are one of eight main climate drivers affecting the coast. WG-1’s discussion of observed changes in the global wave climate addresses variability of wave height only—relying heavily on the visually observed waves from voluntary observing ships (VOS)—and ignores other wave parameters (direction and period) that are equally important. Wave direction is particularly critical for calculating littoral drift and associated estimates of sand budgets to determine coastal erosion. However, VOS data have limitations—most notably the strong bias in observations to major Northern Hemisphere shipping routes that may or may not include regions of increased risk of concern or be subject to wave climate change. Trends in VOS wave heights are significantly positive over most of the midlatitudinal North Atlantic and North Pacific, and these trends were discussed in context with available wave hindcasts and buoy and satellite altimeter data.

Statistical projections of global wave height under limited future climate scenarios have been issued from one research group using observed relationships between sea level pressure (SLP) or surface wind and significant wave height. These projections show increases in wave height in a future warmer climate for many regions following increased wind speeds associated with midlatitude storms. As with the studies of observed changes, these studies disregard other important wave parameters besides wave height.

In recent years, several dynamical projections of regional wave climate have been carried out, where downscaled Atmosphere/Ocean Global Climate Model (GCM) projections are used to force regional wave models. Forcing conditions are typically obtained from a single (at most 3) parent GCM for selected emission scenarios (typically B2 and A2, representing low–high ranges). In reference to regional storm surge modeling, the IPCC WG-1 states “the dynamical downscaling step in providing data for storm surge modelling is robust (i.e., does not add to the uncertainty). However, the general low level of confidence in projected circulation changes from global climate models implies a substantial uncertainty in these projections.” The same applies for regional wave models, indicating that the dominant source of uncertainty in the regional wave projections is the forcing wind conditions (circulation) from the global projections. This uncertainty and its impact on wave conditions need to be quantified.

Coastal managers are increasingly recognizing the role that shifting climate patterns play on the regional wave climate and consequent local sand budgets. Projections of regional wave climate change are likely to be requested for more of the world’s oceans adjacent to...
at-risk coasts. Waves also have important implications for many offshore applications that demand projections over broad spatial domains. Furthermore, while a regional modeling approach is reasonable in relatively closed basins, wave projections for open domains are also required, introducing problems specifying projected open-boundary swell wave conditions that are unavailable. Finally, while researchers continue to apply regional wave models, a consensus on projected conditions for a region will be difficult to establish without considerable repeated modeling effort and coordinated analysis of the results. Given such motivation, we advocate a shift in approach from uncoordinated regional studies to coordinated large-scale (global) projections of wave climate—both dynamical and statistical.

Given that substantial uncertainty exists in the projected circulation patterns derived from available global climate model projections, one key to establishing confidence in ocean wave projections is an ensemble approach. This requires considerable modeling effort, and we propose that global wave projections are of such importance that an intercomparison framework be implemented. Once global wave projections are established, downscaling methods may be applied to obtain sufficient information to assist assessments of the effects of regional climate change on coastal erosion (and other potential impacts).

The proposed Coupled Model Intercomparison Project (CMIP-5) experimental design will archive the forcing variables required to undertake global projections of wave climate, using an approach that resembles the prior regional wave model projections. Forcing requirements of global wave models include surface winds, sea-ice extent, air–sea temperature differences, and surface current fields. CMIP-5 aims to provide long-term (century time scale) simulations driven by representative concentration pathways (RCP) emission scenarios. These experiments will archive the necessary 3-hourly 2-D surface fields (surface winds and SLP, albeit at coarse spatial resolution only) for three specific time slices: the present-day [Atmospheric Model Intercomparison Project (AMIP) period, a future midcentury period (2026–2045), and a future end-of-century period (2081–2100). In order to provide initial surface wave projection estimates, the temporal resolution of secondary influences such as sea-ice extent, air–sea temperatures, and surface current fields need not be as high as the surface winds or SLP, provided seasonal, interannual, and longer-term variations are represented. In addition to the experiments carried out by prior CMIP phases, CMIP-5 will also conduct near-term decadal simulations, which some climate modeling groups are anticipated to carry out at a greater spatial resolution than the long-term experiments.

Three-hourly 2-D surface fields will be archived from these runs (at higher spatial resolution) for the present day (AMIP period) and a future midcentury time slice (specifically, 2026–2045). Together, the long-term and decadal CMIP-5 experiments will archive 3-hourly surface fields for 3 specified time slices providing the necessary forcing fields at sufficient temporal resolution to estimate the present day (1960–2005) wave climate, and provide projections of the midcentury (2026–2045) and end-of-century (2081–2100) wave climates using dynamical and/or statistical approaches. Midcentury projections from high and low spatial resolutions will enable quantification of the resolution uncertainty in trend estimates and biases.

Several climate modeling groups will run global climate models at a spatial resolution equal to, or greater than, the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-40 reanalysis (T159) for the CMIP5 decadal experiments. The ERA-40 data contain information about waves (from a 1.5°-resolution ocean wave model) and capture the variability of true wave heights very well on all time scales. However, as a consequence of the relatively coarse resolution of the atmospheric model and its limited ability to resolve storm systems, high wave heights were severely underestimated. Despite this underestimation, reliable estimates of extreme wave heights (“100-yr-return values”) were possible by exploiting statistical relationships with observational buoy data. Verification of climate model-derived wave climate under present-day conditions will enable development of similar bias-adjustment procedures, which can also be applied to the projected wave parameters, to achieve the best-available estimates of present and future wave climates.

A single wave prediction approach would enable quantification of only the variability associated with the climate model ensembles for a given emission scenario. Uncertainty within the wave predictions must also be accounted for. For each single climate model ensemble, a number of wave projections might be undertaken to quantify uncertainty associated with the use of different wave models and/or statistical downscaling approaches (Fig. 1). The range of wave ensembles will be dependent on the participating research groups, but could include dynamical and statistical approaches, and/or different treatment of biases (of surface winds used to force wave solutions, or of the waves themselves). The skill of the wave model ensemble set may be assessed for the
present-day (1960–2005) wave climate, in terms of reproducing the mean wave climate and any historical trends and/or variability in the observational record.

Many research questions remain regarding the important role waves play in the coupled ocean–atmosphere system, and their contribution to large-scale climate feedbacks. Uncertainty exists in the parameterizations of momentum and heat exchange between ocean and atmosphere, associated with wave-driven processes. For example, the variable roughness associated with surface ocean waves has dynamical consequences for the atmosphere. Operational models have reported improved forecast skill (for wind and waves) and improved comparison with scatterometer winds when using a coupled atmosphere–wind-wave model. Whether this translates to climatological time scales needs quantification on global scales. Similar issues occur regarding the role of waves within parameterizations of surface ocean mixing and surface heat and mass (CO₂) fluxes, altered ocean surface albedo through the effects of wave breaking, and modified marginal ice-zone extent from shifting storm wave patterns. All of these issues deserve considerably more attention in future climate research. Dynamic coupling of wave processes into coupled ocean–atmosphere global climate models is ultimately required to address these research questions, and would have the benefit of providing online projections of surface waves within the climate system. However, in order to provide projections of wave climate in the near-term, the intended archives from the CMIP5 climate model runs can be used, applying the proposed one-way interaction between projected climate conditions and surface ocean wave parameters. These projections are of paramount importance to understanding the effects of shifting climate patterns on our eroding coasts.

**SUMMARY.** The IPCC AR4 recognized that insufficient projections of wave climate were available to assess the effects climate change will have on erosion of the world’s coasts. At present, considerable research effort is placed into regional ocean wave projections, with forcing conditions derived from a select few emission scenarios from a select few GCMs. Such an approach limits the statistical confidence in the projections (limited ensembles), repeats a great deal of modeling effort, and leaves major gaps in the global coverage, particularly in those areas most at risk from changing wave conditions. In order to avoid these problems, we propose a shift to global (statistical and dynamical) projections that will come at substantial computational cost. This cost can be countered by interested parties participating in a coordinated approach (similar to the CMIP experiments), whereby individual research groups carry out global projections for selected scenarios. The aim should be to use different wave models and/or statistical downscaling approaches to produce ensembles of wave projections that correspond to climate projections from different climate models for different emission scenarios. When combined, a distribution of projections will be available that will allow an assessment of all three levels of uncertainty (associated with forcing, climate models, and downscaling methods, respectively), presenting projections with statistical confidence intervals. The proposed CMIP5 design will provide suitable data on a global scale for carrying out surface ocean wave projections, focusing on mid- and late-twenty-first-century time slices, to service the increasing demands of the coastal impacts community. Future studies could include dynamic coupling of wave processes into coupled ocean–atmosphere global climate models.

**Fig. 1.** A schematic summary indicating the additional level of run ensembles introduced into the wave projections. Blue boxes represent global climate model runs that will be carried out as part of the CMIP5 framework. Green boxes represent wave model projections that would be carried out under the proposed program.


