Coordinated global wave climate projections.

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Introduction

It is now widely accepted amongst the scientific community that the impacts of projected climate change scenarios are one of the most serious environmental threats facing the world today (IPCC, 2007). The impacts of these changes are likely to increase the risk of severe coastal inundation, and erosion, via the effects of sea level rise, altered frequency and intensity of storms, and changes in rainfall patterns.

One of the more contentious issues within the IPCC AR4 has been the projections of sea-level rise (SLR). SLR receives considerable interest because of the large number of people who inhabit the coastal zone at risk of change – approximately 10% of the world's population (634 million people) live within 10 m elevation of existing sea level in low-lying coastal regions (McGranahan et al., 2007). Consequently, considerable research effort has been directed towards quantifying projected sea-levels under the range of global climate model projection scenarios, and the IPCC have indicated an expected range of SLR of between 18 and 76 cm before 2100, including the large uncertainty associated with the melting of the major ice sheets (Meehl et al., 2007).

It is not only the direct influence of SLR inundating low-lying coastal areas which is of concern. SLR simply exacerbates the vulnerability of coastal regions to other physical processes, e.g., flooding caused by storm surges, tsunamis and highest astronomical tides. As sea level rises, storms produce increasingly larger areas of inundation. However, coastal inundation accounts for only a proportion of the impacts which will be experienced in the coastal zone. Coastal erosion is an issue of critical importance to coastal systems and communities. At least 70% of sandy beaches around the world are presently erosional (Bird, 1985). Yet to date, the IPCC has not attempted to address the issue of the effects the impacts of SLR and shifting storm patterns will have on the erosion of the world's coasts. While Zhang et al. (2004) present a strong relationship between long-term sandy beach erosion and SLR, Christensen et al. (2007) clearly outline, as part of the IPCC AR4, that the limiting factor in making assessments of the effects of climate change on coastal erosion is the insufficient information on changes in waves or near-coastal currents.

Surface waves in the IPCC AR4

Changes in the surface ocean wave climate are given only minimal attention in the IPCC AR4, despite WG-2's recognition that surface ocean waves are one of the eight main climate drivers affecting the coastal zone (Nicholls et al., 2007). Trenberth et al's (2007) discussion of observed changes in the global ocean wave climate address variability of wave height only, relying heavily on the visually observed waves from Voluntary Observing Ships (VOS; Gulev & Grugerieva, 2004), which provide the longest records of wave height data worldwide. However, the VOS data has limitations – most notably the restriction to wave height data only, and the strong bias in observations to the major shipping routes of the Northern Hemisphere, which may or may not be in regions subject to wave climate variability, or the regions of increased risk of concern (e.g., the South Pacific Islands). Trends in the VOS wave heights are significantly positive over most of the mid-latitudinal North Atlantic and North Pacific (Figure 1), and trends in these regions were discussed in context with available buoy data, available wave hindcasts, based on NRA (Wang and Swail, 2001,2002) and ERA-40 (Caires and Sterl, 2005) winds, and a 14-yr time-series of merged satellite altimeter data (Woolf et al., 2002).

The limitation of the IPCC analysis to wave height only ignores other integrated wave direction and period parameters which are equally important, particularly to coastal impact studies. The IPCC WG-2 recognise the importance of sediment-budget approaches of determining erosion in the coastal zone (Nicholls et al., 2007). An understanding of changes in wave height may assist assessments of the cross-shore contribution to the sand budget, but without wave direction and its divergences (and other variables), an assessment of the along-shore contribution to the coastal sediment budget can not be made.

Current projections of surface ocean wave climate

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 (Wang et al., 2004; Wang and Swail, 2006a,b; Caires et al., 2006). These studies have shown that for many regions of the mid-latitude oceans, an increase in wave height is likely to occur in a future warmer climate following increased wind speeds associated with mid-latitude storms. As with the studies of observed changes, this approach disregards other important wave parameters beside wave height.

In recent years, there has been an emergence of dynamical regional wave climate projections (Perrie et al., 2004; Andrade et al., 2007; McInnes et al., 2007; Lionello et al., 2008; Leake et al., 2007; Grabemann & Weisse, 2008; Debenard and Roed, 2002, 2008, Hemer et al., 2009), where downscaled Atmosphere-Ocean Global Climate Model (AOGCM) projections are being used to force regional wave models. Forcing conditions are typically obtained for a select few projected emission scenarios (typically B2 and A2, representing low-high ranges) from a single (at most 3, Debenard and Roed, 2008) parent, coarse resolution GCM, representing minimal multi-model ensembles, with no perturbed physics ensembles. Christensen et al. (2007) suggest that the dynamical downscaling step in providing forcing for regional surge (and correspondingly wave) models is robust (i.e., does not add to the uncertainty). Therefore, the dominant sources of uncertainty in the regional models are the forcing wind conditions (circulation) from the climate model projections (Wang et al., 2009). Christensen et al. (2007) also comment however that the general low level of confidence in projected circulation changes from GCMs implies a substantial uncertainty in these surge (and ocean wave) projections.

Several of the above mentioned regional wave climate projections encompass the North Sea. Table 1 summarises each of the studies which provide wave climate projections for the North Sea, including statistical projections carried out by Caires et al. (2008). Several of these studies have downscaled the same global projections, using different regional climate models, but show contrasting results. While these studies enable some of the uncertainty of the regional climate models to be established, they demonstrate the repeated effort which results when carrying out regional projections. It is also difficult to determine the cause of the divergent result when not carried out in with a coordinated approach.

Proposed methodology for coordinated projections of the surface ocean wave climate

Coastal managers are increasingly recognising the role that shifting climate patterns play on the regional wave climate, and consequent local sediment budgets and beach response. 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 which demand projections over broad spatial domains. Furthermore, while this regional modelling approach is reasonable in relatively closed basins (e.g., the Mediterraniean, Lionello et al., 2008; the North Sea, Grabemann & Weisse, 2008; the Northern Seas, Debernard and Roed, 2008), wave projections for open domains are also required (e.g., Portugal coast, Andrade et al., 2007; Eastern Australia, McInnes et al., 2007, Hemer et al., 2009). Such domains introduce problems with specifying wave conditions on the open boundaries for which projections are unavailable. Additionally, as long as researchers continue to apply these wave models regionally, a consensus view on projected conditions for any particular region will be difficult to establish without repeated effort. Given such motivation, we advocate a shift in approach, from regional studies, towards determining large scale (global) projections of wave climate –both dynamical and statistical using surface wind forcing from a more complete suite of global climate model ensembles (multi-model and perturbed physics), under a more complete range of emission scenarios.

Given substantial uncertainty exists in the projected circulation patterns derived from available GCMs, key to establishing confidence in ocean wave projections is an ensemble approach. Such an approach is used for the IPCC climate modelling to study the range of plausible climate responses to a given forcing. The ensembles are generated from either collecting results from a range of models from different modelling centres (i.e., multi-model ensembles) or by generating multiple model versions within a particular model structure, by varying internal model parameters within realistic ranges (i.e., perturbed physics ensembles). These ensemble runs provide an indication of the likely range of values for a given scenario so that projections can be presented with statistical confidence limits (e.g., Figure 2, taken from the IPCC AR4 synthesis report, shows the surface warming for various SRES scenarios with likely ranges indicated). Such an approach requires considerable modelling effort, from more than a single research group. Thus, we propose that global wave projections are of such importance, that a model intercomparison framework, along the lines of the CMIP experiments, be implemented to obtain sufficient information on projected surface wave changes to assist assessments of the effects of climate change on coastal erosion (and other potential impacts). At present, this problem is being treated in a piecemeal localised manner. A coordinated effort will both increase value of the output, and reduce overall effort in establishing the required result. Once global wave projections are established, downscaling methods may be applied for regional studies.

The CMIP5 experimental design proposed by the global climate modelling community (Taylor et al., 2008) has two distinct foci of the model experiments: 1) near-term decadal prediction simulations (10-30 years) initialised in some way with observed ocean state and sea-ice, and 2) long-term (century time-scale) simulations initialised from the end of freely evolving atmospheric/ ocean GCM simulations of the historical period. Due to the large number of simulations specified in the CMIP framework, they have grouped the experiments for both time-scales into a ‘core’ set, and subsequent tiers. It is expected that the core experiments should be carried out by all participating climate modelling groups, and tier 1 and 2 experiments have correspondingly lower priority. Figure 3 shows the schematic summaries of the CMIP5 experiments.

Specified outputs from the CMIP5 GCM runs will also enable global projections of surface ocean wave climate, in a manner that resembles the prior regional wave model projections. Forcing requirements of the global wave models include surface winds, sea-ice extent, air/sea temperature differences and surface current fields. Previous statistical projections of ocean wave height (Wang et al., 2006b, 2009) relating significant wave height and the SLP field dictates SLP as an additional variable of interest. 2-D surface fields for the present day (AMIP period) and the future (specifically, the decade 2026-2035) will be available from the CMIP5 decadal experiments. These fields include 3-hourly surface winds and SLP (and it is anticipated that some climate modelling groups may supply the required 2-D surface fields from atmospheric models with greater spatial resolution) which could be used for ocean wave simulation time-slice experiments. The temporal resolution of sea-ice extent, air/sea temperature differences, and surface current fields are of less concern, provided seasonal, interannual, and longer term variations are represented. The long-term (century time scale) CMIP5 simulations, driven by emissions scenarios will also provide the necessary 3-hourly 2-D surface fields (albeit at coarse spatial resolution only) for the period 2081-2100. Table2 summarises the core CMIP5 GCM runs which will provide suitable output fields for global simulations of the present day (1960-2005) wave climate, and projections of the mid-century (2026-2045) and end-of-century (2081-2100) wave climates using dynamical and statistical approaches.

Summary

The paper aims to raise the issue of coordinated global wave climate projections which are of use to the wider coastal impacts of climate change community for discussion. We wish to gauge the interest in the proposed modelling program amongst the wider wave modelling community. There are a number of points which require further attention. For example, in trying to project wave climate into the future, there are an infinite number of wave model run ensembles which could be carried out. Adding the wave model component onto the climate model runs introduces another level of ensembles, which will increase the number of runs from which to establish the projected likely range of wave variables. The wave projection ensembles would consist of statistical and dynamical projections, and perturbed wave physics ensembles, and could include any number of potential variations which require discussion (Figure 4).

Many research questions remain regarding the important role waves play in the coupled ocean/atmosphere system, and their contribution to large scale climate feedbacks. The effect of waves within the climate models, via heat and moisture fluxes, mass transport (C02 fluxes), the ocean surface albedo, and extent of the Marginal Ice Zone, deserves considerably more attention in future climate research. However, of immediate priority is the proposed one-way interaction between projected climate change and surface ocean wave climate outlining expected changes in wave height, period and direction parameters. These projections are of paramount importance to understanding the effects of shifting climate patterns on our eroding coasts.

The IPCC AR4 recognised 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 GCM's. Such an approach limits the statistical confidence in the projections (limited ensembles), repeats a great deal of modelling effort, and leaves major gaps in the global coverage. In order to avoid these problems, we propose a shift to global (statistical and dynamical) projections which 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. When combined, a distribution of projections will be available which will allow an assessment of different levels of uncertainty, presenting projections within statistical confidence limits. The proposed CMIP5 design will provide suitable data on a global scale for carrying out surface ocean wave projections, focussing on mid and end of 21st century time-slices, to service the increasing demands of the coastal impacts community.

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Tables

Table 1. Summary table of regional wave climate projections which encompass the North Sea.

Study	GCM Scenario	Projected time-slice	RCM	Proj Method	Results
DNMI (Debenard & Roed, 2008)	ECHAM4 MPI GSDIO	2030-2050	HIRHAM (55km res)	WAM (55km res)	Insig. Change Hs.
DNMI (Debenard et al., 2002)	HADAM3H SRES A2 HADAM3H SRES B2 ECHAM4 SRES B2 BCCR SRES A1B	2071-2100	HIRHAM (55km res)	WAM (55km)	Insig. Change Hs.
GKSS (Grabemann & Weisse, 2008)	HADAM3H SRES A2 HADAM3H SRES B2 ECHAM4 SRES A2 ECHAM4 SRES B2	2071-2100	Swedish RCAO (~49 km res)	WAM (NE Atl ~ 50km) North Sea ~5.5km)	5-8% increase in Hs
Tyndall (Leake et al., 2007)	HADAM3H SRES A2 HADAM3H SRES B2	2071-2100	HADRM3H	PROWAM (Atlantic 1deg) (NEA, Nth Sea, ~5.5km)	Increase of 10 cm (mean) and 20 cm (max) in Hs. Decrease of 4 cm (mean) and 19 cm (max) in Hs
Deltares (Caires et al., 2008)	ECHAM5 ESSENCE SRES A1B	1950-2100	-	Statistical WAM/SWAN	Insig. Change.

Table 2. Summary of the core CMIP-5 GCM runs which will provide suitable output fields for wave climate projections. These runs will archive 3-hourly 2D surface fields of surface wind vector components, surface pressure, surface air-temperature, and water skin temperature. All runs archive monthly sea ice concentration and surface ocean currents.
* Some climate modelling centres may run the near-term decadal predictions at higher spatial resolution.

Period	Core GCM runs
Present Climate (1960-2005)	Near-term decadal predictions*: 10 & 30 yr hindcast and prediction ensembles, initialised from 1960 through to 2005. Future long-term (century time-scale) simulations for 20C, and AMIP periods driven by RCP concentrations or emissions.
Mid-Century (2026-2045)	Near-term decadal predictions*: 30 yr hindcast and prediction ensembles, initialised in 2005 (2026-2035) Future long-term (century time-scale) simulations driven by RCP concentrations or emissions (2026-2045)
End-of-Century (2081-2100)	Future long-term simulations driven by RCP concentrations or emissions

Figures:

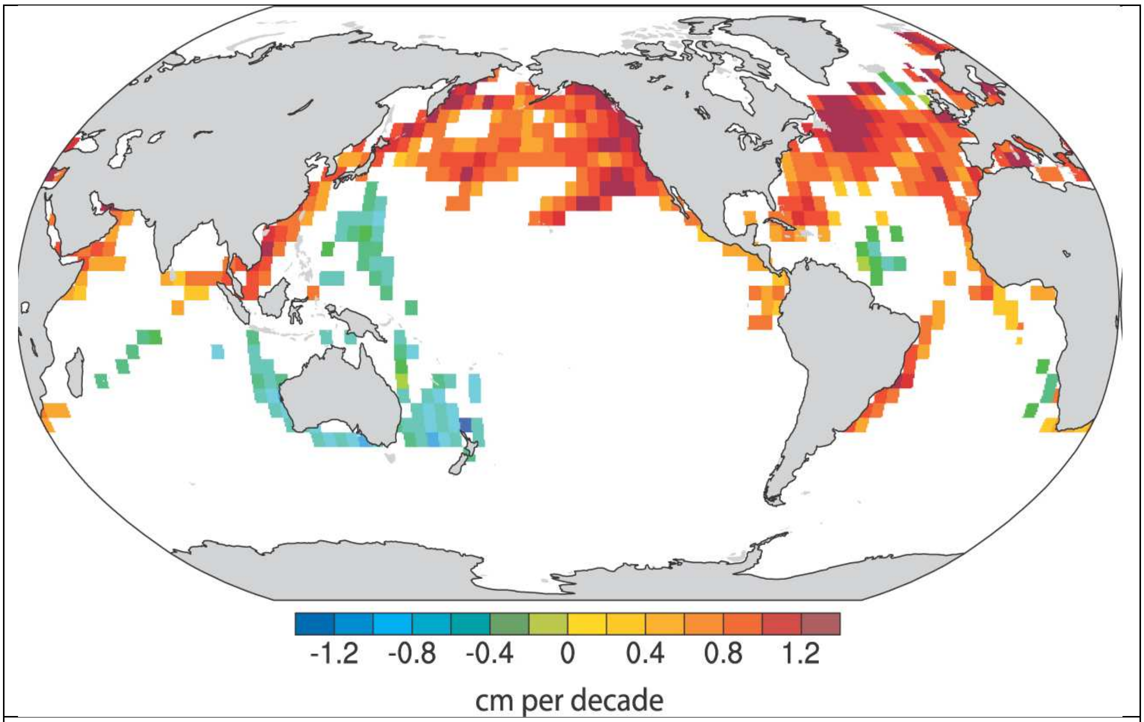

Figure 1. Figure 3.25 of IPCC AR4 WG-1 report: Estimates of linear trends in significant wave height (cm per decade) for regions along major ship routes of the global ocean for 1950 to 2002. Trends are shown only for locations where they are significant at the 5% level. Adapted from Gulev and Grigorieva (2004).

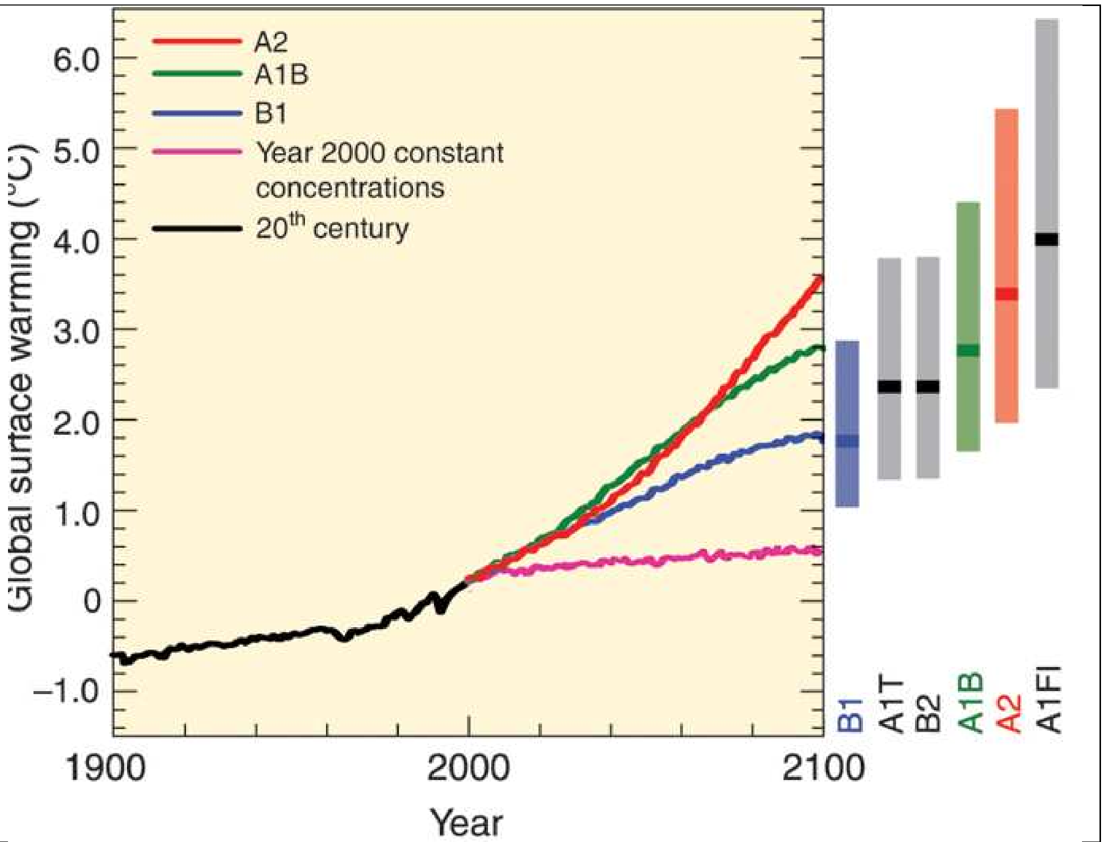

Figure 2. Adapted from Figure 3.2 of the IPCC AR4 Synthesis Report. Solid lines are multi-model global averages of surface warming (relative to 1980-1999) for the SRES scenarios A2, A1B and B1,shown as continuations of the 20th century simulations. The orange line is for the experiment where concentrations were held constant at year 2000 values. The bars to the right of the figure indicate the best estimate (solid line within each bar) and the likely range assessed for the six SRES marker scenarios at 2090-2099 relative to 1980-1999. The assessment of the best estimate and likely ranges in the bars includes the Atmosphere-Ocean General Circulation Models (AOGCMs), as well as results from a hierarchy of independent models and observational constraints.

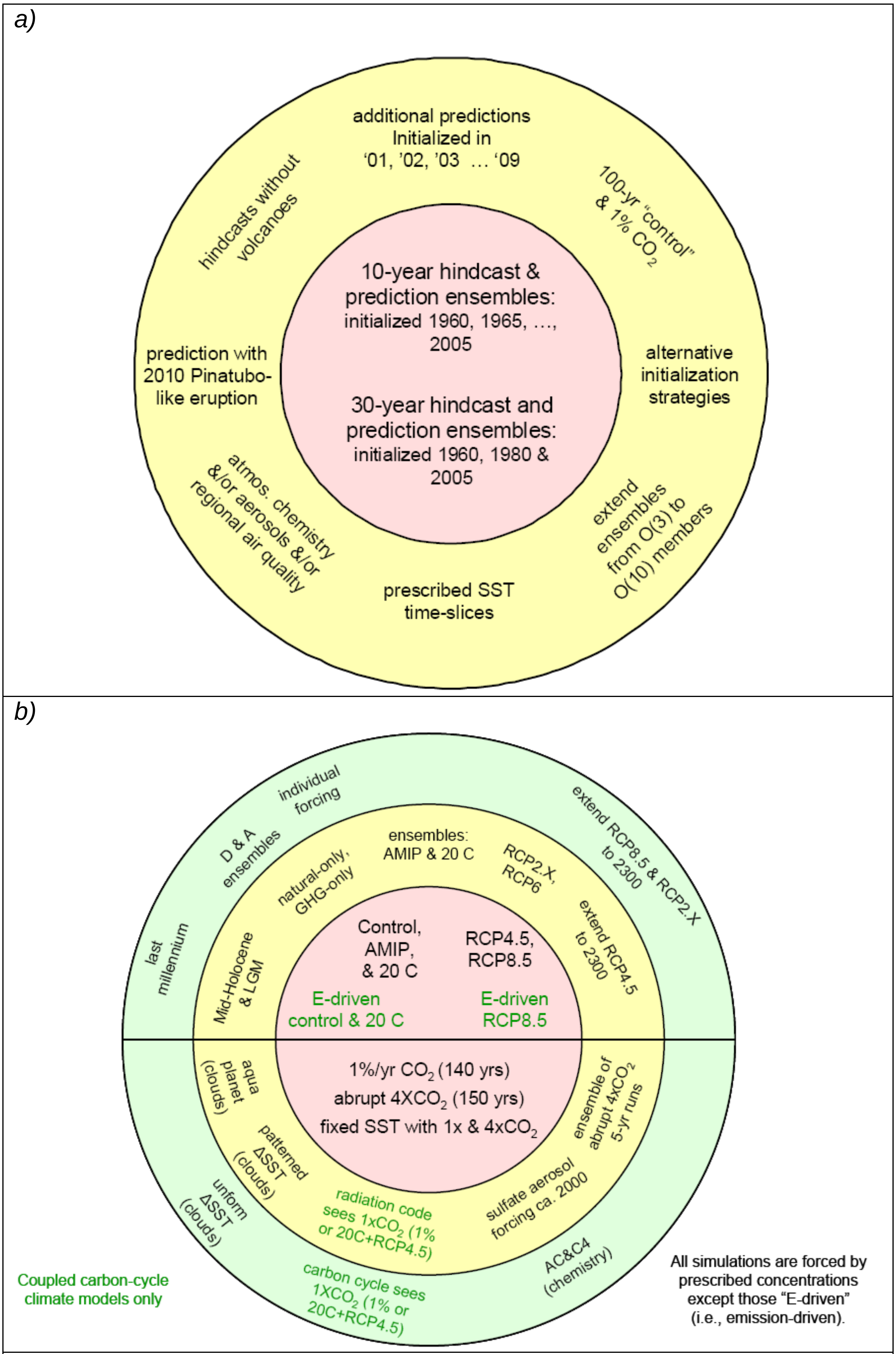

Figure 3. Schematic summary of CMIP5 a) decadal, and b) long-term, experiments. The inner circle represents 'core' experiments, the subsequent circles represent tier 1 and 2 experiments. Taken from Taylor (2008).

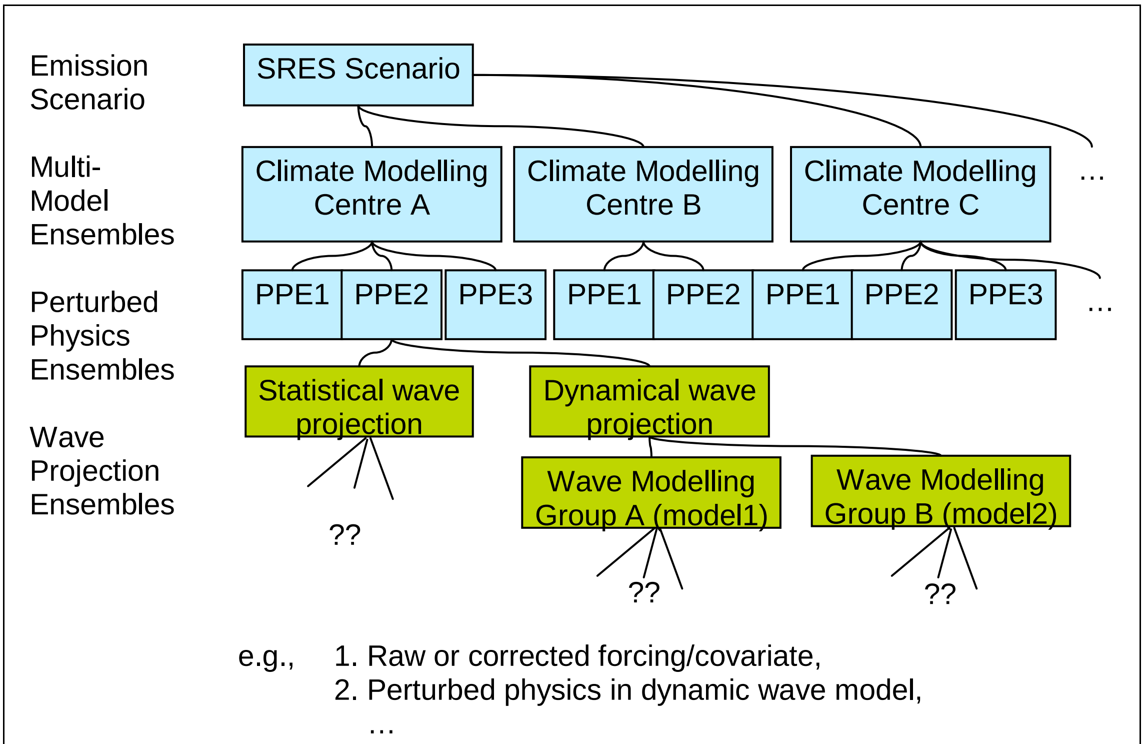

Figure 4. A schematic summary indicating the additional level of run ensembles introduced into the wave projections. Blue boxes represent climate model runs which will be carried out as part of the CMIP5 framework. Green boxes represent wave model projections which would be carried out under the proposed program.