RESPONSES TO COASTAL CLIMATE CHANGE: INNOVATIVE STRATEGIES FOR HIGH END SCENARIOS -ADAPTATION AND MITIGATION-

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DISCLAIMER

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A PROJECT FINAL REPORT

NOTE: Completed and submitted to EC through SESAM application.

B Final Report

Final Publishable summary report

Executive Summary

Coastal zones are subject to increasing pressures of use and impact of climatic factors. Sea level rise in particular, even under measures that allow to mitigate global warming, would keep on increasing because of the thermic inertia for several centuries.

This situation will aggravate under future high end scenarios that suppose a higher concentration of population and uses at the coastal zone plus anincrease in global sea level and a change of storm patterns that could reach values higher than the current best estimates of IPCC.

The RISES-AM- overarching challenge is to make explicit the significant adaptation deficit affecting much of the world's coasts and low climate change adaptation and economic development may become intertwined issues.

For this purpose we have assessed the impacts of future sea-level rise and the effectiveness of adaptation options and strategies. It has also considered the barriers challenging the implementation of adaptation at local, regional and global scales, across a range of representative concentration pathways (RCPs) and shared socio-economic pathways (SSPs), exploring also high-end emission scenarios not included in ICCP reports. High end conditions may refer to drivers of coastal evolution/impacts (such as e.g. sea-level rise) or to the resulting vulnerabilities (e.g. assets or population affected). In RISES AM we have considered such high end conditions from short (months) to long (decades) time scales. The analysis is centred around a plausible scenario (RCP 4.5) and goes up to 2100 but adaptation in practice should consider also more unfavourable projections and even longer time horizons under such high-end conditions.

Impacts correspond both to present practice (business as usual) and to the "additional" adaptation that will be required with the expected acceleration of climate change during this century. For this we have structured sequentially the possible interventions into adaptation pathways to prevent present decisions conflicting with longer term limits or requirements. The emphasis has been on vulnerable coastal systems (e.g. deltas or low-lying coastal areas with large population) looking for sustainable interventions.

RISES-AM- has also dealt with novel types of sustainable interventions derived from local scale analysis to enrich regional and global assessments, subject to global constraints such as the scarcity of energy in our future worlds. Because of that we are considering simultaneously the physical/ecological and social/economic dimensions so that RISES-AM- is providing an objective assessment of impacts under present adaptation. We have also started to consider additional adaptation, motivated by the adaptation deficit that has been identified already in the project. This will allow an improvement in the attribution mechanisms for climatic impacts, facilitating decisions and policy at all scales. Because of that the project has contributed to start answering questions such as: How much climate change can we cope with? or How effective are our interventions for climate proofing a given coastal typology?. The project has also served to pose a number of new questions, such as: What does high end really mean (in the sense of weather it refers to pressures, impacts or responses)?.

From the standpoint of solutions, it should be considered that coastal areas have always attracted population because of their environmental and economic assets in spite of their vulnerability during storms. The future increase of pressures on coastal areas due to climate and socio-economic changes will exacerbate this vulnerability especially under high-end climate change. Such extreme changes are expected to threaten the ability of coastal areas to provide sustainable services especially protection from storms and flooding.

The main synergies to support and help finding policy opportunities should be linked to an integrated assessment of a) available resources (e.g. volume of sand or freshwater), b) effectiveness of the proposed interventions (e.g. limited duration nourishments in a future with scarce energy) and c) resulting utilities (e.g. high value for urban coasts and relatively lower values for low density populated environments unless natural functions and cultural heritage are included).

The reduction of climate impacts due to relative sea level rise (including storm surges) and increasing pressure of uses in coastal areas may result in the need to rank coastal sectors and establish priorities. A universal "hold the line" coastal management or protection policy in the face of increasing climate pressures can be unsustainable and in that ranking there will appear sectors with a) managed realignment, b) no active interventions and c) working with Nature solutions.

Finally, for coastal areas where there is no "room" for coastal dynamics (or for river dynamics) it will be necessary to upgrade coastal defence systems in the most adaptive and flexible manner to cope with uncertain future physical and socio-economic conditions. In low populated areas more resilience-oriented measures can provide an efficient alternative. In all cases a smart planning of land uses and coastal interventions will lead to lowered risk levels for coastal population and activities and a more sustainable coastal environment under future climates.

Summary description of project context and objectives

In RISES-AM- we have evaluated the impact of global projections based on AR5 physical (RCP) and socio-economic (SSP) scenarios. Looking for high end conditions we have focused on RCP 4.5 and RCP 8.5 and SSP-3 and SSP-5. We have selected the main physical and socio-economic variables (mean sea level, storm surges and waves regarding physics and population density and GDP regarding socio-economics). The various case studies have assessed the impact of climate change for the present level of adaptation. This has allowed to raise the social and technical awareness about climate change and the implications of high end conditions.

Such a comparison across scales covers local e.g. the Ebro or the Danube delta, regional e.g. the Croatia coast or the Catalan coast and global and it has required a careful definition of a) projection horizons, b) calculation domains and c) terminology.

Our working hypothesis is that we can enhance coastal zone sustainability by adopting a flexible adaptive pathway that identifies tipping points and that makes use of "green" intervention options, more sustainable than the traditional coastal engineering solutions. Following this the project has five main objectives:

1. Developing a set of adaptation pathways for vulnerable coastal systems at regional and global scales, introducing retreat and accommodate strategies and including local scale derived innovative solutions.

2. Assessing the synergies between these options under a range of scenarios and based on the physical and socio-economic impacts across scales.

3. Introducing the risk-vulnerability-hazard methodology into climatic analyses to achieve a higher level of objectivity in the assessments and to account for uncertainty in drivers and responses.

4. Assessing the compatibility of local scale assessments and interventions with regional and global scale analyses, focusing on feedbacks across sectors and scales.

5. Increasing our knowledge about coastal system functioning under climatic variability, addressing explicitly impact projection, "green" interventions and adaptation tipping points.

RISES-AM- has considered the uncertainty regarding sea-level rise that mainly comes from the current limitations in ice sheet models. Because of that, regarding drivers we have developed new high end scenarios with improved ice sheet contribution effects and concluded that there is a 95% probability that global mean sea-level will stay below 1.80m by the end of the 21 century, even under the highest greenhouse concentration scenario RCP 8.5.

We have also addressed downscaled wave and storm surge projections for the North Sea and the Mediterranean, since the resulting coastal impacts will be a function of the combined effects of enhanced mean sea-level plus the action of extreme storm events. Figure 1 shows a projection of storm surges and wave heights along the Mediterranean coast based on the work of the CMCC partner.

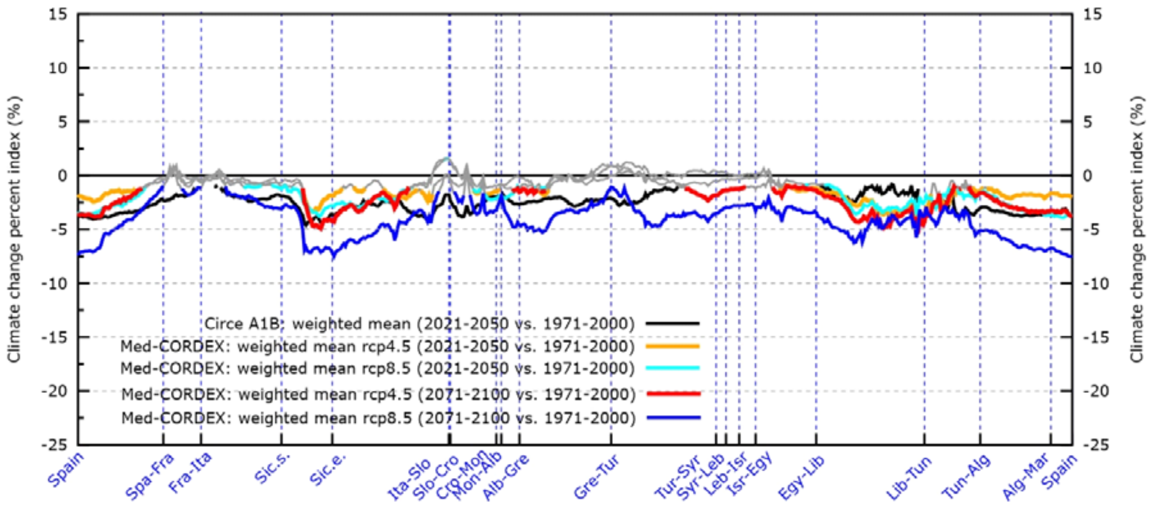


Figure 1. Percentage change of the storm surge index (average 10 highest surges along the Medirerranean coast) considering the A1B ensemble mean and the MedCORDEX simulations. The latter include two time slices (2021-2050 and 2071-2100) and two emission levels (RCP4.5 and RCP8.5).

Climate change coastal impacts are expected to grow in the next decades due to the increases in meteo-oceanographic factors but mainly because the coastal population will keep on growing at a higher rate that for the rest of the planet. At present, more than 10% of the world population lives near the coast but with rapid urbanization we expect that population to exceed 1 billion in 2050 with consequences on land uses and vulnerable infrastructures and economic activities. The only way to reach acceptable risk levels would be an adaptation agenda for coastal zones incorporating the socio-economic challenges plus climate change.

The obtained project advances can be summarized in four categories, according to what was described in the Description of Work. The first category (Adaptive Management) has supposed the preparation of a range of coastal interventions and adaptation options, particularly focussing on retreat and accommodation which was not considered in global scale models before. This has served to develop adaptation pathways, starting local scale cases and to assess the synergies and trade-offs between the various adaptation options and types of coastal interventions for these cases.

The second block of objectives (decisions and uncertainty) has been also developed looking at extreme values of climatic variables such as for instance mean sea level in probabilistic terms, advancing clearly with respect to the purely deterministic approaches available until now. We have also considered the uncertainties in the responses to a given mean sea level or to a given wave storm so that the capacity of natural systems to withstand those physical pressures could be assessed in a quantitative manner. This has also supported introducing all our analysis within a risk-vulnerability-hazard methodology so that a higher level of objectivity in the assessments could be obtained and to enhance the social and political confidence on the performed evaluations.

We have advanced in preparing existing models for carrying out dynamic analysis of pressures, impacts and responses. Within the CAS structure developed in RISES-AM- we have prepared our models to directly simulate, to the best possible level available, the impacts associated to the main climatic pressures (essentially, mean sea level and storminess). That has allowed to start investigating the compatibility of local scale interventions and assessments for regional or even global scales. That has also allowed to start preparing the sequential set of interventions that will be required to improve coastal sustainability under future climates and to determine the level and timing of adaptation measures.

The final block of specific objectives (coastal sustainability) has been based on the knowledge about the functioning of the coastal system under varying climates, considering a battery of models and interventions that emphasize natural solutions linked to the working on natural systems. We have also involved interested researchers, administrations and general stakeholders in the participating countries, presenting also our results in front of international audiences. This has served to establish links with other projects and to enhance the transfer of project approach and results.

The final achievements of project objectives can be summarized by the following five blocks:

a) Comparative structure for consistency across scales

   To ensure comparability of project results at different scales, a coastal typology has been developed by classifying the coast into segments that are quasi-homogeneous in terms of coastal hydromorphology, socio-economic development and, thus, also in the response to climatic drivers. We have considered for the first time a multi scale assessment in connection with innovative adaptation strategies and making use of previous developments in former European projects with the aim of reducing uncertainty. Starting from global assessments we have identified vulnerability hotspots and then performed local scale analyses of novel versus conventional interventions, feeding back into regional and global analyses. One of the key points considered in this selection of typologies is the vulnerability level, prioritizing coastal systems already experiencing a “surrogate” climate change effect (e.g. deltaic units where subsidence may lead to rates of relative sea level rise –RSLR– that are an order of magnitude higher than current rates of climate-induced global-mean SLR).

b) Adaptation and tipping points

The robustness of coastal adaptation strategies (under current or future climate and socio-economic scenarios) has been assessed using the Adaptation Tipping Point – ATP– approach. ATP's are defined as points where the modification due to climate change (e.g. relative sea level rise) is such that a strategy will no longer be able to meet its essential objectives. The ATP analysis has defined critical thresholds in the physical, policy and management components of the coastal system. Under different high-end scenarios and adaptation strategies these thresholds will be sooner or later reached. In our assessment cases we have investigated the ATP's for our proposed alternatives (e.g. "green" adaptation options) using a dynamic modelling approach for quantification. The ATP's have been further used to structure pathways of alternative measures, varying with time. This will contribute to advance the concepts of adaptation pathways, path dependency and adaptation tipping points for coastal adaptation. It will also provide new light into the risk assessment under climatic "threats". This is a significant deviation from many existing studies, which only consider the 'endgame' of adaptation and not the 'pathway' for getting there. These pathways may be of particular relevance under high-end scenarios, where uncertainty on future climate impacts is expected to be large and, thus, the flexibility of adaptation may become critical.

c) Innovative (Nature-based) interventions

To further delineate our adaptive approach, we have incorporated into the analyses novel coastal interventions, specially suitable for high-end scenarios, such as the raising land elevation in natural or farming areas or "green" adaptation to flooding in urban areas we have considered the interplay between sea-level rise, river floods and land use / habitat structure and changes, addressing for the first time innovative options in response to combined marine/riverine flooding under future conditions. We have also included the possibility of applying controlled river floods to deliver sediment to low-lying coastal areas, as it is being incipiently applied in some deltaic areas of United States. We have incorporated the support of managers and stakeholders, whose opinion has been taken into account from the beginning for the inventory and ranking of options from the social/management standpoint.

d) Multi-scale socio-economic effects

We have provided improved projections of the distribution of population in coastal regions and by incorporating those estimates into assessment models, we have better informed policy makers about potential risks and improve adaptation planning in coastal regions at regional to global scales. We have addressed the differential growth of population in coastal regions and developed coastal population growth projections, under different Shared Socioeconomic Pathways (SSPs). We have then integrated these projections into impact assessment models (such as DIVA) to allow for an improved quantification of impact and risk for the coastal population. These estimates, primarily at global and regional scales, aim to assist adaptation planning and better inform policy and decision makers about population and assets at risk in coastal regions.

In our set of assessment cases, we have evaluated adaptation pathways and learning processes in economies exposed to environmental hazards and climate change risks. This is a significant deviation from the current static-deterministic approaches to account for the wider economic impacts of disaster events in CBA based on constant economic growth and discount rates. Starting from participatory multi-criteria approaches we have proposed a

MCA risk assessment that will serve as an integrative framework across different key hazards in coastal zones in Europe, providing directly applicable outputs and a road map for prevention strategies under uncertainty. In addition we have included a CBA analysis to improve the agreement in direct impacts across scales. This illustrates the novelty of our approach for climate impact evaluation and the subsequent management or policies.

e) Multi-scale physical-ecological effects

We have dealt with coastal impacts and vulnerability due to high-end scenarios by combining the long-term and extreme event scales which is a more comprehensive approach that the standard type of climatic analysis. Since there is considerable uncertainty in the projections of future changes (e.g. extreme sea levels), sustainable adaptation strategies need to cope with these uncertainties at all scales. Adaptation strategies that cost-efficiently work under a broad range of possible scenarios (robust strategies) or which can be easily adopted to changing conditions in the course of time (flexible strategies) have been favoured. Moreover, they should go together with a comprehensive social dialogue communicating opportunities and risks involved in developing such strategies.

For the dynamic modelling we have combined local and global “tools. Local approaches provide methods that are detailed in scale/resolution and process-based, but the problem remains that the outcomes cannot be extrapolated in a straightforward manner to larger scales in space and time. Regional and global approaches lead to outcomes that are valid for a larger scale, but the problem is that they are “aggregated” and semi-empirical and, thus, too simple to reproduce the complexity of the interactions and feed-backs between climate drivers and coastal responses. To sort out this problem we have worked at different spatial scales and have assessed impacts at regional scale for coastal areas and watersheds combining local and global models to better include the feed-backs between physical, ecological and socio-economic processes which are relevant from the point of view of climate change. We have explored a wide range of adaptation paths to be incorporated into the impact models (for our coastal typology) under a range of scenarios of socio-economic change, determining the performance of adaptation paths for a variety of geographic settings. This provides guidance for broad-scale adaptation planning in response to policy makers’ needs.

Description of main S & T results / foregrounds

Integrated assessment

The RISES-AM- foreground starts with a nested assessment approach and the corresponding methodology to determine vulnerability and risk from local to regional and even global scales. The results span a comparative analysis of vulnerability as a function of coastal typology, with analysis at different levels of resolution that include traditional versus novel or “green” types of interventions. This has resulted in informed analyses and policy briefs where adaptation pathways have been developed and classified, according to their contribution to climate impact and mitigation.

The main results from the project, further developed in the following paragraphs can therefore be linked to five main axes:

1. Developing innovative and effective mitigation and adaptation strategies across scales.

2. Working with uncertainties in drivers and responses associated to long term projections of climate change impacts.
3. Preparing a homogenized protocol for the various coastal typologies so as to improve the resulting consistency.
4. Incorporating new processes, higher resolution levels and parameterization factors often not considered.
5. Producing a set of policy briefs at regional European and global scales dealing with coastal adaptation under extreme climate scenarios.

The obtained results are based on a set of models that consider global projections especially prepared for coastal systems to allow evaluating climate impacts for present adaptation levels. Next the adaptation deficit has been made explicit as a function of coastal archetype. The local scale analysis has addressed processes not often considered together, such as flooding, erosion and salinization. Figure 2 shows the distribution of salinity levels in one of our case studies (the Ebro Delta in the Spanish Mediterranean coast) where the effect of salinity on the main economic activity (rice fields) has been assessed and this has led to a preliminary determination of the maximum rate of sea level rise, considering that the delta is also subsiding so that the relative land-sea levels are rising at a rate higher than that normally associated to present conditions and comparable to that expected with accelerated climate change.

The regional assessment can be illustrated by the categorization of coastal typologies along the Catalan coast (Spanish Mediterranean) where we have projected future mean sea level surges and wave conditions and combined that with the space availability so as to determine adaptation levels and possible interventions (Figure 3).

Finally at global scale we have also carried out a similar assessment, considering in a combined manner flooding and erosion and introducing for the first time retreat as an adaptation option for an intermediate level of retreat, suitable for rural and intermediate areas (Figure 4). The results of our assessment show an important reduction in climate change impact.

The socio-economic modelling included in our project has allowed to start assessing the implications of the physical impact on socio-economics and the feedbacks of socio-economics on physical impacts. This can be illustrated by the type of interventions prepared which are a combination of a) grey interventions (based on rigid structures), b) green interventions (based on natural principles, aligned with natural processes) and c) soft interventions (based on sand nourishment and territory planning).

The direct economic effects have been estimated based on land availability while a number of analyses have been carried out to start calculating the indirect effects (e.g. via sea transport responsible of more than 80% of world trade).

The benefits of adaptation (by reducing e.g. flooding costs by more than one order of magnitude worldwide) and the need for flexible adaptation pathways to enhance coastal sustainability have been addressed using a process-based analysis. We have here shown that sustainability can be increased by providing additional sedimentary volumes and this can in turn be achieved by enhanced water fluxes. Our analysis has considered cost in monetary terms but also in energy terms and the associated CO_2 footprint.

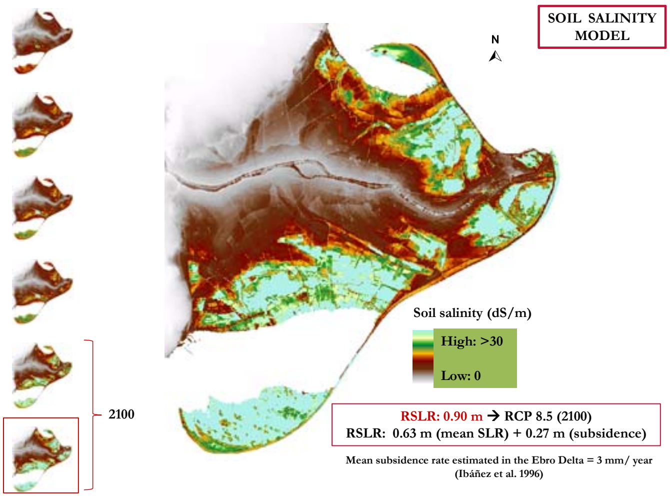


Figure 2. Salinity field in the local case Ebro delta.

In all cases we have started to show the advantages of flexibility in times of uncertainty and how the use of a pathway generator can contribute to a better structure for a) data, b) models, c) interventions. The role of natural habitats and ecosystem functioning has also been considered, to promote this energy–friendly type of interventions (e.g. based on vegetation or a reed beds) so that the natural accretion mechanisms well known for wetlands can be exported to other coastal systems.

We have considered within the project the general suitability of novel interventions (e.g. raising land levels as for instance in the Netherlands or the Maldives, two our study cases) versus vegetation base approaches (e.g. the mechanism for wetlands already mentioned exported to other coastal zones). This has allowed presenting new questions that were not so clearly identified before. For instance the concept of high end and weather that refers to pressures acting on a coastal system or to the combination of pressures state and responses. The same regarding the need to combine average trends and extreme events so as to find the worst possible combination and assess from that coastal vulnerability.

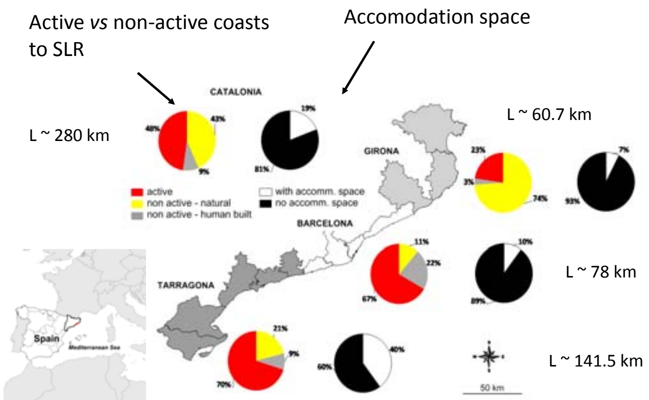


Figure 3. Feasibility of accommodation for a regional case such as the Catalan coast.

We have finally considered the linkages across scales, illustrated by the suitability of indefinite some nourishment for a variety of coastal systems, the implications of cross cutting cases such as coastal cities in deltaic areas (therefore subject to the combined flooding from river and sea) and the global constraints on coastal responses (e.g. the limits of energy foreseen in a near bay future to condition the type and duration of coastal interventions).

The preparation and development of the project activities has also led to a number of peer reviewed papers and communications in a) scientific, b) technical and c) political-oriented conferences

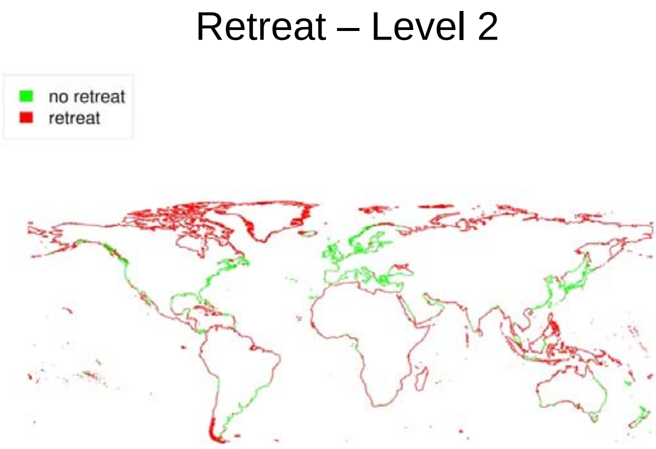


Figure 4. Intermediate retreat versus no retreat for world-wide coasts.

In the project we have also addressed the technological, economic, financial, social and cultural barriers to coastal adaptation under high sea-level rise. This has supposed studies at different scales, associated to the different field cases in the project: Catalan coast, Croatian coast, Danube delta, Hamburg and Elbe estuary, Ho Chi Minh City, Liverpool Bay, Aveiro coast in Portugal, the Maldives and The Netherlands. The main conclusions are that the barriers mainly belong to the socio-economic dimension rather than the technical one which for a limited period of time should be able to provide viable solutions. Although adaptation can therefore be technologically possible the effect of climate change and particularly its acceleration will lead to coastal zones looking very different from present ones, particularly for densely populated regions where coastal cities provide a good example where classic protection may result economically possible.

The difficulty to overcome barriers for coastal adaptation, due among other reasons to the difficulty of generating high upfront investments with long term returns in a situation of economic crisis and with large future uncertainties means that there will be bifurcations in our common coastal future. We anticipate that rich and urban coastal areas will evolve to a high level of engineering and protection, while poorer rural areas will have a hard struggle to maintain livelihoods and may be forced to eventually retreat. The resulting social conflicts that, depending on socio-economic scenario projections may affect large areas, will require a balanced analysis of coasts locally and worldwide, addressing the financial, economic and social conflicts and putting the emphasis on the equity dimension of coastal adaptation.

The first year of RISES-AM-

In condensed terms we have produced during this first year an inventory of coastal typologies, models and interventions, all within a Comparative Assessment structure (WP1). We have also prepared a set of consistent high-end projections at global scale to assess impacts for the most "unfavourable" combinations of physical and socio-economic conditions (WP2). Based on this we have run hydro-morphodynamic models to assess impacts with present adaptation (WP3) and to start deriving the corresponding implications for land availability and marine transport. From here we have started to prepare adaptation pathways and an assessment of the direct/indirect effects on the economy, with emphasis on the main sectors present / affected by the coastal zone (WP5). The so obtained advances have been discussed with stakeholders and presented in scientific and general dissemination events (WP6) in parallel to the production of the initial set of project papers.

In more detailed terms we have developed a logical structure that facilitates the comparison of impacts, interventions and adaptation policies across scales. This has proved to be particularly useful for the rest of RISES-AM- tasks since we have case studies at local, regional and global scales, including crosscutting cases that represent a natural relationship throughout scales (for instance coastal cities).

The methodology to establish the cross scale assessment structure (CAS) to be employed throughout the project and particularly for crosscutting cases is based on the DPSIR concept and a multi-layer model. The DPSIR concept starts from drivers (D), then goes on to calculate pressures (P) and from that we can assess the a) state (S) and b) impact (I) of a given coastal tract. From that the response (R) can be established and in turn modelled with the available simulation tools and calculating methods.

The definition of a given coastal zone as a function of coastal typology has also been part of the project development during this first period, looking for geometrical definitions of the coastal zone but also considering the functionality. This has led to the identification of a domain of interaction and a domain of influence. The domain of interaction can be represented by the sandy belt that with or without structures forms the border between land and sea. The domain of influence can be illustrated by the river catchment basins that contribute to sustain the coast with water sediment and nutrient fluxes (for instance as studied for Ebro Delta case by IRTA and UPC partners).

The obtained result points out the need to have a flexible sandy belt as one of the most efficient ways to dissipate ocean incoming energy (essentially waves and surges) and at longer time scales (climatic scales) allow a smart planning of the coastal territory so as to achieve sustainability with limited costs in monetary and energetic terms. It has been shown (in the paper being now finalized) how the natural evolution of a given coastal system leads to a sandy beach, the natural defence mechanism against storms and sea level rise. However the existence of barriers normally designed for short term needs implies making the coast artificial and therefore requiring permanent maintenance. The avoided loss of territory has the price of losing the sandy belt.

The elaboration of coastal typologies has been based on the two most clearly perceived impacts that can be quantified by scientific means and in objective terms. They refer to erosion and flooding, where we have identified the importance of erosion for local to regional scales and the importance of flooding for global scales. The variety of indicators identified pertains to the type of coastal sectors considered. Some indicators are suitable for all case studies while some others can only be applied in a meaningful manner to a few types of case study. The same happens with the evaluation criteria we have prepared and the adaptation options we have ranked initially. The effectiveness of adaptation measures has been clustered into three groups, according to the three dimensions of sustainability: socio-cultural (affecting social and cultural values of e.g. present or relict coastal cities), b) ecologic (affecting the natural function of the coastal system) and c) economic (linked to the monetary values of all identified resources and functions). For the socio-cultural dimension the indicators are related to risk, calculated as the product of a hazard times the vulnerability and times the exposure. For the ecological domain the effectiveness indicators are based on water quantity and quality. In a similar approach the ecosystem characterization is based on quantity (e.g. production) and quality (e.g. bio-diversity). For the economic dimension the indicators are related to the costs and benefits at various scales, since considering, as it is commonly done, one single scale or sector may provide misleading results.

The questionnaire distributed to all study sites has served to inventory data and models, and to identify the main gaps for projecting climatic impacts. Such questionnaire prepared as part of WP1 and WP3/4 has served to link adaptation in local case studies with global models. As an illustration the Glofris model for flooding (IVM and Deltares model) does not take into account adaptation but DIVA (Southampton, GCF, CAU and US) does. To facilitate the cross scale comparison the different methods of adaptation against the typologies and segmentation has been prepared and implemented in DIVA. This has allowed DIVA to be used for determining gaps between local adaptation and regional to global adaptation.

The evolution of obtained results has been presented in an interactive manner within the project team but also with stakeholders and users from the various participating countries. This has included the initial coordination workshop which allowed to establish the skeleton for developing the CAS and where the presentation and discussions across the project and with external users prepared the foundation for all subsequent work.

The CAS has been next applied under different climate and socio-economic scenarios to determine the state of the costal system under each of the scenarios and from here the most appropriate response measures have been initially assessed.

Regarding the projection of future conditions we have collected the set of scenarios to be considered in the project, focusing on the consistency between physical and socio-economic projections (for instance avoiding the more “rosy” futures in socio-economic terms since they should not appear to be very consistent in physical terms coupled to high end conditions). The available set of scenarios led to a selection of the main socio-economic variables and physical variables that were finalized in month 10 and were discussed among the partners in the yearly meeting of month 12 at the University of Sussex.

We have also discussed in depth the sequence of physical and economic conditions, since there is an expected acceleration of changes (e.g. sea level rise) near the end of the century. We have also discussed and presented one paper (and another one in preparation) showing how the timing should be considered so that when climate change will be detectable from regional observations there is already a plan (adaptation pathway) prepared. The aim was to anticipate when climate change signals will be sufficiently large to overcome the “noise” of inter annual variability. The timing has been also discussed with research partners from the IMPRESSIONS project, where we have established a joint scientific committee for the three projects to coordinate these issues.

The socio-economic projections at global scale have considered demographic and economic distributions under the various SSP scenarios. This information, already being used in the initial impact assessments under climate change has shown the importance of considering the socio-economic variables to calculate vulnerability and the resulting risk levels. Also it has shown the uncertainty associated to the variety of projections and assessments since in general or global terms, there is an upper trend for coastal population that will increase in density at a higher rate than the rest of the planet. However looking at the Mediterranean basin the projection is not so clear since there are recent publications and discussions (among them the official opening of the Italian Presidency of the European Union where the project was represented) where it was considered a decrease in coastal tourism density in all Mediterranean areas with except of Balkan countries.

The physical projections at global scale have considered sea level rise, storminess and associated surges and wave fields. Although without a joint statistical analysis our approach has considered how to best combine an increase in mean sea level due to water mass and steric components with an increase in mean sea level due to atmospheric pressure and wave storminess. The combination of these four factors may “double” the actual mean sea level for a given coastal tract under storm conditions with corresponding implications for impact assessment.

The performed analysis has combined physical models (nested sequences of models so as to approach wave conditions close to the coast even if starting from global deep water projections) and statistical models (based on multiple regression models for predictors encompassing additional variables such as temperature, pressure gradients or nearby observed values). We have carried out a re-analysis of the existing simulations in the participating centres and also provided by the European Centre to provide a range of variables wider than what is usually available. We have also carried out a number of dedicated high resolution simulations for the regional cases, in this case illustrated by the specific simulations carried out for the Mediterranean and the Black Sea.

We have also looked at historical trends and compared projected rates with those derived from historical evolution. We have analysed in depth the intensification of coastal hazards resulting from a higher intensity of wave storms or a higher mean sea level. To this we have added the expected change in wave direction that will mean a coast out of wave equilibrium which for pristine conditions would suppose no big impact but that for the heavily urbanized coastal fringes typical of some of our case studies (in Asia but also in the US and in the Mediterranean) will suppose a costly impact and therefore a high risk level.

To address the long term scale regional sea level changes we have considered temperature increases from 2° to 4° and are considering the option of even higher temperatures. We have used for that regionalized projections the fields from CEMIP-5/GCM and the main RCPs considered in our analysis.

The importance of using a probabilistic assessment for mean sea level rise highliths the relevance of selecting a suitable shape for the probability distributions. The proposed upper limit corresponds to a 5% probability mass from the full distribution. However as also indicated in WP3, the upper limit should not be neglected since the management of future coastal impacts may well demand such extreme values to provide a risk level consistent with that experienced by coastal populations in other daily activities (e.g. transportation, building, etc). The question of how to use the sequence of time horizons has also been considered by means of a sensitivity analysis for some of the selected case studies.

The selection of RCP and SSP scenarios and particularly their combination should be carefully considered so as to avoid inconsistencies (e.g. mild SSP scenarios with high end RCP scenarios) and to include the explicit assumptions about mitigation policy that are being adopted by the international community. The use of SSP linked to different levels of radiative forcing than those for RCPs may introduce inconsistency in the impact projection. We have tried to bound those inconsistencies so that the main uncertainties come from the RCP pressures and SSP impacts. For instance the uncertainties in global sea level projections due to the ice sheet contributions that we have addressed by using alternative high estimations from studies and supplemented by a sensitivity to impact analysis. In the same manner the uncertainties for storminess have been investigated at regional scales considering the depletion of Arctic summer ice and the effect that has on atmospheric circulation patterns and therefore storm tracts outside the Arctic.

Regarding storminess we have based the analysis on projected atmospheric circulation patterns and from that deriving extreme storm surges and wave heights. That exercise carried out for the North Atlantic, the Mediterranean and the Black Sea has allowed combining in a physically consistent manner the main pressures acting on coastal systems and forcing erosion and inundation processes. We have run a full Atlantic and a full Mediterranean wave model and a nested surge model worldwide. This has allowed an assessment on past and future events so as to end up with the most reliable projections that can be achieved with present modelling tools. We have also considered the possible changes in frequency of occurrence by looking at the changes in patterns from GCM runs under CMIP-5 or by using the MEDCORDEX RCM simulations. For the Black Sea we have considered also the master plan for the protection against erosion of the Romanian Black Sea littoral so that we can incorporate all local information available.

In all cases we have discussed the suitability of future scenarios for coastal impact projections, coastal interventions and the design of adaptation pathways. This has shown that IPCC scenarios are often inappropriate or incomplete for the management of high risk coastal areas. This is because they exclude the potential impact of extreme sea level rises or extreme sea level rises combined with wave/surge storms. This information, missing in present analyses, is considered to be a key element for coastal policy such as for instance the discussion by G7 countries to establish climate insurance policies and allocation of adaptation funding by the “green” climate funds. Such an approach has been developed in a paper published by the project researchers in Nature Climate Change, where the value of high end sea level rise scenarios is put in context for coastal risk management.

The combination of global scale models (e.g. for surges) with regional to local scale models (e.g. for waves) has allowed a critical cross comparison in terms of consistency and robustness. For instance the regional storm surge projection for the North-East Atlantic and North Sea was prepared by dynamical down scaling of the regional atmospheric projections from RCP 8.5. The model runs, conceived following the CAS structure from WP1 considered the European Continental shelf with 12.8Km resolution and then zooming into our coastal cases with a grid size one order of magnitude smaller (1.6Km resolution). The same approach has been used in the Mediterranean for the wave fields in front of the Catalan coast. The changes in surges or waves have been calculated considering the annual percentiles (e.g. defining high end as the 95 to 99,9 percentile and comparing that with present day conditions). In all cases the new RCP scenarios are compared and assessed in terms of observations and previous SRES (AR4) projections.

The work has continued with an integration of the coastal archetypes and the high end scenarios to assess impacts for the expected high end climatic physical and socio-economic conditions across a variety of scales. In this work package we have improved the existing modelling tools available within the partnership to account for the high end conditions and for the novel interventions and adaptation options. In particular we have improved our models to consider at global scales flooding and erosion in a combined manner. At regional scales to consider in a combined manner riverine and marine flooding and eventually erosion/accretion. At local scales to incorporate into the models the new types of interventions based on “working with Nature” and the new adaptation options derived from the initial analyses and the stakeholders criteria.

The coordination of case studies has been organized by selecting a focal point for local scales and a focal point for global scales. The focal point for local scales, partner num. 3, has coordinated from the beginning with the focal point for global scales represented by partner num. 9 and partners 10 and 4 for specific modelling aspects. The combination of global modelling (DIVA in our case) with higher resolution models at regional and local scales has allowed developing cross scale assessments and the integration of different impact types and adaptation alternatives normally derived from local scales and introduced into regional and global assessments. All this has been coordinated with the typologies included in the CAS framework from WP1 and based on the initial coordination workshop. Here the in-depth discussion about case studies, existing modelling tools and scales of work has allowed to refine the initial list and to select some extra cases so as to have a consistent overall view that allows preparing more generic adaptation options and upgrading the modelling tools for a wide set of cases.

The upgraded modelling tools at local, regional and global scales (as described before) have served to advance the work on impact evaluation under present adaptation options. The upgraded models have been enlarged in terms of processes (e.g. combined marine – riverine flooding or combined damage from flooding and erosion). They have also been updated regarding resolution and considered scales such as for instance the increase in segmentation for the global scale model and a comparison with a regional model results based on detailed, process-based models such as the ones that have been carried out for Mediterranean cases.

The quantification of morphodynamic, ecologic and socio-economic impacts has started considering the cost of the proposed interventions in terms of initial construction and maintenance but also adding the cost of the impact and in energetic terms. An evaluation of the CO2 footprint for the main proposed alternatives is also being carried out to rank the interventions and adaptation pathways according to their climate “friendliness”. The results of the global work has served to identify the more vulnerable hot spots and apply in those cases a nested hydro-morphodynamic modelling sequence that has allowed characterizing the impact of the average trend of sea level rise or temperature and the combined impact of enhanced sea level rise and extreme storms.

Based on this structure we have modelled the high end climate change impacts on the case studies. After setting up contacts and teaming up with local partners, we have obtained data sets and compared local available modelling tools with the ones available in the partnership. This for instance has been the approach employed in Ho Chi Ming City where a model cascade has been set up to simulate flooding in the city including upstream river network, urban drainage system, precipitation changes and sea level rise projections to determine urban damages.

The model runs for this and other case studies, address the present adaptation and the additional adaptation in a consistent manner, using local data or global projections based on validated global reanalysis. For instance we are using a validated global reanalysis of sea levels for the period 1979-2014, including extreme sea levels, for various locations and return periods around the world to carry out a first assessment of storm surge coastal impacts.

The role of uncertainty in model projections, based on past model calibration and present validation, has also been considered to better reproduce the coupling between scale and processes and to better convey a robust impact assessment to our stakeholders. The inclusion of this adaptation options in the upgraded codes has been a major task and a significant research effort.

In all cases the impact assessment under present adaptation has followed the eight steps of the CAS structure (case study description, model development and validation, impact assessment, impact assessment with additional adaptation, development of an adaptation pathway, interaction with stakeholders, selection of preferred adaptation pathways and implication for regional and global assessments). More specifically in this work package we have aggregated these eight steps into three levels of activities:

i. Introductory work
ii. Methodological work

iii. Results

(see 1st Progress Report for further details)

All these advances have been discussed at various levels of development in stakeholder meetings held in all participating countries and the additional study sites outside Europe (e.g. HCMC and Maldives). Here the preliminary assessments of impacts under future conditions have been presented to stakeholders. These stakeholders have included local level policy makers, regional and central Government representatives, NGO's, researchers from local institutions and other relevant socio-economic agents. Out of these meetings there have resulted suggestions for novel adaptation measures included in WP4.

The performed impact assessments have aggregated the various coastal typologies existing in a given region. By way of illustration the Catalan coast case now includes low lying beaches, artificial beaches, groin supported beaches and harbours. The socio-economic impact analysis covers all of these elements and is based on the long term rise in mean sea level (including subsidence in the case of deltas, notably that of the Ebro Delta) but also the effect of impulsive storms so typical of the Mediterranean climate. This impacts are been calculated without additional adaptation measures, but they are being prepared to incorporate novel adaptation solutions based on working with Nature and avoiding the artificialization of the littoral, which will be difficult to maintain under future climates.

For the purpose of having a more robust calibration some of the case studies (for instance the Danube Delta) have launched additional field campaigns to characterize the present bathymetry and beach profiles so that the diagnostic can be reliable and used for actual coastal decisions. In this case the campaigns have been carried out during the summer of 2014, winter and 2014 and 2015. The obtained data have been used for the high resolution hydro-morphodynamic sequences based on PREMOS and this approach has served as a leading analysis for other similar regional scale cases.

The importance of the regional patterns obtained show the relevance of non-linear interactions for shallow areas while for the most off shore regions sea level rise, tides and surges can be considered to interact linearly and therefore a statistical model can be combined with hydrodynamic projections. The importance of the non-linear interactions for complex bathymetries is therefore an important part of the advances we have obtained based on these case studies.

Regarding the economic component in this first year we started to update previous work on adaptive capacity and demand for safety, using data on protection levels and natural hazards from dispersed literature and from our own research work in the project (Figure 5). This has allowed establishing new standards and recommendations for the role of uncertainty in decision making. We have developed the implications for direct impacts, indirect impacts and policy. This has allowed to replicate and improved existing work on the economics of sea level rise, by considering the propagation of the impact through market and scales.

For the first time we have included the impact on transport costs due to the impairment of harbour facilities. This can be illustrated by the paper submitted to Regional Environmental Change where we start to calculate at regional scale the effects of climatic change and variability on a coastal system composed by low lying beaches and ports of different characters (industrial and touristic plus fishing). We have also started to estimate the impact of subsidence in physical and statistical terms. For this we are considering the rice production in deltaic areas where a paper is also underway and for the coastal countries of the USA where there is enough analytical information to allow that work and to consider how risk spread in space and time.

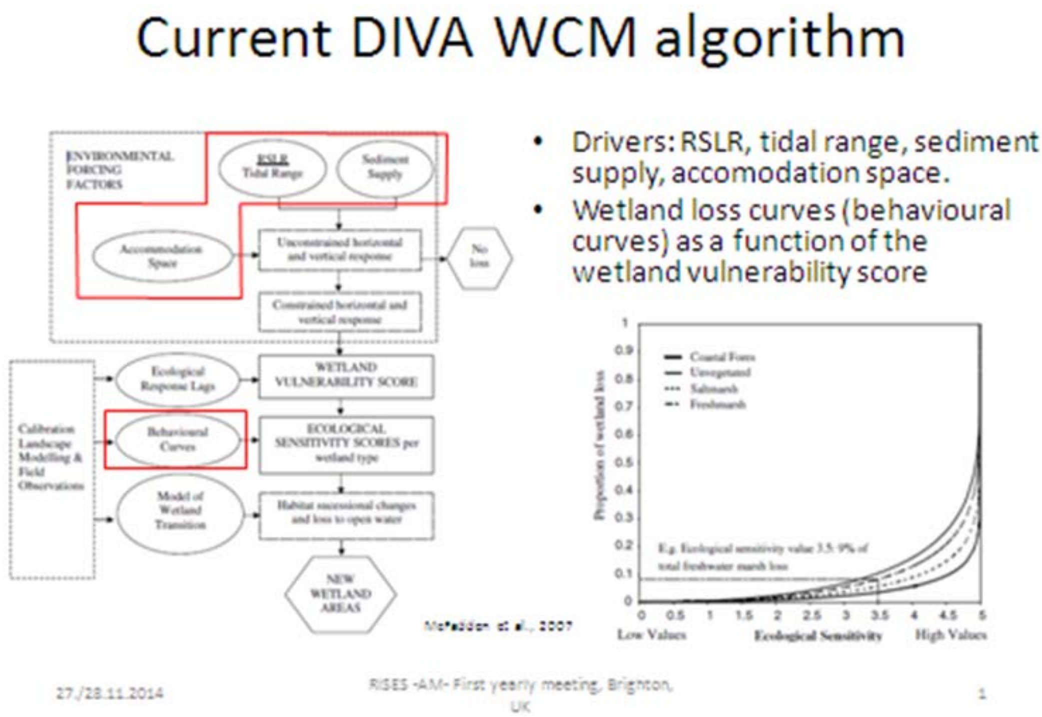


Figure 5. Schematization of one of the DIVA algorithms, as a way to illustrate the new demand for safety function and the complexity to introduce it into a global scale model. This illustration corresponds to the wetland loss as a function of sea level rise.

The work developed so far has allowed an updating of the economic impact of sea level rise and future climates in long term quantitative models (DIVA and Glofris). From here we are assessing the effect of future climates on general equilibrium and growth and as a consequence on the policy implications, with emphasis on dangerous interferences and adaptation assistance.

The improvement in global scale models such as DIVA, based on the newly proposed demand for safety equation will allow an estimation of direct economic impacts of climatic factors (essentially sea level rise) for a variety of socio-economic and physical conditions and a range of credible parameterizations, leading to better estimates on the linkage between economics and adaptation.

We have set up the basic structure of a general equilibrium model where the regional and sectorial aggregation of the economy has been defined. Here we have modelled land loss and specified the changes in cost of water transport within the basic model structure, so as to facilitate the impact assessment.

We have also considered the loss of productive land due to sea level rise based on available literature for the first assessments and counting on the appropriate data from the DIVA model once they are available. The direct impact of sea level rise on water transport has been modelled in terms of the efficiency reduction of the technology used by the water transport sector. This reduction is unknown and for that reason we have taken a distribution of values between 0% and 10% technological change, allowing for some model flexibility until that information becomes available.

The demand for transportation services has also started to be modelled. Since the GTAP model does not allow for substitution between different modes of transportation, the code has been modified to allow for such substitution between a) air, b) water and c) land transport. Since the elasticity of substitution between transportation modes is not readily available nor there are enough data, we are working on procedures to extract this information from literature or to estimate it from the calibration of the CGE model. Once these modifications to the GTAP model are completed the simulations will be run and the model results will form the basis for assessing the indirect effects of sea level rise taking, account of both direct and indirect impacts in the water transport section.

This research extends earlier work that was limited to land loss and coastal protection and thanks to the use of a quantitative model such as DIVA this will allow to add other effects such as salt water intrusion, transport infrastructure and flooding risks. The variety of climatic factors that via these mechanisms can affect economic growth (and be affected by population variability across SSP space, figure 6) will be also considered. By way of illustration floods can reduce productivity and re-direct savings towards defensive investments rather than productive investments. We have measured this relation empirically based on the available data on economic growth, particularly for areas where the information is detailed enough (e.g. US coastal countries) to support this spatial regression analysis.

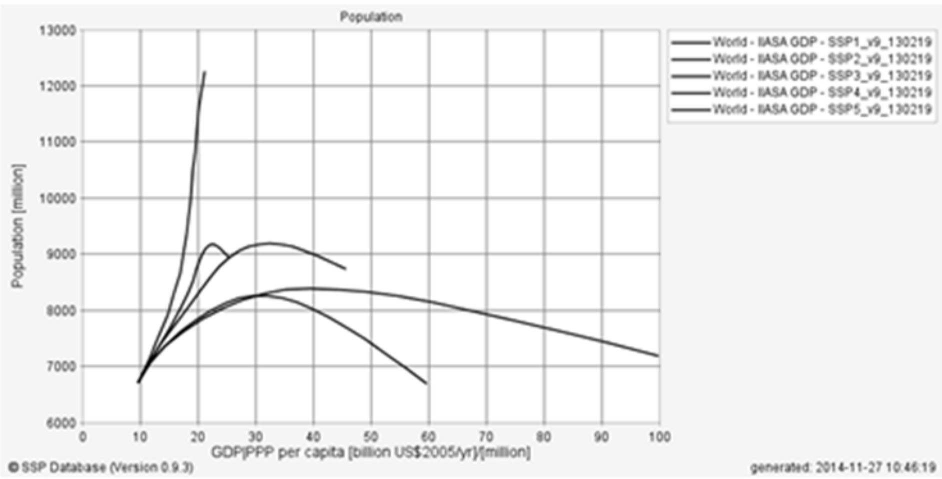


Figure 6. Graph illustrating the relation between population and GDP per capita as a result of the IIASA projections for the full range of SSPs. The huge dispersion is a key element to estimate the effect of climatic variables on social and economic sub-systems.

The work on communication and outreach has contributed to raising awareness at local scales on climatic impacts and the required coastal adaptation.

Our main targets are a) the scientific community, b) authorities and decision makers and c) users and stakeholders. For that purpose we have announced the production of a set of guidelines for cross scale assessments (draft already available) and a report on generic adaptation road maps. The same regarding a working paper on direct economic impacts, on the general equilibrium effect of climatic factors and on dangerous climatic factors.

This transfer work has shown how our scientific results are of interest for general assessments and can also contribute to technical guidance for assessing coastal impacts, vulnerability and adaptation, contributing to future generic guidance in actions such as PROVIA.

We have also disseminated project results (and provided transfer whenever it was required) to participative forums in the workshops organized per country and per case study (e.g. in Ho Chi Ming City and in Maldives). The country workshops were based on the questionnaires that previously were filled up by the partners. This has also resulted in more than one "visible" project session per year in participating countries and international conferences which has helped to liaise with ongoing research on complementary topics. For instance RISES-AM- participated in the Belmont Forum meeting during the Deltas in Times of Climate Change conference.

The topics covered in these publications and presentations have addressed the various coastal typologies (WP1), the projected high end physical and socio-economic conditions (WP2), the impact projection with present adaptation (WP3) and the economic implication (WP5). In all cases we have emphasized implications of upper limits (for instance our 2.0 limit for sea level rise) and the consistency across scales and across impacts for different sectors. The work has started using downscaled projections from AR4 since the values from AR5 were not available at the beginning. However at present and since we have already produced some general projections from AR5, we are starting to receive RCP ISSP downscaled projections, and the impact assessment is naturally evolving to the latest scenarios.

Finally, in this first year we have organised the ITAB to provide advice to steer the project development. The primary aims have been to i) promote the transfer of project results, ii) transmit to the partnership their concerns and challenges (site specific or global) in the face of climatic threats and iii) provide guidance for steering the project in a coordinated manner with on-going research (e.g. other projects in this call) and identify future joint or individual work.

The second year of RISES-AM-

The work during this second year has continued the advances in regionalized projections, additional adaptation and economic implications. The main impacts and foreground refer to:

1. Coastal typologies from our set of study cases at local, regional and global scales. The main impacts have been the selection of vulnerability hot spots: deltaic areas, estuarine areas, urban coastal areas and those tracts of coasts that are subject to a background erosion or subsidence.

2. Indicators related to the physical and socio-economic properties of a given coastal system. Physical indicators can be illustrated by the width or height of the sedimentary body and the associated sediment fluxes. Socio-economic indicators can be illustrated by population density, infrastructure density and gross domestic product for a coastal zone. The results are a set of process-based indicators, a novel definition for the boundaries of an adaptive coastal zone and a set of guidelines and considerations for the applications of such indicators.

3. Adaptation options for the morphodynamic component, the ecologic component and the economic component of the coastal system. The main advances come from the improved structuring and the inclusion in the developed pathways of a combination of hard, soft and green solutions that should lead to an improved coastal sustainability under present and future climates.

4. Guidelines for cross scale assessments where the results refer to a) drivers, b) pressures, c) state, d) impact and e) responses. The impact will affect the geomorphic substratum of the coastal zone and its management, the infrastructure development plans and the activities that occupy or are hosted by the coastal fringe.

5. Physical projections of the main variables to assess future impacts in the coastal zone, encompassing different coastal morphologies and harbour units built in the studied cases. The impact has supposed an integration of so far considered separately coastal activities (e.g. beach tourism and port activities) and a generic methodology for variable combinations and horizons for impact projection.

6. Socio-economic projections referred to population and economic activity where the use of density–like estimations for a process, based definition of the coastal zone has been introduced. The impact will affect the consistency between physical and socio-economic projections (improvement with respect to the present state of the art) and the level of resolution and accuracy suitable for each of the scales considered (local, regional or global). By way of illustration we have selected SSP-3 and SSP-5 combined with RCP 4.5 and RCP 8.5 as the initial space for impact assessment.

7. Dissemination activities (communication and outreach) to scientists (peer reviewed journals and international conferences) and ad-hoc workshops and news elements for stakeholders and relevant coastal agents.

The work to assess impacts at local to regional scales has required an important research effort to downscale physical and socio-economic projections. The detailed analysis appears in the Second Progress Report but here we shall illustrate, for completeness, the additional work on the combined drivers (sea-level rise plus storm surges and waves) that went beyond the initial planning in the Description of Work and which has allowed a much more comprehensive multi-variable impact assessment for the case studies.

Surges

In previous work, Gaslikova et al. (2013) showed projections for surges under future climate in the North Sea. Comparing the 30-year averages of the annual 99-percentiles of the wind-induced water levels between the four climate realisations and the respective control climates, a small tendency toward an increase is inferred for all climate change realisations toward the end of the twenty-first century. Projections for storm surges over the NW European Shelf were reported in the main D2.5 report (Jevrejeva et al., 2015). An increase for the mean 99.9-percentiles along the western Danish coast of about 7-15 cm and in the Irish Sea of about 5-10 cm (which is approximately 5-10% of the mean local high surge magnitudes) is a common feature for all the realisations. A more or less intense decrease of the surge 99.9-percentiles to the south-east of the British Isles is also a persistent feature for all considered scenarios and projections. This distribution is in line with the typical storm wind situations with prevailing westerly winds. It should be pointed out that the spatial pattern of changes does not necessarily remain the same when other percentiles (e.g., 99- or 99.5-) or annual maxima are considered. Along with the inter-model differences there is a strong inter-decadal internal variability for each projection.

Vousdoukas et al. (2016) made surge projections for all the coasts of Europe forced by wind and pressure fields from an 8-member ensemble of CMIP5 models, using the Delft3D model. They found acceptable validation of the rather coarse model results without downscaling, using simple bias correction (adjusting mean and variance of the coastal sea level data). The estimated extreme surge levels appeared to follow similar spatial patterns among the different scenarios and return periods, with values along the North Sea coasts increasing eastwards, and being substantially higher than those along the rest of the coasts of Europe. Another area characterized by higher surge values was the UK coastline of the Irish Sea, followed by marginal areas of the Baltic Sea (e.g. Kattegat, Gulf of Finland and the North Gulf of Bothnia) and the Norwegian Sea. Anticipated extreme surge levels appeared to be less than 2 m for most of South Europe with higher values observed along parts of the North Adriatic and of the North Black Sea. Values for most scenarios and return periods indicate a projected increase in storm surge level (SSL) at several locations along the North European coastline, which is more prominent for RCP8.5 and shows an increasing tendency towards the end of the century for both RCP4.5 and RCP8.5. Projected SSL changes along the European coastal areas south of 50°N show minimal change or even a small decrease, with the exception of RCP8.5 under which a moderate increase is projected towards the end of the century. Note that GFDL forcing seems to produce the lowest negative bias i.e. least underestimate of surge levels before bias correction.

For the UK, the investigation of climate change impacts on surges has been examined over several years e.g. Lowe et al. (2001, 2009), using the UK operational storm surge model (Flather and Williams, 2004) normally forced by numerical weather prediction (NWP) models, but now forced by climate models (Lowe et al., 2001). One of the key issues is the distinction between changes in weather-induced sea level changes (surges) and the effects on extreme water level i.e. including the effect of mean sea level (MSL) and tides. Skew surge is a useful measure of the importance of surge, being the surge level at maximum water level. Howard et al. (2010) show that increasing storminess (should it occur) would be expected to increase surge heights but more direct effects on extreme water levels can be attributed directly to changing MSL. Results show that large increases in MSL (even up to 5 metres) have very little effect on the dynamics of extreme surge events, the primary effect being on the speed of propagation of tide and surge which produces changes in phase, usually preventing the peak surge from occurring at tidal high water.

Around the UK coast, the changes in the skew surge extremes (not including changes in regional MSL), diagnosed from projected changes in climate model forcing, are physically small (figure 7, left hand panel), for example a projected change of 8cm over the 21st century could be compared with observed global MSL rise during the period 1961-2003 of around 1.8 mm/year (Church et al., 2010), and in most locations they are not statistically significant (i.e. do not exceed natural variability). This study also demonstrated that globally driven simulations are capable of predicting changes in extreme SSL without the need for downscaling (Howard et al., 2010).

Scaling of wind and pressure fields was used to give a representative simulation of a potential future storm surge climate under a strengthened storm track, and found to produce changes in surge heights at the UK coastline an order of magnitude larger (figure 7, right hand panel). These results illustrate the effect of the large uncertainties in current model projections of changes in the north Atlantic storm track.

Groll et al. (2014) and Grabemann et al. (2015) have looked at changes in North Sea wave conditions forced by GSM projections using the SRES scenarios with a forcing ensemble of different models and emissions scenarios. Mean and extreme wave heights tended to increase in the eastern parts of the North Sea towards the end of the twenty-first century in most of the projections, but the magnitude of the increase in extreme waves varied between the projections. For the western parts of the North Sea more than half of the projections suggest a decrease in mean and extreme wave heights.

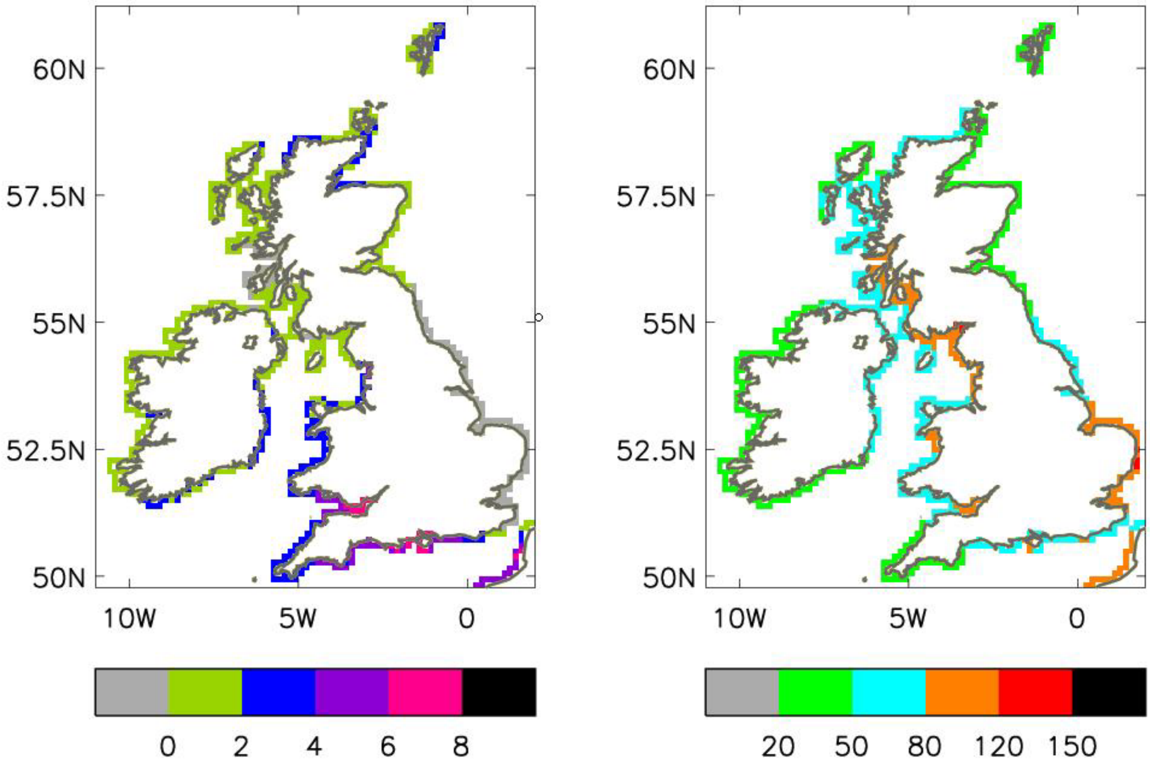


Figure 7. Projected century-scale change in 50-year level of skew surge from changes in atmospheric storminess only (centimetres). Left-hand panel: Mean projection of the perturbed physics ensemble of HadCM3. Right-hand panel: Crude estimate of potential changes under a strengthened storm track. Both panels show projected changes from 1990 to 2090.

Referring now to marine storminess in the Mediterranean region, it is associated with a well-defined sub-branch of the mid-latitude storm track and this seems to be decreasing in intensity, so storm surges and waves are also projected to decrease (Lionello et al., 2016). In previous work, Lionello et al. (2005) identified large inter-decadal fluctuations, but no clear trends, in extreme storm surges over the Adriatic Sea. Double CO2 simulations (Lionello et al., 2002) indicated a reduction of extreme wave heights, but no clear trend in storm surge levels (Lionello et al., 2003). Lionello et al. (2008a) examine changes in cyclone climatology over Europe as inferred from a regional climate simulation, finding that, compared to the present day, in the A2 and B2 scenario conditions the annual average storm track intensity increases over the North-East Atlantic and decreases over Russia and the Eastern Mediterranean region. Conte and Lionello (2013) present storm surge results using a 7-member climate model ensemble for the A1B scenario in the Mediterranean and show a reduction in surge amplitudes in the future projection. The choice of the global climate simulation, which is used for the boundary conditions of the regional climate models, is shown to be the largest source of uncertainty for the assessment of the climate change signal.

This analysis has been further integrated and storm surge projections for the Mediterranean Sea have been obtained, driving the HYPSE storm surge model (Lionello et al. 2005) with a set of regional climate simulations carried out in the MedCORDEX programme for the RCP4.5 and RCP8.5 pathways. Results shown in figure 8 consider the 10 highest events in each year and describe the variation of their mean value for the period 2021-2050 and 2071-2100 with respect to the reference period 1971-2000.

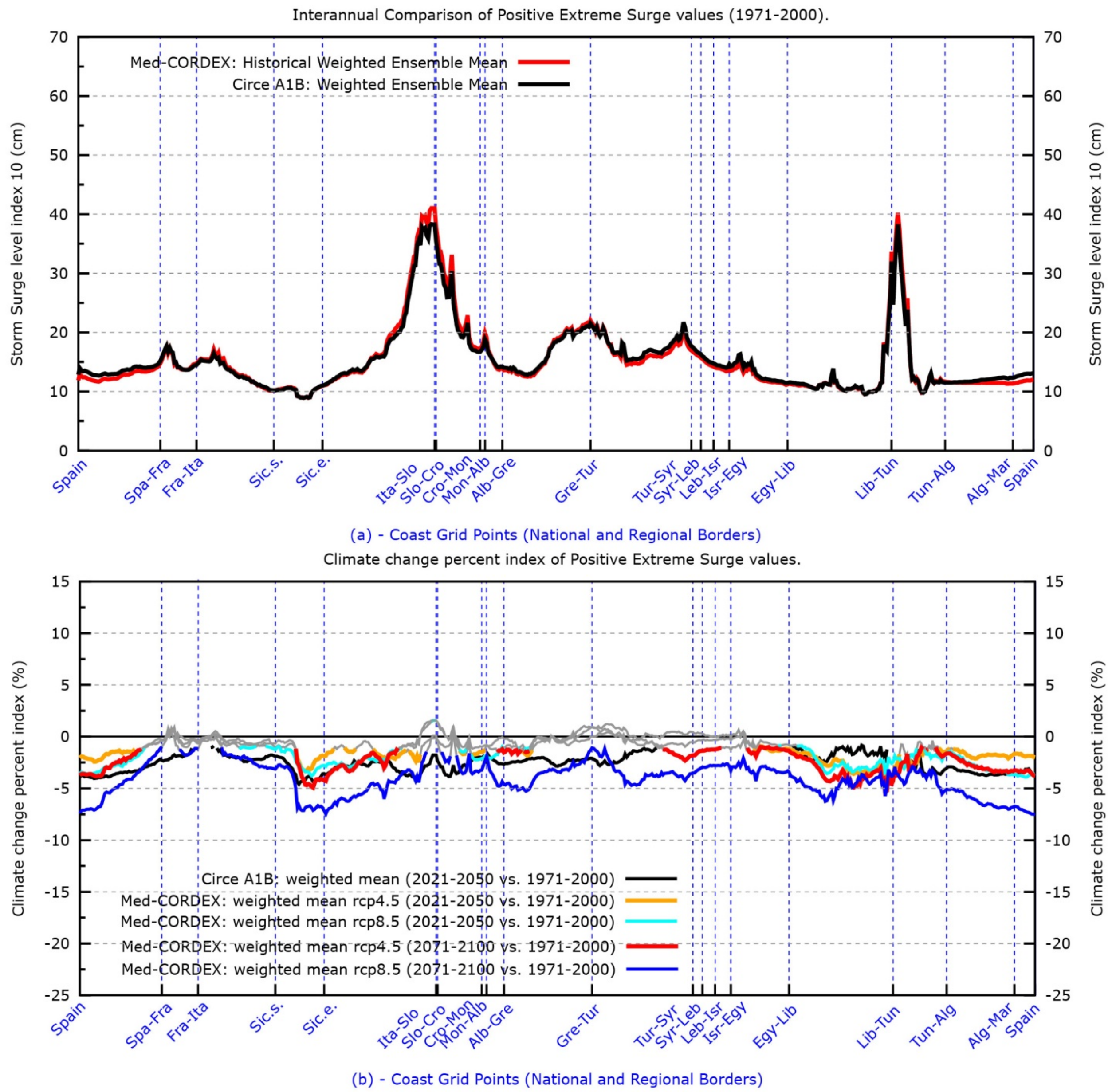


Figure 8. Distribution along the Mediterranean coastline of the mean value of the 10 highest annual surge events. Upper panel: reference value in the period 1971-2000 of the historical simulation considering the ensembles of the CIRCE and MedCORDEX simulations. Lower pane: climate change (%) signal. Each curve represents the ensemble mean of a different set of simulations and time slices as annotated in the panel. Colored parts of the curve denote significant changes.

The figure shows a widespread decrease of the intense surge events, which progressively decrease their intensity with time and emission level, being most attenuated in the RCP8.5 scenario at the end of the 21st century (2071-2100, blue line). In this scenario a reduction larger than 5% occurs along many parts of the coastline, particularly in the westernmost part of the basin, Sicily channel and Ionian Sea. Also coasts where the largest surges occur (north Adriatic and gulf of Gabes) present a 4% (approximately) reduction. However, the reduction is significant along most of the coastline also in the lower emission scenario, and for the RCP8.5 already occurs in the period 2021-2050.

Waves

For waves in the North Sea, (Gaslikova and Weisse, 2006) examined near-shore wave statistics from regional hindcasts, using different methods of downscaling, including dynamical and dynamical-statistical methods, where the latter are generally less expensive in computational effort. Grid nests of 50km, 5km and 100m were used with the WAM model for the coarser grids and the K-model for the finest, nearshore grid. They found that improved coastal wave hindcasts could be obtained using all of the downscaling methods. For dynamical downscaling differences were introduced by better coastal resolution including resolving islands, shadowing and differing shallow water effects in the finer models. Statistical downscaling methods are shown to provide improved extreme wave statistics at lower cost, after training on the highest-resolution model data.

Previous work with the wave model WAM forced by the HadCM3 ocean-atmosphere GCM downscaled with the atmosphere-only HadRM3 regional climate model (RCM) using SRES scenarios is described by Wolf et al. (2015). The model forcing included the perturbed parameter ensemble (PPE) in which different climate model parameter settings and their effect on climate sensitivity was explored. The future climate storm track was seen to be displaced to the south over UK/NW Europe, leading to an increase in wave heights to SW of UK and a decrease to the north of Scotland.

Figure 9 shows the differences in significant wave height (SWH) from the present day, for the three of the PPE ensemble members (i.e. future minus present day). The pattern is similar in each case with an increase in SWH in the south and a decrease to the north, although there are also distinct differences.

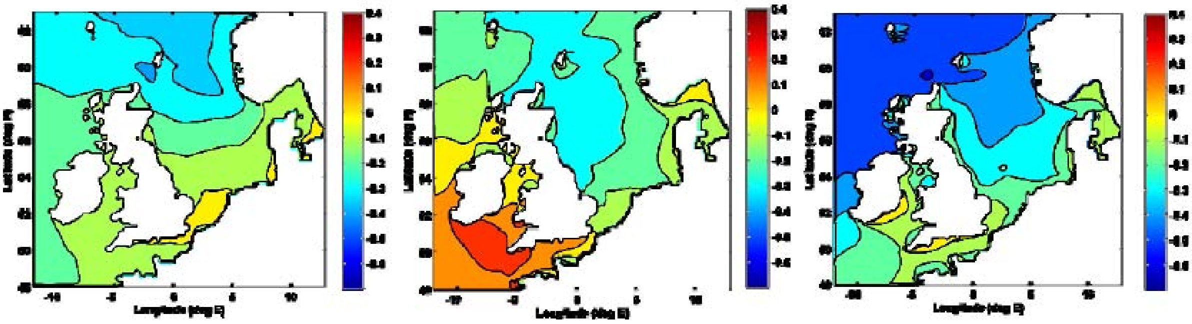


Figure 9. Differences in mean winter wave height from present day for selected PPE members – standard, low and high sensitivity respectively (left to right). Colour scale is wave height in metres.

Figure 10 shows changes in the winter maximum wave height. This has large error bars especially with the projected extreme values, as in this case a Generalised Extreme Value (GEV) distribution (Coles, 2001) has been fitted and the confidence limits are used to identify where the differences are significant or not. Dark shaded areas correspond to areas where the differences are not statistically significant at the 95% confidence level. Projections of longer return period waves reflect the same pattern but with larger error bars.

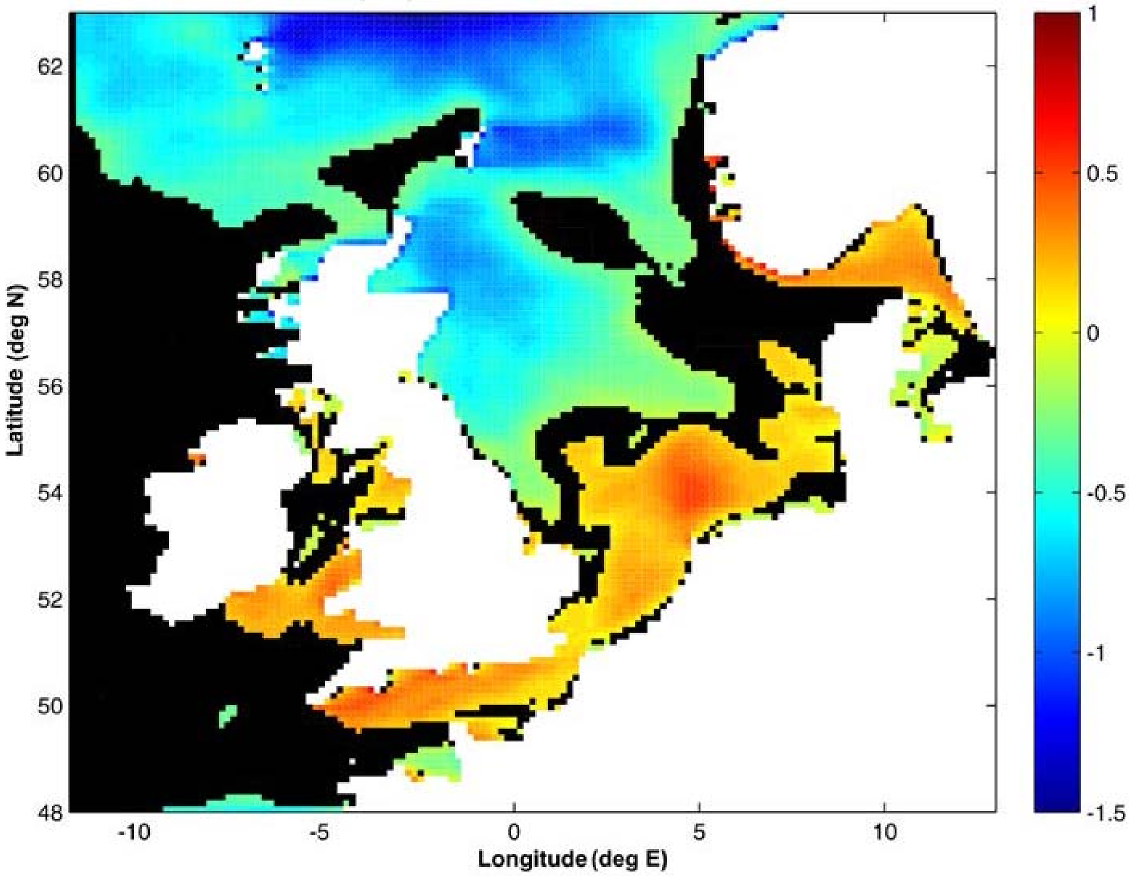
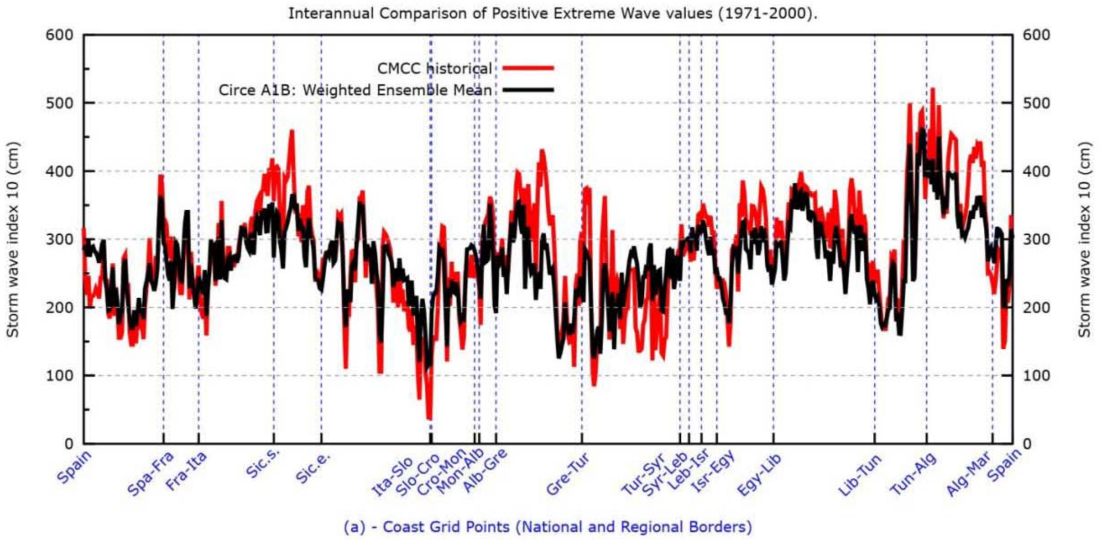


Figure 10. Differences in extreme wave height; brown shaded areas are where the differences are not statistically significant.

Brown et al. (2011) used these wave model projections (as well as the surge projections) at a single location to examine the likely changes in extreme waves in Liverpool Bay, in the eastern Irish Sea. Similarity in the trends between the global and regional climate models at different vertical levels, suggests that changes in the surface wind are largely determined by large scale physical processes affecting the circulation of the free atmosphere. Comparison of the percentile values for wind observations at the mouth of the Dee estuary with the modelled winds at the WaveNet location for the period 2005–2009, suggests that the climate model wind distribution is linearly related to that observed, but with increasing under-prediction for each percentile e.g. the bias in the 90th-percentile is −3.0 m/s for an observed value of 12.6 m/s. This under-prediction of the winds for coarse resolution models is a well-recognised problem with various bias corrections being suggested (Brown et al., 2014). This bias will influence the wave model results and to a lesser extent (due to the external surge generation being predominantly due to atmospheric pressure in this location) the surge projections. Thus to analyse future trends using these data it is advisable to look at changes in specific metrics such as the mean conditions or the 90th percentile values rather than the absolute values or extreme value analysis. Trends in the future climate are therefore inferred by comparing the modelled present climate with the modelled future climate using monthly, seasonal and annual means along with extreme events. Wolf et al. (2011) examined extreme value projections for the present-day Liverpool Bay wave climatology, using a hindcast model run and observed data. The 50-year return period SWH varies from 6-7 m depending on the data period and methodology, indicating that taking a return-period projection from a limited amount of data in different decades may give different results, apart from the climate model under-estimation problem.

Figure 11 considers wave extremes. Following the same approach as in Conte and Lionello (2013), model results have been extracted along the Mediterranean coastline in order to analyse the impacts of climate change on the coast. The upper panel shows the distribution of the mean value of the 10 annual largest wave storms (storm wave index). The extension of this analysis to a set of Med-CORDEX simulations will be provided before the completion of RISES-AM. However, preliminary results in this case also suggest a reduction of storminess.



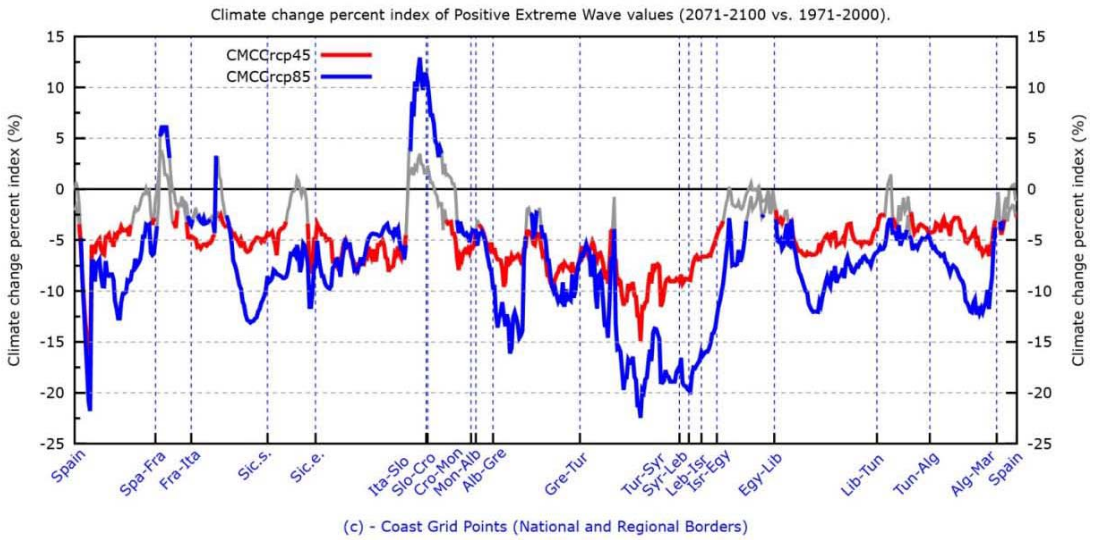


Figure 11. Upper panel: Average value of the 10 highest SWH storms (storm wave index) according to the CIRCE multi-model ensemble mean along the coast of the Mediterranean and of the CMCC RCP8.5 and RCP4.5 simulations. The bottom panel shows the percentage change of the CMCC rcp4.5 and 8.5 simulations comparing the present day and 2071-2100 period

For assessing the hazard posed by future storms, the projection of storm surges should be added to the steric variations in MSL as well as the changes in the crest level for wind-generated waves in some way, such as provided by the maximum water level indicator proposed in Lionello et al., (2016). The maximum water level "indicator" is defined as the five year return period maximum water level that can be reached under a storm, combining storm surges, wave effects and steric sea level variations. A consensus on a decrease of storminess intensity in the Mediterranean has progressively emerged in the literature (Lionello and Giorgi, 2007; Lionello et al. 2008a; Zappa et al. 2013b), which is especially evident for the RCP8.5 scenario in the latter study. Correspondingly, SWH and storm surges are projected to decrease (Lionello et al., 2008b; Marcos et al. 2011b, Conte and Lionello, 2013). For both wave and surge maxima the value of the reduction varies, depending on the basin, in a range from 2% to 5% for the period 2021-2050 with respect to 1971-2100, for the A1B scenario.

Note that the MSL of the Mediterranean Sea has shown substantial deviations from the global values at decadal time scales, in the recent past. In the period 1960–1990, the sea level in the Mediterranean actually decreased, mainly because of a persistent positive anomaly of sea level pressure (Tsimplis et al., 2005; Marcos et al., 2011a). Later, during the 1990s, it increased at a speed greater than the global one, and subsequently remained static from 2002 onwards (Marcos et al., 2011a). This behaviour can be due to mass exchange with the Atlantic across the Straits of Gibraltar, to change of volume because of change of temperature and salinity or a combination of both (Scarascia and Lionello, 2013). A mean flow of mass across Gibraltar can be the consequence of ice melting, which increases the mass of the oceans globally, and/or changing sea level pressure distribution over the North Atlantic and Mediterranean regions. Calafat et al. (2010) have estimated the mass contribution to sea level variability in the Mediterranean, finding that the mass content of the Mediterranean basin has increased at a rate of 0.8 ± 0.1 mm/y for the period 1948–2000, and up to 1.2 ± 0.2 mm/y if the effect of the atmospheric surface pressure is removed.

Extreme sea levels show pronounced short-term and long-term variability partly associated with seasonal and nodal tidal cycles (Weisse et al., 2014). Long-term trends are mostly associated with corresponding MSL changes while changes in wave and storm surge climate mostly contribute to inter-annual and decadal variability, but do not show substantial long-term trends. It is expected that this situation will continue for the upcoming decades and that long-term variability dominates over long-term trends at least for the coming decades.

In order to provide some confidence in the wave model results, some statistics have been extracted from wave observations and compared with ‘present-day’ statistics from the model climatology in figure 12.

The panels show the minimum, mean and maximum monthly wave height at a point, from 4 different locations, representing exposed (West Hebrides, NW Approaches; Scilly Isles, SW Approaches) and sheltered locations (Liverpool Bay, Irish Sea; South Knock, southern North Sea). The observations are from CEFAS WaveNet buoys (https://www.cefas.co.uk/cefas-data-hub/wavenet/), and in the model, the closest point was chosen.

The monthly data have been averaged over a series of years. For the wave buoys, different lengths of observed data are available. To make a more 'direct' comparison, the same length of data from the model is sampled at each site.

The mean values of SWH are generally in good agreement, while the extreme / maximum events tend to be slightly under-predicted by the model, particularly for the more sheltered locations. This is not unexpected as the model winds tend to underestimate extreme events, especially for the low resolution global model.

Figure 13 shows the benefit of the higher resolution nested model in terms of coastal resolution and fetch. It may be seen, for example, that higher waves penetrate into the Irish Sea and closer to the western coast of Ireland in the higher-resolution model.

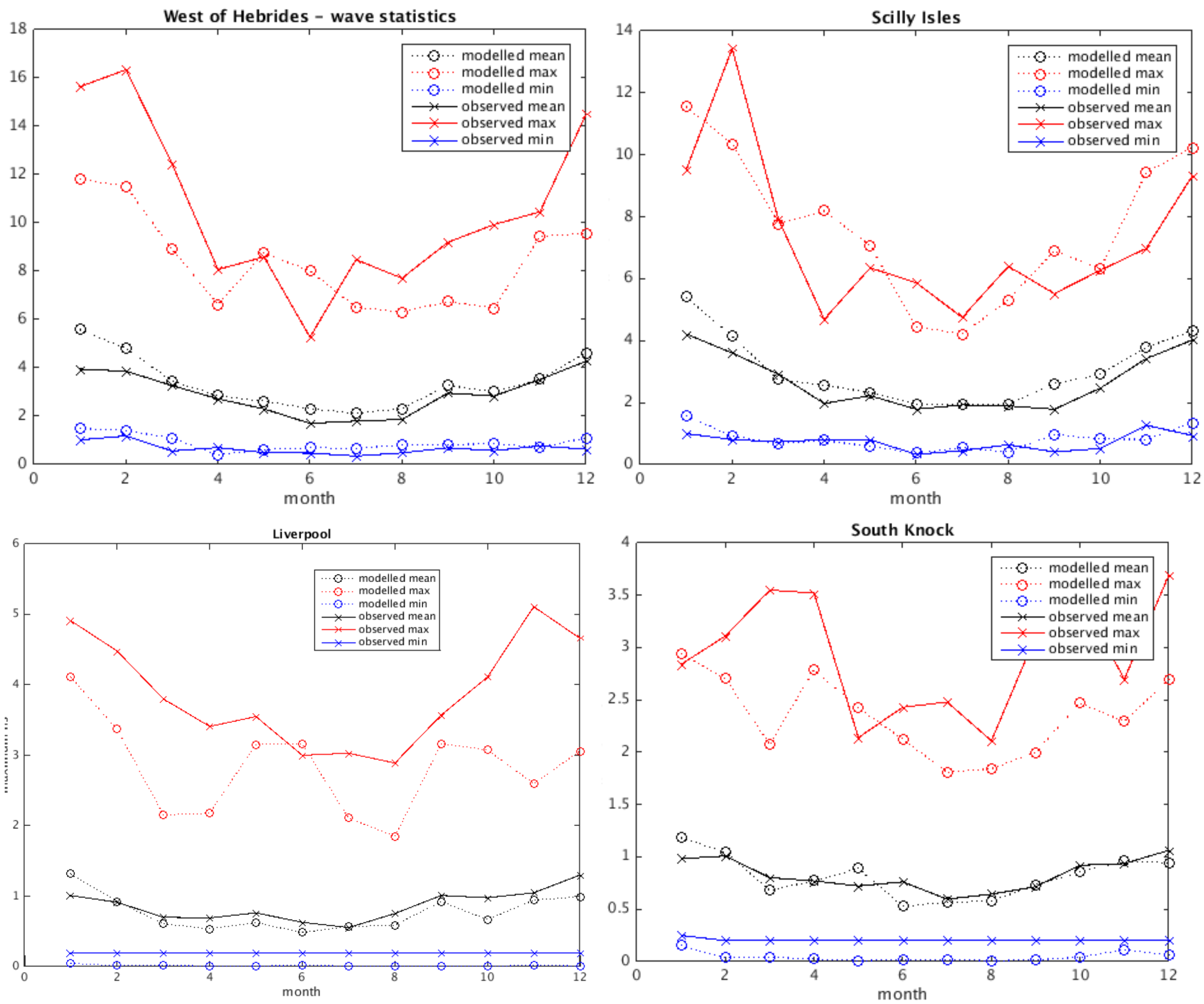


Figure 12. Monthly statistics from 4 locations, comparison of modelled and observed data. Vertical axis is SWH in metres.

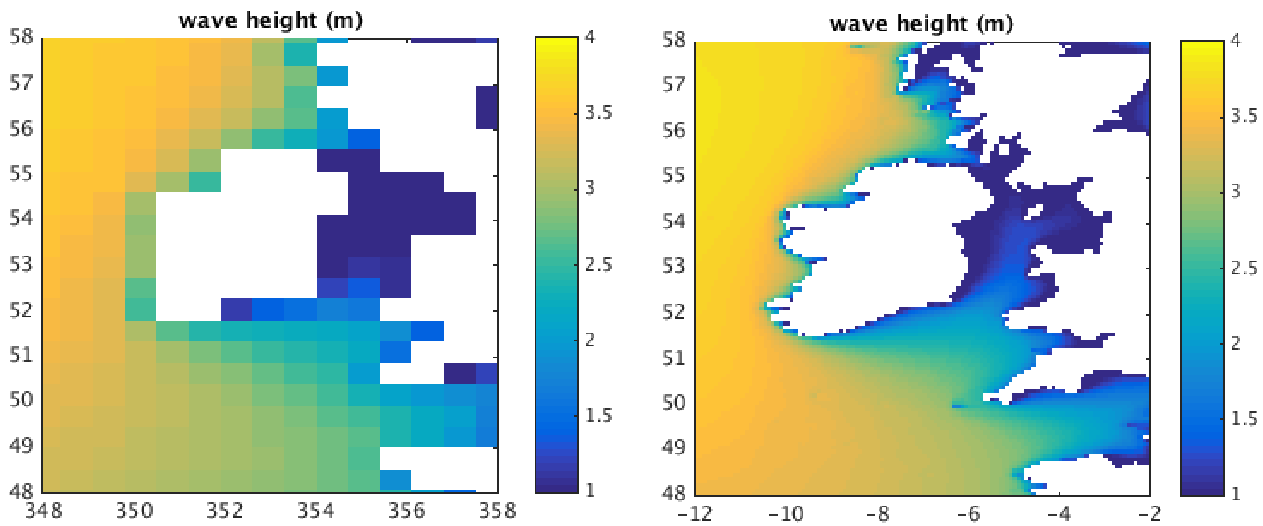


Figure 13. 30-year mean (1970-1999) maps of SWH for the global model (left) and the European nest (right) showing the added value of dynamical downscaling.

Some summary results for the wave projections are shown below for illustration, starting with maps of present-day and future wave climate (using climatic mean conditions over a 30-year period) and differences for annual mean and maximum wave heights.

Figure 14 shows seasonal differences for the global model in mid-century for RCP8.5. The maximum increase in wave height can be seen in the Southern Ocean in the northern hemisphere summer. Areas at high latitudes in the Arctic and Antarctic are seasonally covered in sea ice and the marginal sea ice zone needs more sophisticated averaging so these maps should be interpreted with caution.

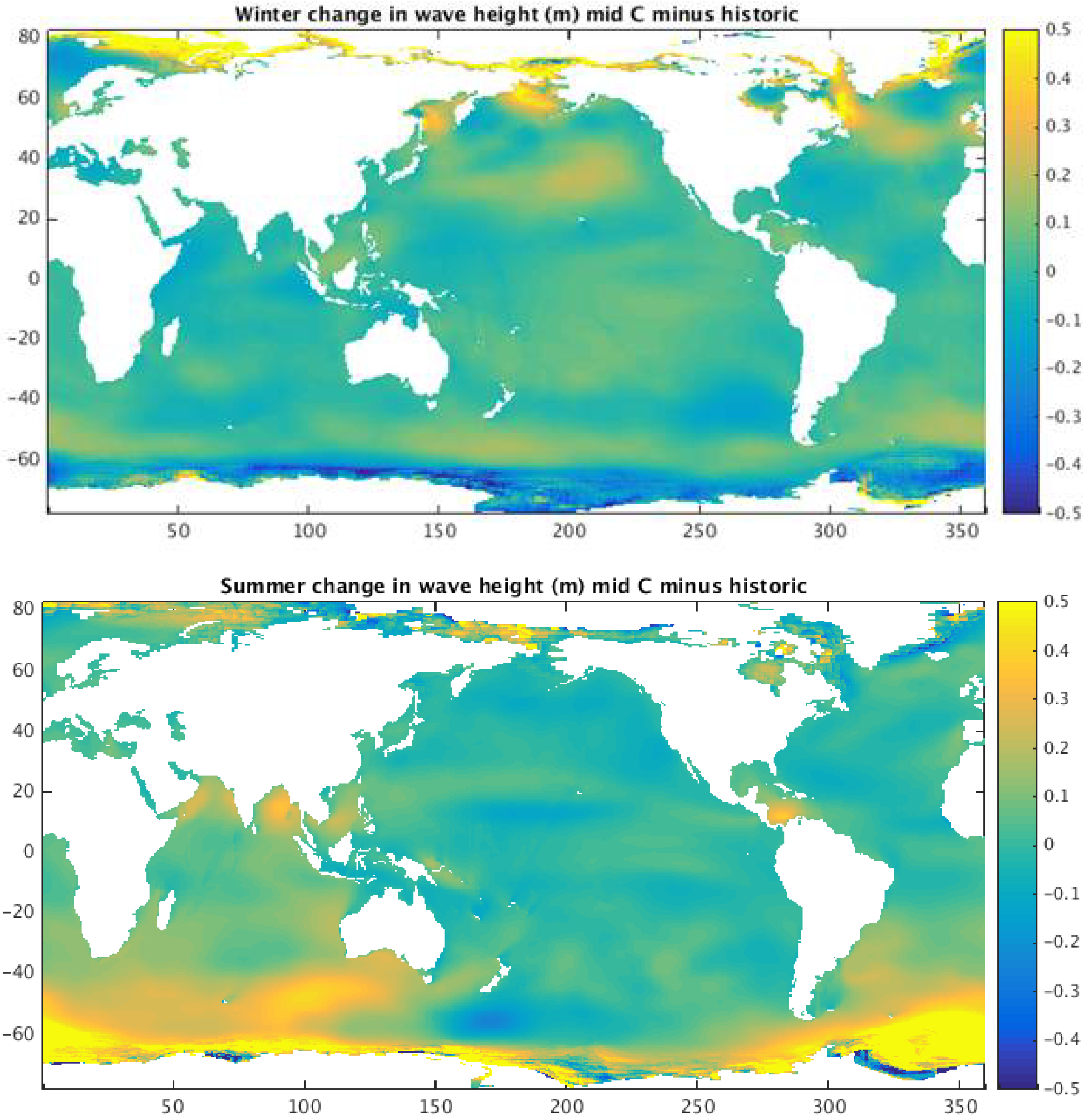


Figure 14. Seasonal change in SWH between present-day (1970-1999) and RCP 8.5 mid-century projection (2030-2059). Northern hemisphere winter (DJF) above, summer (JJA) below. Yellows indicate higher future wave height and blues reduced wave height. Note: the ice mask changes monthly, so time-averaged SWH should be treated with caution near the poles, i.e. ignore all points N/S of +/- 70 degrees.

Figure 15 shows the present-day mean wave height, averaged over 30 years (using 1970-1999 to represent the present-day climatology). The more exposed Atlantic coasts can be seen to experience larger wave heights than the North Sea and Irish Sea.

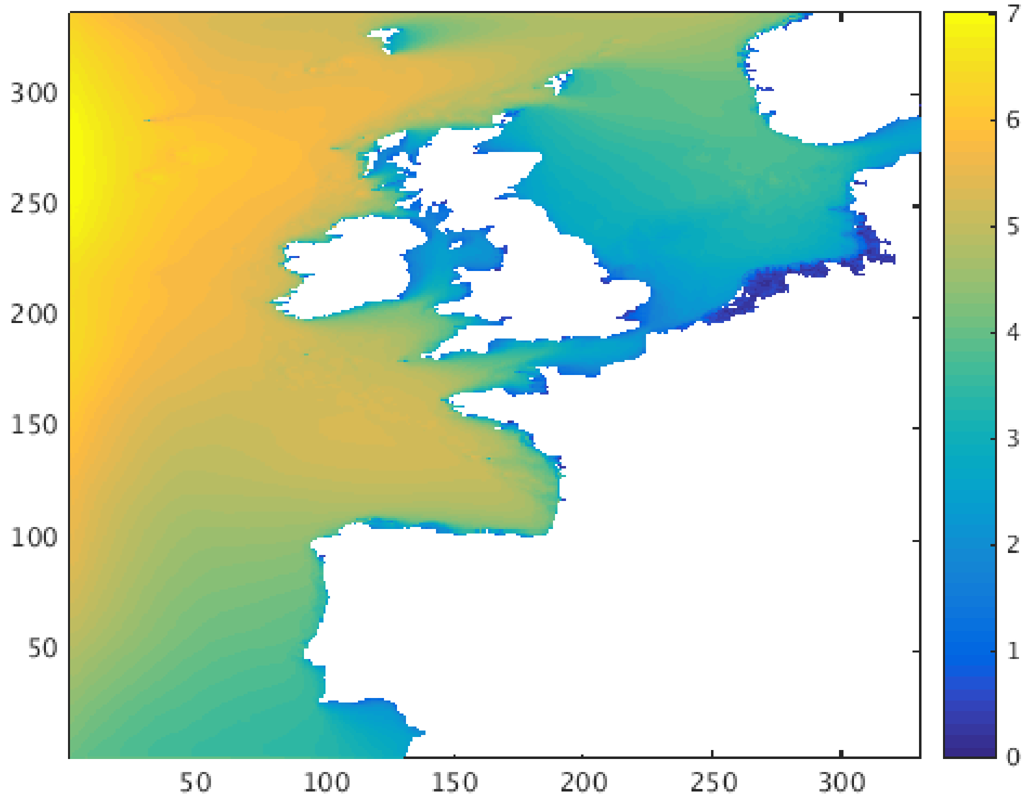


Figure 15. 30-year mean present-day SWH (m). Note that in this and subsequent figures the Mediterranean is masked out as waves were not fully modelled in this area.

In Figure 16 the mean wave direction and the change in wave direction in mid-century is shown for RCP4.5. A change in the direction of exposure is observed in the North Sea, possibly due to changes in sea ice in Nordic Seas, leading to changes in fetch, but this result needs to be examined more carefully.

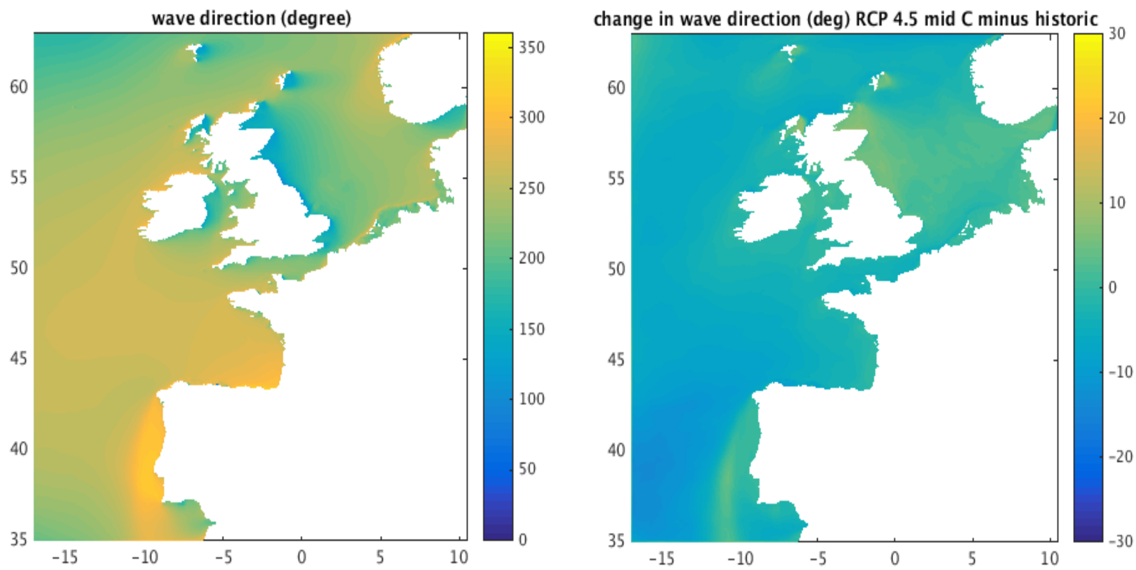


Figure 16. Change in mean wave direction (right) between recent past (1970-1999, left) and mid-century future (2030-2059) for RCP4.5.

Figure 17 shows changes in mean SWH between the recent past and the future projections. Increased wave height is seen in the north of the domain in mid-century, with lower waves observed to the south-west of Britain, but increased wave height in the NE Atlantic, west of the Iberian Peninsula. This pattern is more intense in RCP8.5 than in RCP4.5. At the end of the 21st century, however, the pattern has shifted, with slightly reduced wave heights to the north-west of Scotland. There are more differences between RCP4.5 and RCP8.5, with the latter showing much larger waves to the north of the North Sea, a reversed east-west gradient in wave height changes across the North Sea and lower waves west of the Iberian Peninsula. Further work will identify the significance of these changes.

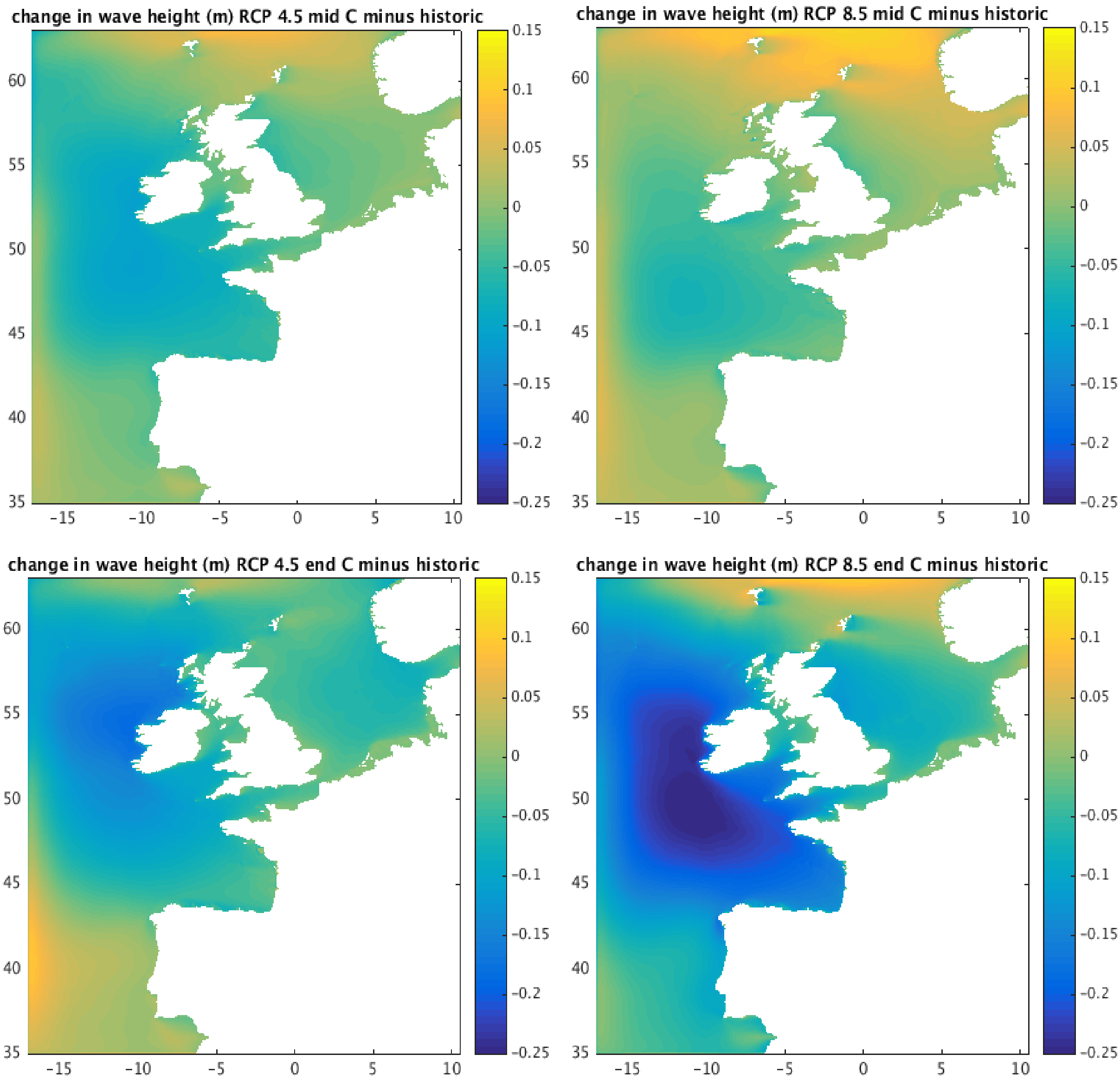


Figure 17. Change in mean SWH between present-day (1970-1999) and future projections. Top row = Mid-century (2030-2059), bottom row = End-century (2070-2099); RCP 4.5 (left) and RCP 8.5 (right).

Regarding the estimation of extremes, the *r*-largest method (e.g. Guedes-Soares and Scotto, 2004) has been applied to calculate extreme wave statistics and return periods for sites of interest around the UK and European coastline, for a present-day climatology and 4 examples of future 30-year wave climatologies (RCP4.5 and RCP8.5 for mid-century and end-century. Examples for an exposed location (Scilly Isles) and a more sheltered location (Liverpool Bay) are shown in figures

18 to 21. The absolute values of the SWH for a given return period cannot be relied upon as they will be underestimated as explained above, however comparisons between stations and between future projections and the present day probability density function (pdf) can usefully be made.

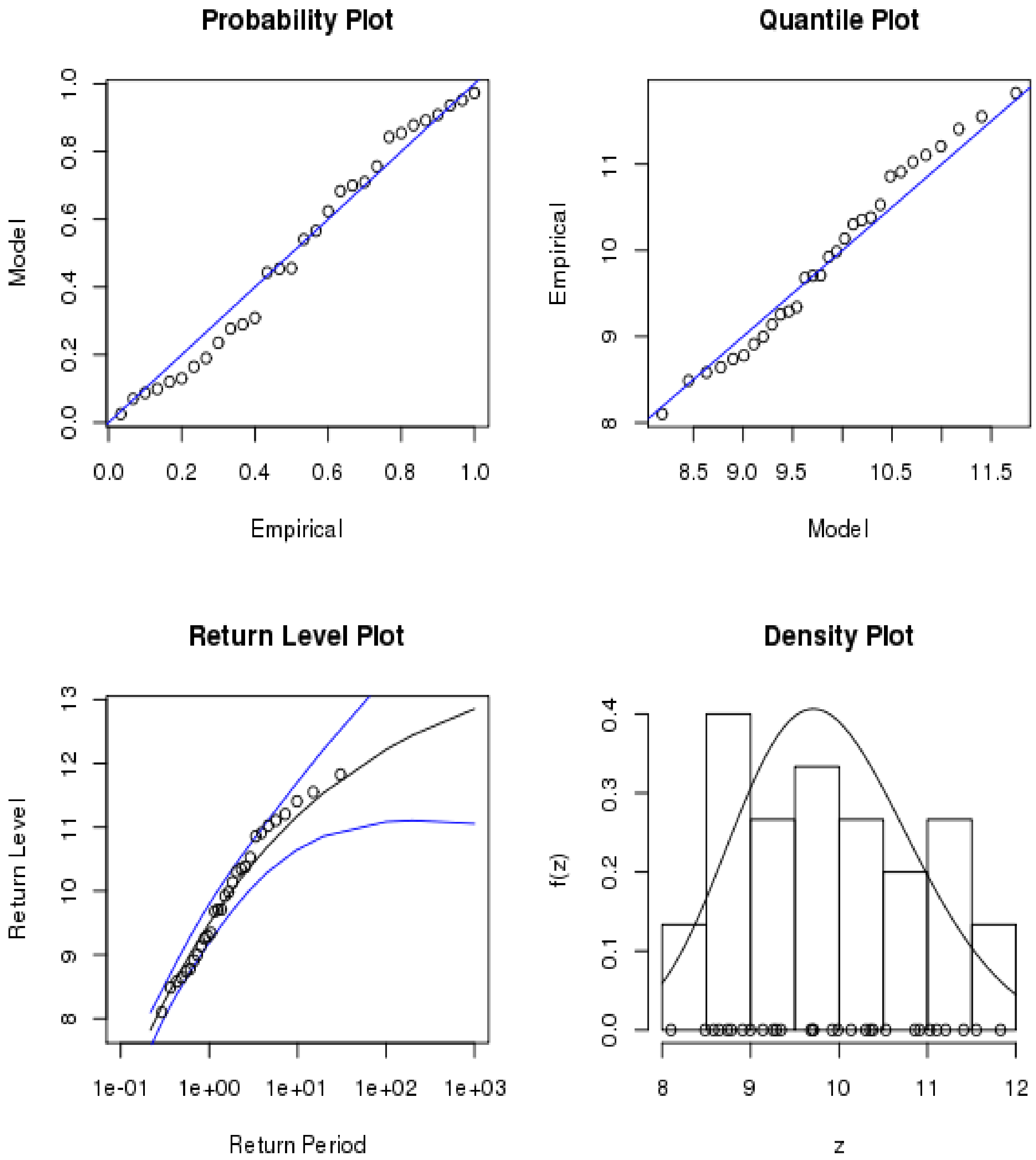


Figure 18. Scilly Isles r-largest statistics for present-day 30-year time-slice (1970-1999).

The optimum number of events to be selected per year (*r*) was found to be 5. A minimum separation of 120 hours between wave maxima (representing an estimate of the maximum duration of a storm in this area, has been used, in order to ensure that only independent events are included in the statistics. Figures 18 and 20 show standard statistics: probability plot, Q-Q plot, return period plot and pdf plot (model versus data) from the 5-largest fit while figures 19 and 21 only show the return period plots for each future projection. The scattered points are the top 1 event per year (so there are 30 points), and the lines are the fit and error, based on the mean, μ, and standard deviation, σ, calculated using the r-largest method.

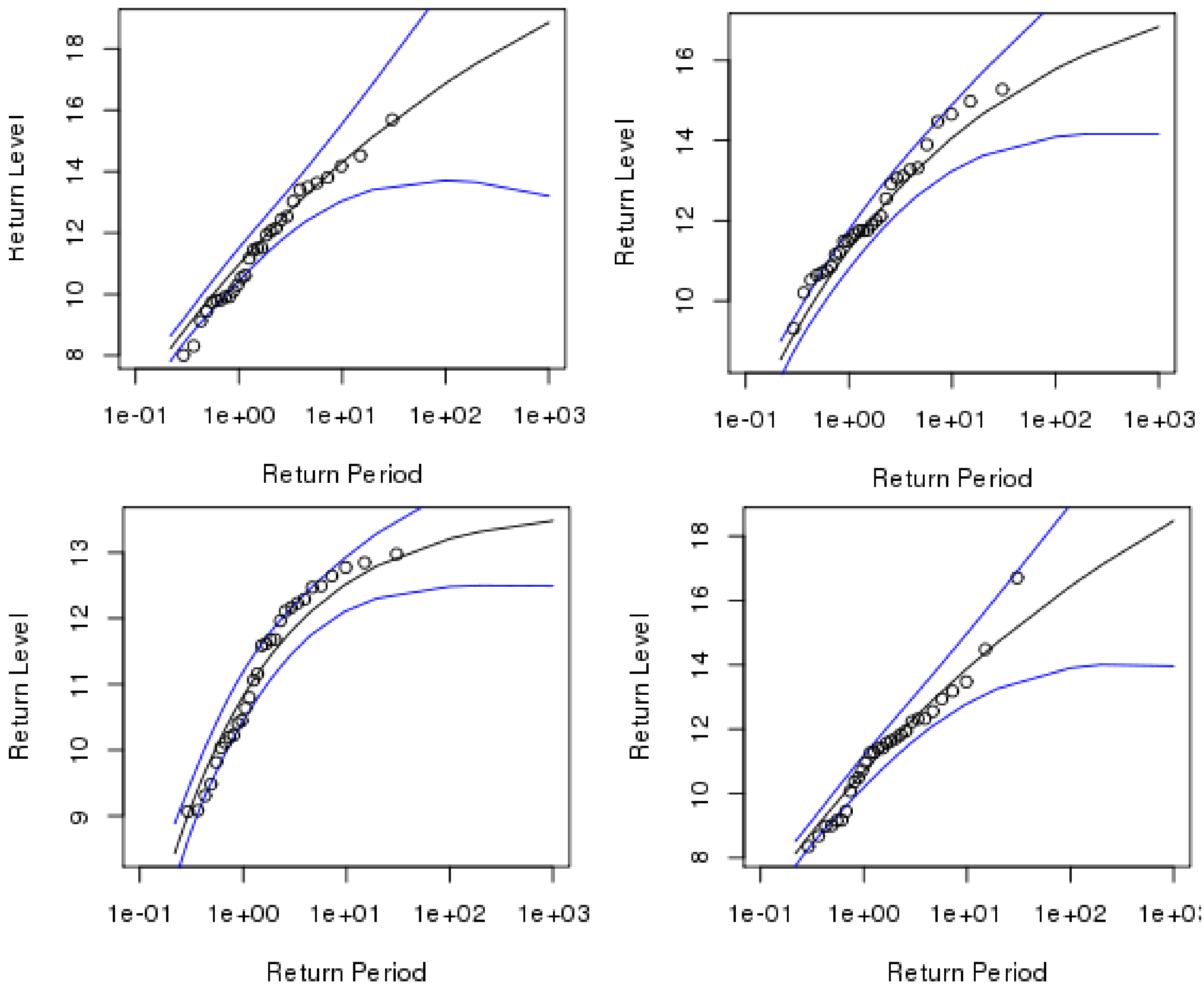


Figure 19. Scilly Isles return levels for future 30-year time-slices; top row, mid-century; bottom row end-century; left column RCP4.5, right column RCP8.5.

In general, a better fit for the pdf is seen at the exposed (Scilly Isles) location than for Liverpool Bay, probably due to the fetch-limited waves and shallow water effects in Liverpool Bay which can limit the maximum wave height. As expected a much larger extreme SWH is to be expected for the Scilly Isles than for Liverpool Bay.

Examining figures 19 and 21 for the changes in the return period plots for each future projection show that there are large variations between mid-century and end-century, and between RCP4.5 and RCP8.5 as discussed above. For example, the extreme waves at the Scilly Isles increase in all scenarios but the largest increases are seen in (i) RCP4.5 for mid-century, and (ii) RCP8.5 for end-century. On the other hand, the Liverpool Bay extreme waves show quite small changes for all except the increase of about 20% for the RCP4.5 mid-century scenario.

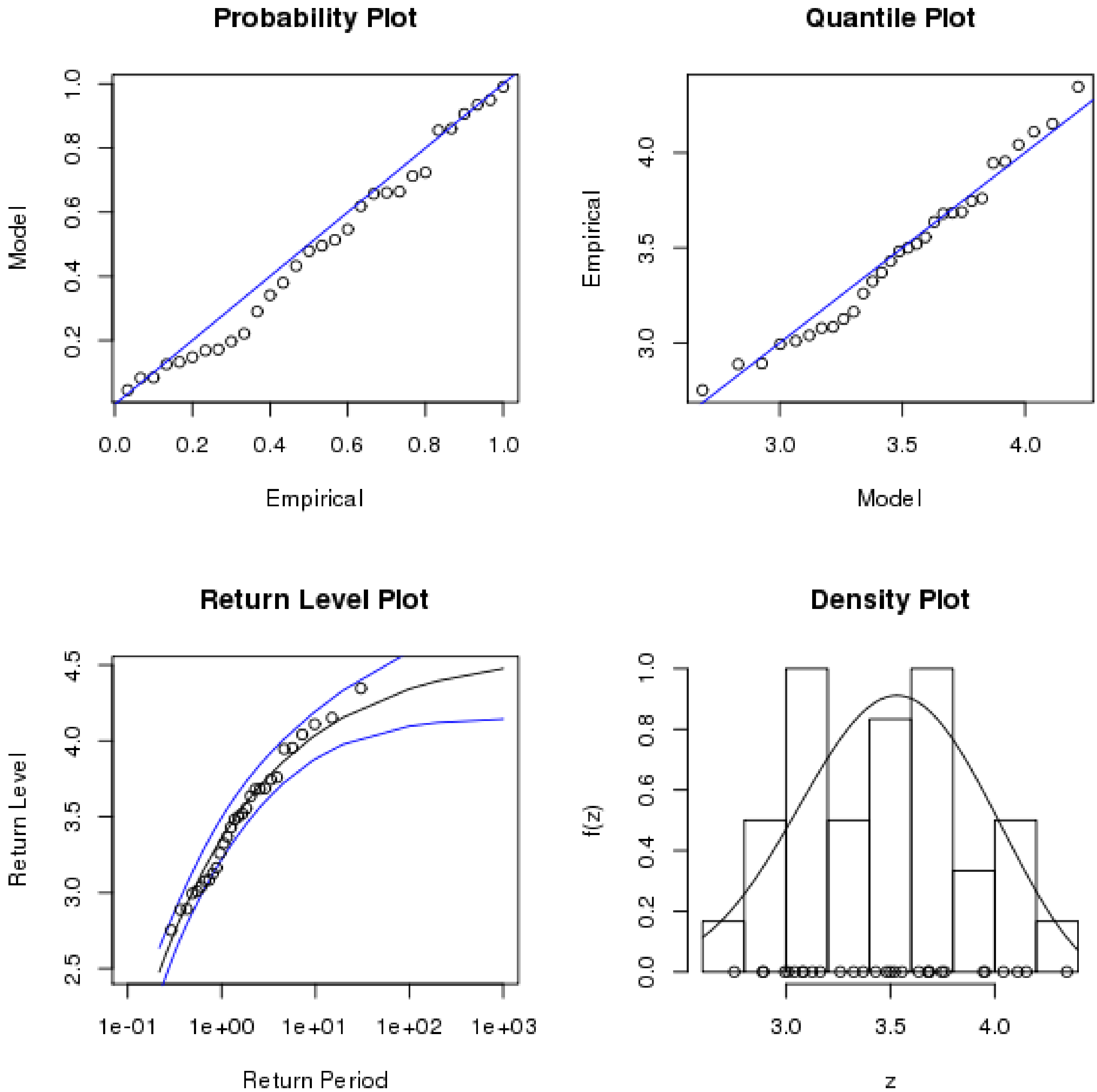


Figure 20. Liverpool Bay r-largest statistics for present-day 30-year time-slice (1970-1999).

This work on the combined effect of drivers has allowed significant advances in assigning confidence intervals to model projections and all this based on the best available scientific knowledge as for instance illustrated in the estimation of extremes that has been just presented. This has led naturally to our transfer work for stakeholders, policy makers and decision makers.

The policy context is cantered on the fact that coasts across the planet are facing both increasing population and socio-economic activities and, simultaneously, a reduction of available space and resources. This reduction will be aggravated by climatic factors, such as sea level rise, changes in storminess decreasing freshwater availability and intrusion of saline water. Coastal conflicts are already at dangerous levels in many coastal tracts and are expected to increase under future climates. There is a wide set of national and international legislation addressing the various sectors affected by these conflicts: resources (Common Fisheries Policy and Common Agricultural Policy); natural values (Birds and Habitat Directives, Biodiversity Strategy 2020); socio-economic values;

flooding (Water Framework Directive); and integrated planning (framework for Integrated Coastal Zone Management).

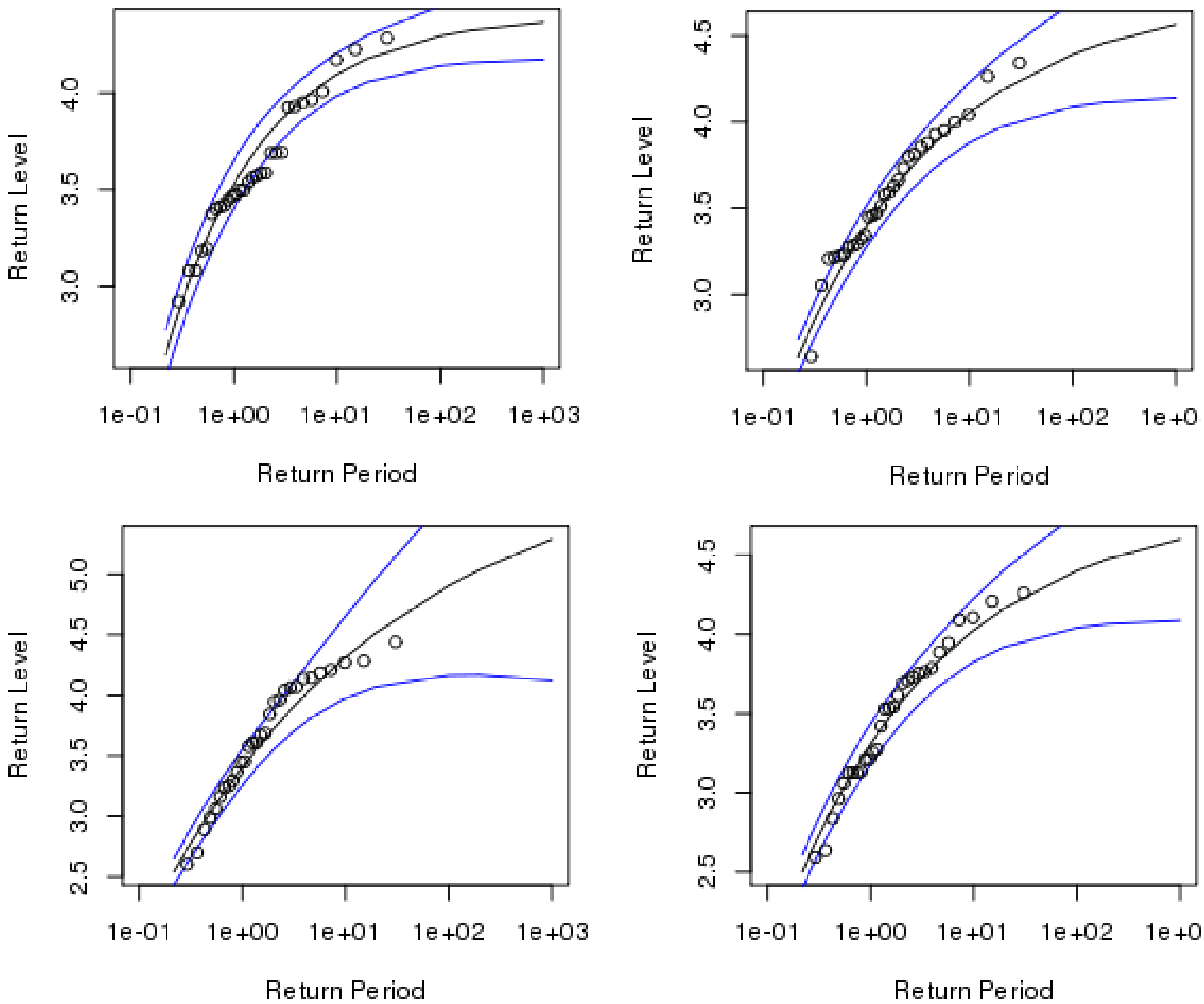


Figure 21. Liverpool Bay return levels for future 30-year time-slices; top row, mid-century; bottom row end-century; left column RCP4.5, right column 8.5.

The coastal fringe is a narrow border area between land and sea, usually considered as public domain, with management responsibilities in the hands of Member States (e. g. public domain), Regional governments (e.g. land use planning), municipalities (e.g. local infrastructures and uses) and global level institutions (e.g. coastal sustainability worldwide). These management challenges span a wide range of sectors: environment, agriculture and fisheries, transport and tourism, with decision centres located in different departments and administrative levels.

Policy goals commonly deal with the maintenance of coastal status under present conditions, due to the difficulty of considering long term planning or investing. This is also because present conditions provide a natural reference state against which to compare future plans.

Within this context the foreground work has been related to a) vulnerability, b) impacts and c) adaptation as summarized in the following paragraphs.

Vulnerability

Coastal zones are vulnerable for different reasons. These are described in Table 1, following a spatial layer approach (base defined by eco-geo-physical features, network defined by infrastructure and occupation defined by inhabitants, as used in RISES-AM-).

Table 1: Schematization of a structured approach to vulnerability based on layers.

Spatial layer	Nature of vulnerability	Geographical examples	Example
Base	Geomorphology and Geography Low-lying (open or deltaic), small or remote islands, mangrove forest	Ganges-Brahmaputra Meghna (Bangladesh/India), Maldives, Netherlands	
Network	Land uses Nuclear power plants, coastal roads, railways, ports	Dawlish Warren railway (UK), Flamanville nuclear power plant (France), Hamburg port (Germany)	
Occupation	Inhabitants Use of land and distance/flexibility to sea dynamics	High density cities (Barcelona, Istanbul), lower density agriculture land (ubiquitous).	

Vulnerability remains a combination of these spatial layers, so it has geographical and temporal variation. Coastal planning and management (measures of human intervention) can reduce vulnerability. For example, coastal protection through the network (e.g. sea dikes) or occupation layer (flood warning systems) can reduce vulnerability of the base layer, such as seen in the Netherlands, a case study in RISES-AM-.

Compared with other global regions, European coasts are less vulnerable, mostly as they have a high adaptive capacity and coastal management measures, such as dikes, groynes, monitoring and warning systems. Although there are exceptions, countries in north-west Europe are generally the more aware about the risks of sea-level than those in the south-east Europe. This may be because of management approaches, but also that sea-level rise is perceived as less of a threat. Over the last decade, awareness to sea-level rise and action to manage or mitigate has substantially improved throughout Europe.

Low lying coasts and urban (artificial) beaches are among the most vulnerable. Extremes cases of exposure may be illustrated by the coastal region of Bangladesh where relative sea level rise (RSLR) including subsidence of 1m to 1.5m (likely at decadal scale) may affect 6 to 8 million people, respectively.

Reducing vulnerability through coastal management often happens with new infrastructure and is thus undertaken on cycles coinciding with the design life of the infrastructure. For instance, sea-level rise and associated storm surges have been considered in the Danish Metro system, by rising infrastructure 0.25m above the existing level. However, many towns and villages remain vulnerable as they have not been planned for sea-level rise and wider coastal change. Inevitably, coastal protection measures follow economic activity and areas of high population density. Cities and large towns therefore are highly likely to be offered protection, but many small areas of population or villages will remain vulnerable, unless their protection offers a greater good for society. What is becoming increasingly apparent is that coastal management (including the type of management practiced) remains a matter of choice, responding to local needs, politics and finances.

Impacts

The large thermal inertia of the oceans will result in a continued sea-level rise due to global warming that cannot be entirely avoided through climate change mitigation. This means that sea levels will continue to rise well beyond 2100 due to global warming, until reaching equilibrium conditions, even if greenhouse concentrations are hypothetically stabilised at today's level, or under a future world of a 1.5°C rise and stabilisation in temperature. Hence, climate stabilisation leads to a stable (rather than accelerating) rise in sea level. This has been termed the commitment to sea-level rise. Under unmitigated climate change, a 1.5 to 6.6 m rise could be expected by 2500. As with the 21st century estimates, the uncertainties are large. Under present levels of global warming, , it is suggested that we are already committed to 1.3m future sea-level rise above current levels due to cumulative greenhouse gas emissions. Hence a combination of mitigation and adaptation are required for coastal zones: mitigation to reduce rises in sea level to manageable levels and adaptation for the residual rise.

Projections of coastal hazard showed that for many European regions, the increase in extreme storm surge level (SSL) can be locally of the same magnitude as the expected sea level rise, especially under a worst case scenario such as the RCP8.5 concentration pathway. A large part of the Northern Europe coastline will, thus, experience a significant increase in the impact due to storm surge extremes. This implies a significant increase in the expected annual damage from coastal flooding. The expected number of people forced to relocate or affected by coastal flooding in Europe is projected to increase by almost an order of magnitude (compared to present) under RCP 8.5.

Adaptation

RISES-AM analysed technological, economic, financial and social (conflict) barriers to coastal adaptation under high-end sea-level rise in a range of case studies at different scales including Croatia, the Catalan Coast, the Danube delta, Hamburg, Ho Chi Min City, Liverpool, Portugal, The Maldives and The Netherlands. The research found that barriers to coastal adaptation lie more in the socio-economic realm than in the technical realm. Across all cases, adaptation was found to be technologically possible, but costly and leading to coastal zones looking very different from today. Generally, adaptation pays off in pure monetary terms for urban, densely populated regions. Very high benefit-cost ratios were found for protecting cities as well as for nourishing beaches used for tourism, as illustrated by sectors of the Catalan coast in the Spanish Mediterranean, another case considered in RISES-AM-. This suggests that these two measures may become wide-spread in the future for such coastal archetypes. In rural and poorer areas, however, protection measures generally have benefit-cost ratios smaller than one, which suggests that it will be difficult to mobilise the required resources for protection if those regions do not receive transfers from elsewhere.

Even when coastal protection is attractive in monetary terms, mobilising the financial resources for this may be difficult due to high up-front investments paired with long-term stochastic returns on such investment. Taken together, these findings highlight the importance to consider the equity dimension of coastal adaptation and we are likely to see bifurcating coastal futures with rich, urban highly engineered and protected areas on the one hand and poorer rural areas struggling to maintain livelihoods and eventually retreating from the coast on the other hand. Irrespective of the technological, economic and financial situation, it was also found that most coastal adaptation options involve significant social conflicts of interest due to the diversity in coastal stakeholders, activities and policy goals (e.g., flood security, tourism, nature protection, fisheries, shipping and ports). The conclusion was that addressing financial, equity and social conflict issues would be a key factor for advancing coastal adaptation.

The reduction of climate impacts due to relative sea level rise (including storm surges) and increasing pressure of uses in coastal areas may result in the need to rank coastal sectors and establish priorities. A universal "hold the line" coastal management or protection policy in the face of increasing climate pressures can be unsustainable and in that ranking there will appear sectors with a) managed realignment, b) no active interventions and c) working with Nature solutions.

For coastal areas where there is no "room" for coastal dynamics (or for river dynamics) it will be necessary to upgrade coastal defence systems in the most adaptive and flexible manner to cope with uncertain future physical and socio-economic conditions. In low populated areas more resilience-oriented measures can provide an efficient alternative. In all cases a smart planning of land uses and coastal interventions will lead to lowered risk levels for coastal population and activities and a more sustainable coastal environment under future climates.

The third year of RISES-AM-

In WP4 the specific aims are the technological limits to adaptation that arise when there are no technological (Klein et al., 2001) or structural (RISES deliverable D1.1) measures available to effectively reduce the impacts of climate change. The RISES deliverable 1.1 defines structural adaptation measures as any biogeophysical measure to reduce or avoid possible impacts of climate changes and sea-level rise. This includes both hard engineering as well as soft and 'green' measures such as sand nourishment or ecosystem-based measures. In RISES, we have assessed these technological limits through modelling impacts under additional adaptation measures and comparing this to impacts under the business as usual (BaU) baseline (as assessed in Deliverable 3.1). If there is no option available that effectively reduces impacts, this constitutes a technological limit. Technological limits relate to the policy criterion of effectiveness as specified in Deliverable 1.2.

It is important to note that it is impossible to provide a single measure of effectiveness of options and hence of technological limits across diverse case studies, as investigated in RISES. An important aspect of this deliverable is thus to motivate and discuss what effectiveness and technological limits means in the specific case study. Furthermore, technological limits and effectiveness must always be evaluated against specific indicators and the choice of these indicators is case specific and normative. For example, building a dike may be very effective in terms of the indicator "reduced flood damage", but at the same time be very ineffective in terms of the indicators "aesthetically pleasing" or "enhanced ecological value".

The second specific aim are the economic barriers that arise if the implementation and maintenance of an option is more costly than the impacts avoided through the option. Note that this definition excludes the consideration if financial resources for implementation and maintenance are actually available, which will be treated under financial barriers further below. Economic barriers thus relate to the policy criterion of benefit-cost ratio as specified in Deliverable 1.2. These barriers arise if an adaptation option has a benefit-cost ratio (i.e. benefits divided by the cost) of below 1. For example, if building a dike costs more than the flood damage the dikes is expected to reduce during its life span, this constitutes an economic barrier. The presence of economic barriers means the actors responsible for adaptation (e.g., the local government, a community, etc.) have a net monetary loss when implementing adaptation as compared to not implementing adaptation. On the contrary, if the benefit-cost ratio of adaptation options is above 1, the responsible actor has a net gain, which provides a strong argument for implementing these options. Economic barriers may also be described through the net present values (NPV) of the available options. If the BaU option has a lower NPV than all other adaptation options, then adaptation is not economically attractive, and an economic barrier to adaptation therefore exists.

A general issue with evaluating benefit-cost ratios or NPV of options is that while the monetary costs of options can usually be estimated in a straight forward manner, it is often difficult to assess the benefits (i.e. the avoided impacts) in monetary terms. If impacts can-not be monetized, we will use the cost-effectiveness ratio (= avoided-impact/cost of option) to compare the different options assessed. See Section 4.3 “cost” of Deliverable D1.2.

Associated to economic barriers are **financial barriers**. Financial barriers arise if there are not sufficient financial resources available for financing the implementation of effective adaptation options. This may be the case irrespective of the presence of economic barrier. For example, protecting coastal cities is generally cost-efficient on the long run (Hallegatte et al., 2013), but may require substantial investments. Because of the benefits of those investments lying in the far future, the required resources may be difficult or impossible to mobilize due to a number of reasons including: contained public budgets, unavailability of market finance (because the investment does not match risk-return profiles of investors) or development aid or climate funds can not be accessed.

Finally we have in this work package the aim of institutional barriers that arise whenever stakeholders' conflicting interest impede or exacerbate adaptation (Biesbroek et al., 2013; Bisaro and Hinkel, 2016; Eisenack et al., 2014). Conflicts of interests in coastal adaptation are widely documented (Wong et al., 2014) and overcoming these has been found to be one of the most difficult challenges for coastal adaptation (Moser et al., 2012). Conflicts may arise both within as well as across levels of governance. Institutional barriers relate to the policy criterion of governance complexity as specified in Deliverable 1.2.

Uncertain changes in climate, technological, socio-economic and political situations, and the dynamic interaction among these changes, and between these changes and interventions, pose a challenge to planners and decision-makers. Due to these uncertainties, there is a risk of making an inappropriate decision (too little, too much, too soon, or too late), especially when planning and decisions have to be made at the long-term. The challenge is to develop robust and or adaptive plans to be successful under a range of possible future or flexible to adapt to changing conditions.

An approach to develop adaptive plans is the Dynamic Adaptive Pathways Planning approach (DAPP) (Haasnoot et al. 2013), where a plan is conceptualized as a series of actions over time (pathways). The essence is the proactive planning for flexible adaptation over time, in response to how the future actually unfolds. The DAPP approach starts from the premise that policies/decisions have a design life and might fail as the operating conditions change (Kwadijk et al., 2010). Once actions fail, additional or other actions are needed to achieve objectives, and a series of pathways emerge; at predetermined trigger points the course can change while still achieving the objectives. By exploring different pathways and considering path-dependency of actions, an adaptive plan can be designed, that includes short term actions and long term options. The plan is monitored for signals that indicate when the next step of a pathway should be implemented or whether reassessment of the plan is needed. Within this context, a pathway consists of a concatenation of policy actions, where a new policy action is activated once its predecessor is no longer able to meet the definition of success.

Previous studies and engineering experience tell us that portfolios of coastal adaptation measures are most effective in practice than single options. In this sense, based on results obtained in previous research tasks within the project (see e.g. deliverables D3.1 and D4.1), impacts due to multiple forms of adaptation have been analyzed. The objective is to create sets of adaptation pathways for each case study to identify the more effective ones as well as potential local tipping points. To this end, a dialogue with local (case study) stakeholders has been established to catch local views and settings which can be policy relevant for conditioning and/or selecting final options.

Here we shall only present the more mature cases, referring to the Deliverables (4.1 and 4.2) for a more in-depth treatment.

a) The Catalan coast

Adaptation and selection of preferred pathways

BaU stands for the business as usual situation in terms of coastal management, that without considering any additional increase in SLR has determined the existence of significant problems in many locations along the coast related to background erosion and storm-induced damages. Due to this, different coastal protection measures such as beach nourishment (more than 25 Mm3 of sand have been used for nourishing Catalan beaches during the last 30 years) and coastal structures have been implemented during the last decades.

The proposed adaptation pathway, based on the preferences of stakeholders, responsible Administrations and technical efficiency, appears in figure 22. Here we show as absolute horizontal axis the mean sea-level (termed sea-level rise because present level is set to zero). The time scale varies depending on the selected scenario, in the sense that for optimistic green-house concentrations (lower line), the mean sea-level by 2100 will be about 0.6m above present level. For an intermediate scenario the mean sea-level by 2100 will be close to 0.8m above present levels. For a high-end scenario (upper line) the mean sea-level by 2100 will be approximately 1.8m above present level.

As stated in deliverable D4.1, the selected adaptation pathway for the Catalan coast is a strategy where different adaptation measures are combined (AA4C). It includes: (i) beach nourishment to compensate for SLR-induced retreat in those areas without accommodations pace putting emphasis on those locations of high tourism interest and beaches close to populated areas which are important for leisure and/or providing protection to the coast; (ii) managed retreat in areas with accommodation space; (iii) artificial dunes in areas with accommodation space and a hinterland that requires protection against inundation and (iv) additional works to protect the hinterland in areas without accommodation space (e.g. Maresme coastal railway).

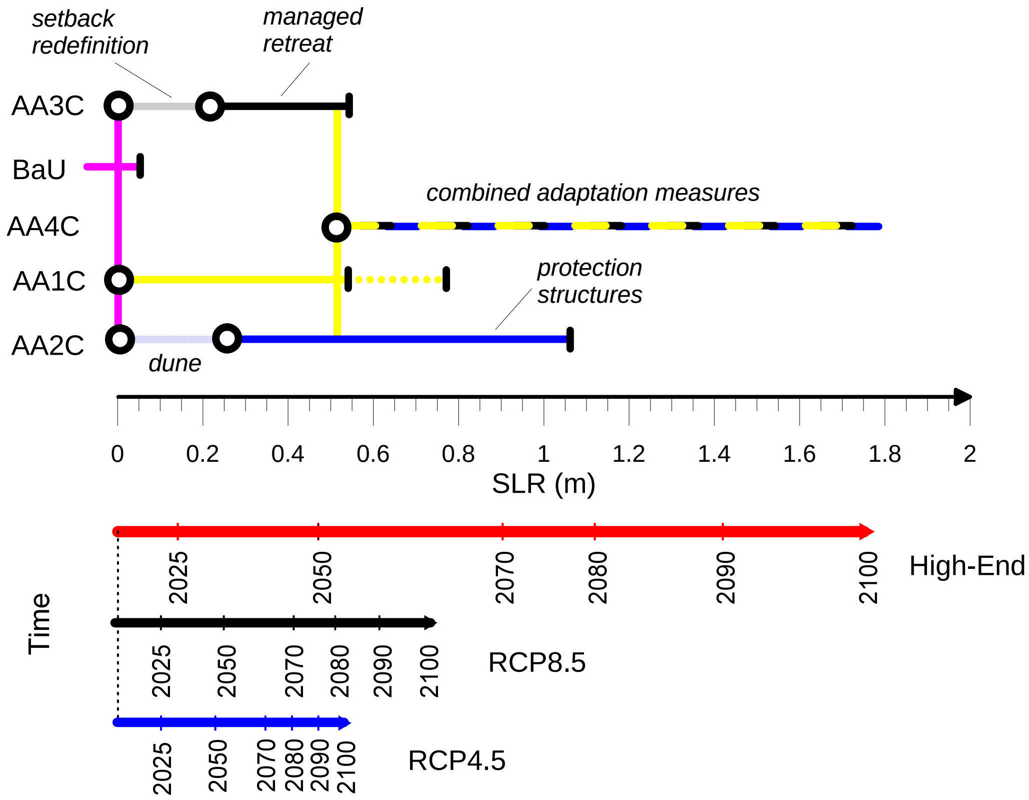


Figure 22. Proposed adaptation pathway for the Catalan coast. Dotted lines represent uncertainty in tipping point, depending on the available sediment stock. Vertical black lines represent adaptation tipping points. Circles represent switches to other measures.

b) The Ebro Delta

Adaptation pathways

New dikes to be built along the bays have been determined by the administration to be 1.5 m high. This height will be sufficient for most of the potential SLR scenarios except for the RCP 8.5 Upper limit (figures 23 and 24) which is predicted to be 1.8 m by 2100. In this worst case scenario, the adaptation pathway can be continued by either elevating the dikes (upgrade to 2.5 m) or by rising grounds with river sediments or from other sources (or a combination of both). Yet, if the raising grounds pathway is chosen to reach the 2100 tipping point after the failure of initial dikes, it would be highly recommendable that sediments are progressively supplied along time in order to facilitate the works and avoid possible problems associated to the delivery of large inputs by the end of the century, since this option may not be feasible.

Selection of preferred adaptation pathways

At present, the project for constructing 1.5 m height dikes along the two Ebro Delta bays is ready to be implemented as soon as the administration allocate the necessary funding for starting the works (which have been delayed due to the economic crisis in Spain). Therefore, this has already been the first adaptation pathway selected by the case study stakeholders with a high consensus. This adaptation pathway will be sufficient for most of the future RCP scenarios, and will only need an upgrade (up to 2.5 m height) under the 8.5 Upper SLR.

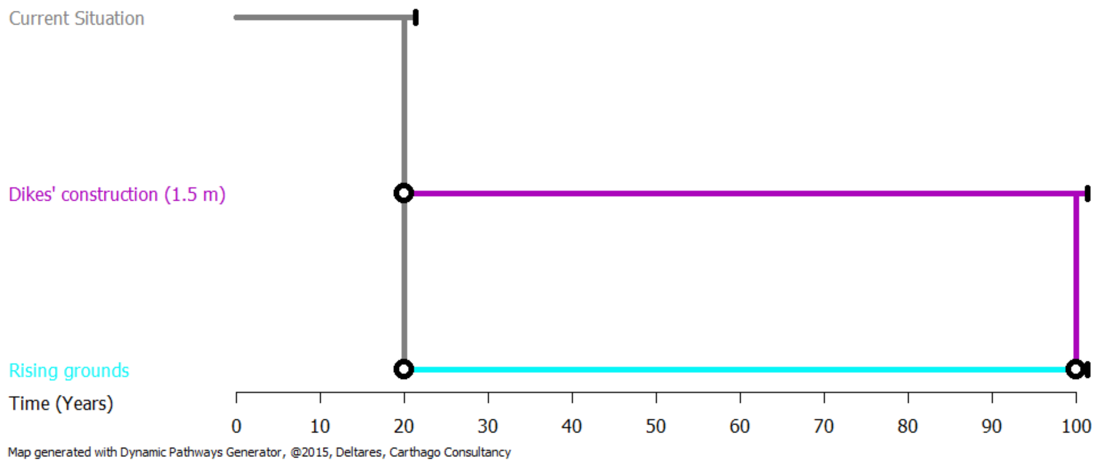


Figure 23. Possible adaptation pathway for mean and high RCP 4.5 and mean 8.5 SLR.

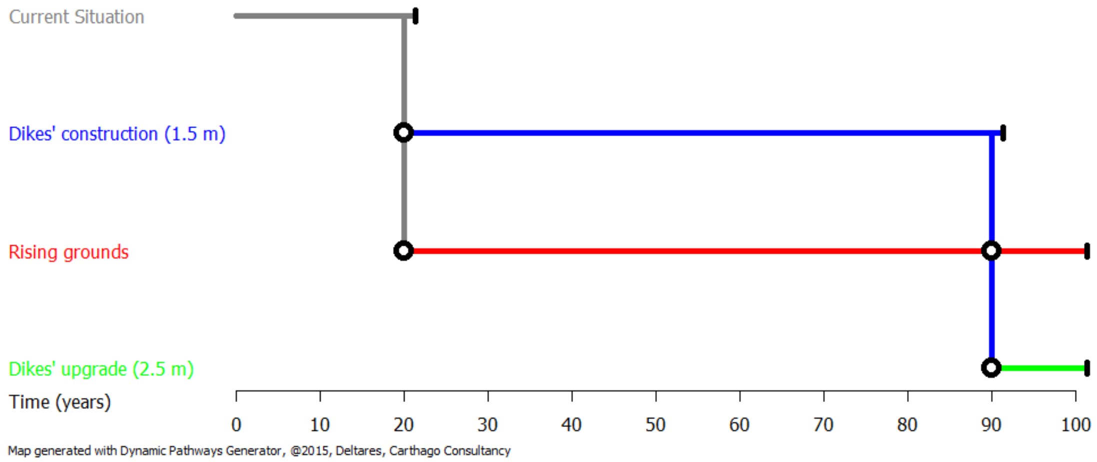


Figure 24. Possible adaptation pathway for high RCP 8.5.

However, although dike height and forced drainage can be enough to avoid rice field inundation, rice productivity will be affected trough underground salt intrusion, unless land is elevated with the supply of sediments. Therefore, a second adaptation measure such as rising grounds would be very beneficial for improving soil salinity, rice production, and energy costs of water pumping, and are already being implemented by some rice farmers at the small spatial scale of their own property. At the large spatial scale of the whole Ebro Delta, our estimates for sediment requirements range from 1 to 7 million tons per year, an amount that, in the lower range, is fully available within lower Ebro River reservoirs and could be mobilized by a sediment bypass system (a feasibility study is available, with estimates of economic costs; see Rovira and Ibáñez 2007); but in the case of high end scenarios fluvial sediment recovery may not be sufficient to cope with relative sea level rise. Other additional sources of sediment have been identified, such as that generated by the construction of infrastructure, water treatment plants, dredging, among others. Therefore, our view is that both adaptation pathways should be implemented simultaneously, regardless of the RCP scenario. If the worst case arise (8.5 Upper SLR), then either a dike upgrade or further land elevation or both can be considered.

Other potential pathway that could help to mitigate the local effects of SLR in soil salinity and rice production is the segmentation of the irrigation and drainage network, isolating the low-lying rice drainage system from the rice fields above the sea level that can still be drained by gravity. This will reduce the necessary pumping of freshwater and concentrate the costs in the most affected rice fields adjacent to bays and coasts until they are unsustainable and therefore abandoned or transformed into wetlands or other land uses.

c) The Elbe estuary and the port of Hamburg

Adaptation and selection of preferred pathways

As an example for Elbe estuary and the port of Hamburg the introduction of two retention areas for sea level rise of up to 2m a possible adaptation pathway scheme was constructed. BAU stands for business as usual, maintenance but no enhancement of existing flood defences. AA1 indicates the adaptation option by opening of the seaward retention area A, while AA2 stands for the implementation of the landward retention area B (figure 25). AA3 is the combination of AA1 and AA2. Crest level increase means heightening and/or reconstruction of dykes and seawalls.

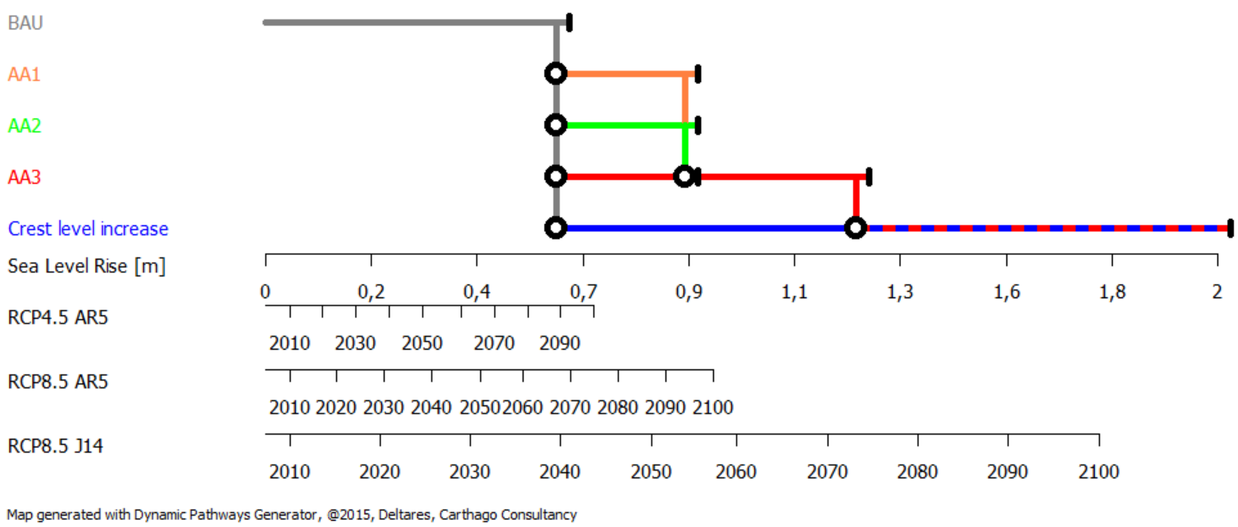


Figure 25. A possible adaptation pathway for the Elbe estuary and Hamburg.

Depending on the climate projection a certain SLR will occur a different times in the future. In the lower part of Figure 25 the respective time axis are given for climate projections RCP4.5 AR5, RCP8.8 AR5, and RCP8.5 J14, which have also been investigated in Deliverable 4.1.

After discussions with stakeholders involved in or responsible for flood protection in Hamburg (Hamburg Port Authority, Landesbetrieb Strassen, Brücken, Gewässer Hamburg) the following tipping points were chosen dependent on the peak water level at the gauge St. Pauli, located in the center of the port. The design level for flood protection at this site is 8.10 m, but the actual height in 2016 is only 7.30 m. Additional measures (AA1 to AA3 or crest level increase) would be considered for water levels greater than 6.70m, (MSRL = 0.60 m). The reasoning behind this value is that the highest hitherto observed water level at St. Pauli was 6.50m during the 1976 storm surge. For peak water levels greater than 7 m (MSRL = 0.90 m) the only remaining adaptation strategies are AA3 or an increase in dike crest level. Should peak water levels exceed the current crest level at St.Pauli of 7.30m (MSLR = 1.20 m) only a further increase in crest level (heightening of seawalls and dikes) is feasible.

The authorities responsible for flood protection remain sceptical about the effectiveness of the retention areas for general storm surges, since their effect was only assessed for the 2013 type of storm surge. From the analysis of Albers (2015), the reduction of the peak surge height in Hamburg is strongly dependent on the timing of the filling of the retention areas, that implies the dike height. People living in the vicinity of the retention areas are strongly opposed to this adaptation option (see Deliverable 4.1).

d) Hulhumalé, Maldives.

Adaptation and selection of preferred pathways

In Deliverable 4.1, the following adaptation options were assessed for Hulhumalé:

- Flood warnings
- Beach nourishment
- Eastern side sea wall
- Eastern side sea wall and beach nourishment
- Sea wall around island and land raising
- Land raising

In constructing pathways, three further options were assessed:

- Monitoring
- Local level protection
- Abandonment

These pathways were primarily constructed with a qualitative assessment of how each could affect flood impacts (the flooding was modelled with consideration of land area and building plots affected by different scenarios of sea level). There was a simple assessment of how sea walls, beach nourishment/loss, and reef loss could affect overtopping (and subsequent flood impacts) on eastern Hulhumalé. This was by adjusting the representative (of east Hulhumalé) bathymetry-topography profile in the 1D overtopping model.

The pathway indicates, that from modelled results only, that the current policy of maintaining the defences at present level would remain appropriate for approximately 0.4m to 0.7m of sea-level rise, where thereafter nuisance flooding may result. This range is indicative of the uncertainty of when the onset of flooding could occur mainly due to wave height and reef representation in the model. At this point, local level protection may also become suitable, depending on how often wave events occur. Also, if local level responses include manually operated elements (e.g. gates, sand-bags) early warning systems would be complementary to this. With continued sea-level rise, monitoring the conditions of the defence becomes increasingly important, and could result in further beach nourishment and dike construction. In the absence of land raising (which could in principle be introduced at any time, but is easier before buildings are constructed), abandonment may occur with sea-level rise in excess of 2m, since drainage would be increasingly challenging, dikes would be more frequently overtopped and beach levels through nourishment potentially unsustainable, leading o an increase in flood risk.

The pathway was discussed with the Maldivian Ministry of Environment and Energy. The Maldives government liked the idea of linking different adaptation strategies together but recognise that a pathway cannot take place due to decisions made on electoral and planning timescales. Planning timescales tend to take place on a maximum of a 20-30 year timescale, so adaptation pathways remain abstract for them. Their long-term pathway preference is to maintain the quality of life and environment through local level protection, beach nourishment, with abandonment being the last resort.

e) Ho Chi Minh City

Adaptation and selection of preferred pathways

For HCMC, we have run the modeling exclusively under two specific extents of sea level rise (i.e., 49 and 180 cm), we thus cannot directly ascertain the amount of sea level rise (and in a way, the year) by which adaptation measures cease to satisfy the policy requirements. Therefore, to locate tipping points on the sea level rise axis, we interpolate our results between the 49 and 180 cm marks. Because this practice leads to even further uncertainty as to the location of the break-point in adaptation performance, the tipping points should be taken as semi-quantitative estimates only meant to provide a first-order indication.

To enable the generation of adaptation pathways, we distil from the policy objectives quantitative performance thresholds that indicate when adaptation measures cease to perform satisfactorily towards the objectives. We define such thresholds as the inflexion point at which the performance decreases most steeply.

The criteria that we chose to better reflect the chief policy objective of reducing floods and flood impacts are: 1) the economic risk, with as indicator the expected annual economic damage; 2) the population affected, with indicator the annual count of people flooded by at least 0.1 m and 1 m, and 3) the city area flooded, indicated in surface units.

In our case study, we found that inflexion points, and therefore thresholds and tipping points, roughly coincide for the three selected criteria. Thus, for the sake of simplicity, and because the measure of retrofitting building does not imply changes in the population affected and in the city area flooded, we adopt the tipping points resulting from the criterion of economic risk.

As can be seen in figure 26, the adaptation pathways for Ho Chi Minh City start with several measures that are both feasible and highly effective in tackling the problem of flooding. On the one hand structural measures will entirely negate flooding of entire parts of the city: building a ring dike, or elevating the area’s most at risk. On the other hand, building-scale measures, like retrofitting, can mitigate damage when flooding does occur. A ring dike of only 2 m will likely lose its protective function around 1.1 m sea level rise, whereas elevation will reach its tipping point at 1.4 m. Similarly, retrofitting up to 1 m will cease to be effective, but at a later stage, whereas a higher ring dike of 3 m and retrofitting up to 2 m seem able to withstand the worst scenario of sea level rise for this century.
Creating retention areas both within the urban area and upstream (to contain the compounded effect of river and coastal floods), and managing the river discharges via operation of the dams upstream seem plausible measures, but we have not addressed them in our study.

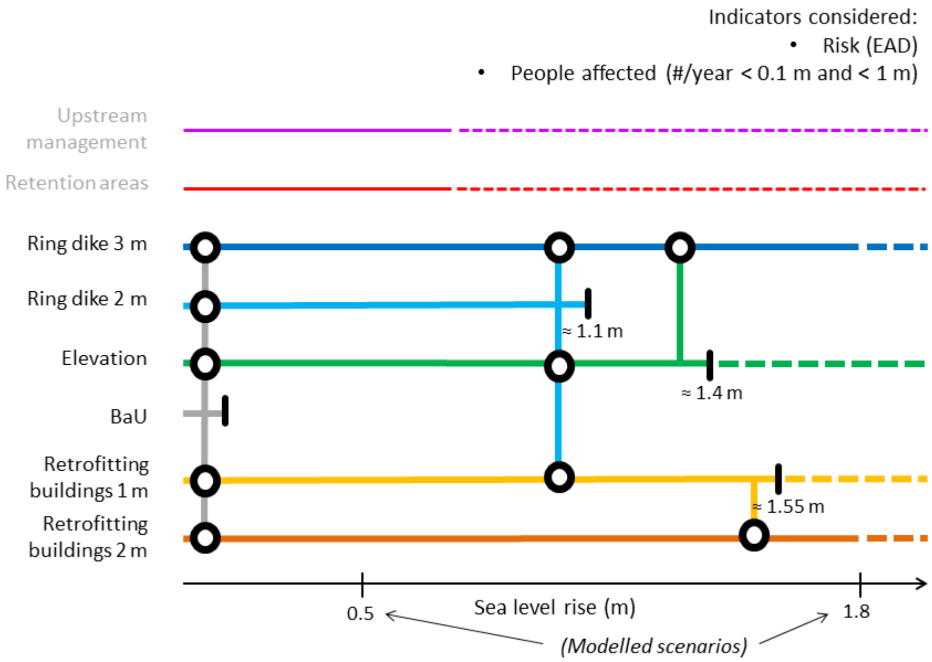


Figure 26. Proposed adaptation pathway for Ho Chi Minh city. Dashed lines represent effectiveness uncertainty, meaning that the measure may be effective under those conditions depending on the sea level rise scenario. Circles represent switches to other measures, vertical black lines represent adaptation tipping points.

f) Sandy strategies for low-lying coasts

Adaptation and selection of preferred pathways

The proposed adaptation pathways are (see figures 27 and 28):

- Holland:
  - Given abundant sand resources in the North Sea, stepwise increase in the amount of nourishment required provides both a flexible and robust long term strategy for the Dutch coast.
  - No need to go to larger nourishments until needed.
  - No need to switch back to old expensive policy of continually raising dykes.
  - Note that sand nourishment volume increases could change in smaller (more frequent) or larger (less frequent) increments.

- Aveiro:
  - Depending on economic value of the protected coast, local nourishment at hard structure locations can also occur in a stepwise fashion for the coming 1-2 centuries.
    - Flexible approach.
    - No need to go to larger nourishments until needed.
    - Note increased in sand nourishment volume could change in smaller (more frequent) or larger (less frequent) increments.

- Retreat always remains the transformative robust option for all areas, to be transitioned to when it becomes no longer economically (or socially) viable to sustain nourishment activities at specific locations.

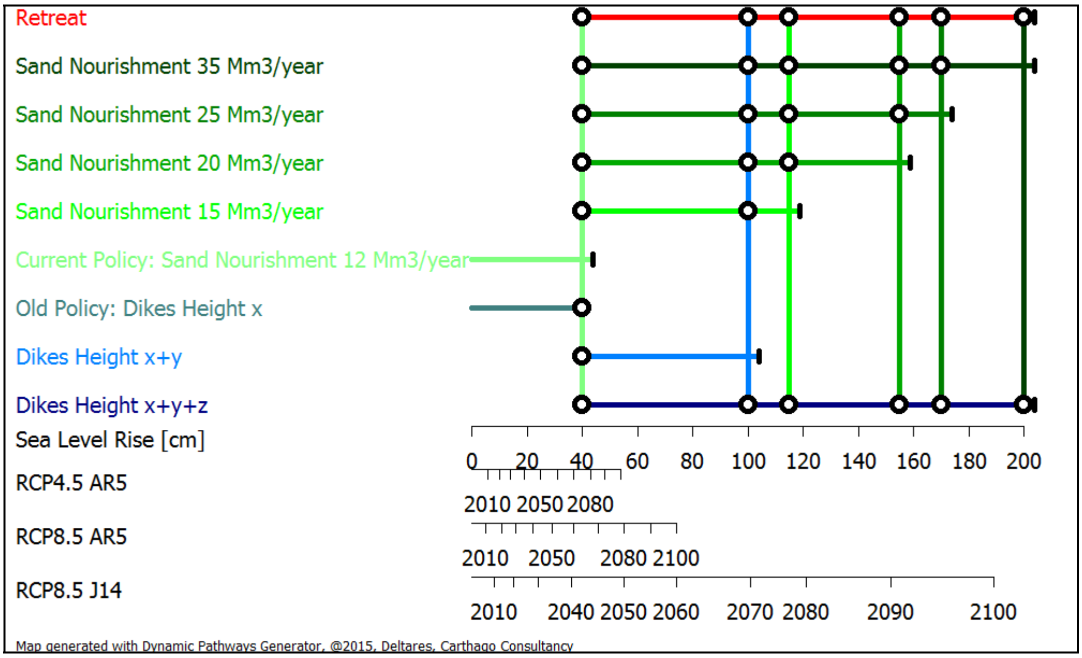


Figure 27. Potential adaptation pathways considered for the Holland coast. Preferred pathway is highlighted, whilst non-preferred pathways are greyed out.

Political institutions play a vital role in developing disaster mitigation and adaptation capacities in an economy. As Tol and Leek (1999) point out, defensive investment needs sacrifice in opportunities because protection does not necessarily mean direct economic development. Nevertheless, if the political regime has the will and ability to duly identify potential impediments to the economic development and welfare of the society, and take corrective measures promptly, it is not difficult for any country to achieve prosperity. Over the past 150 years the Netherlands could easily surpass Bangladesh to achieve a remarkable economic development as a result of good governance, desire and focus of political institutions to successfully manage continuous severe floods which was a devastating common problem to both the countries due to their lower altitude in location. So, it is apparent that political institutions substantially contribute in deciding the effects of natural disasters on any economic indicator. In this context, political institutional variable enters the regression. In the opinion of Plumper and Neumayer (2010), polity2 variable from the Polity IV Project is the most appropriate and popular measure of a country's political regime. In this light, political institutional data in the current analysis are taken from the Polity IV Project and polity2 which indicates openness of a country's political institutions is used as the political institutional variable. In Polity IV database, the democracy indicator (democ) which varies in an additive eleven-point scale (0-10) represents the institutionalized democracy of a state. It is dependent on 3 elements which cover the democratic rights of citizens and the necessary constraints on the executive in exercising its powers. Similarly, the institutionalized autocracy indicator (autoc) is also an additive eleven-point scale (0-10) which measures authoritarian regime of a country. These two scales democ and autoc do not share any contributor categories in common.

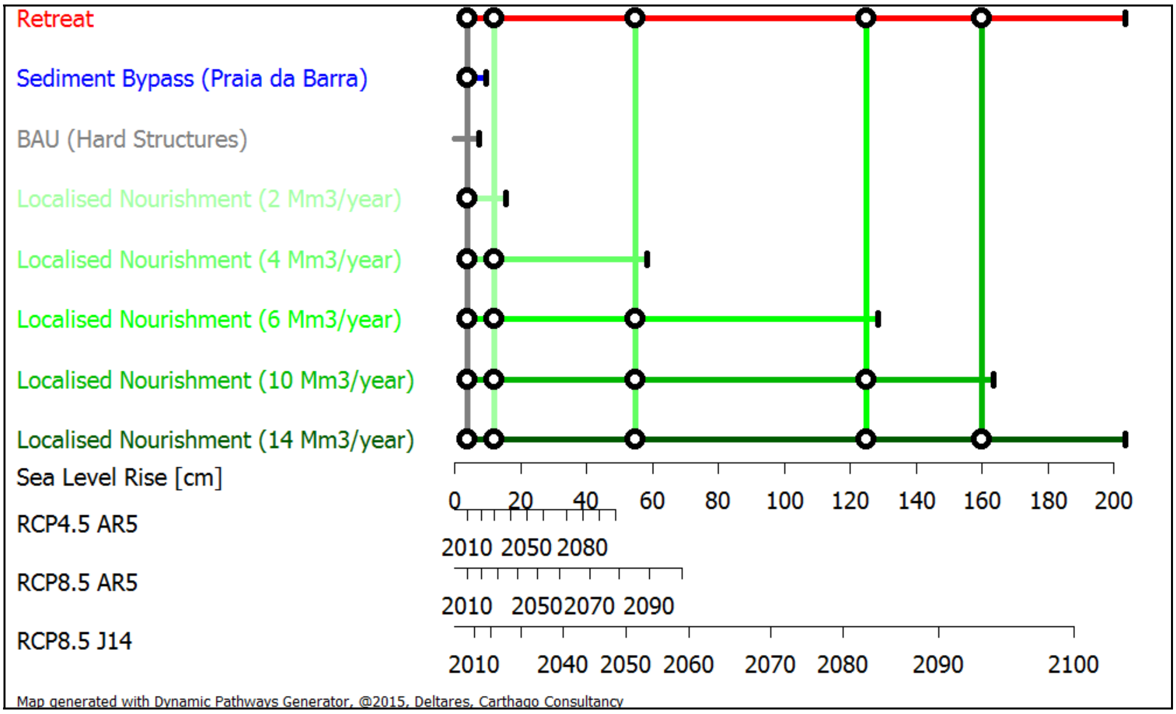


Figure 28. Potential adaptation pathways considered for the Aveiro coast. Preferred pathways are highlighted, whilst non-preferred pathways are greyed out.

We employ a panel regression estimator with country and year fixed effects as the main estimation strategy in our analysis. Fixed effects estimator is chosen since country and year fixed effects control for time-invariant country heterogeneity and time-variant shocks that simultaneously affect all the countries, respectively. As such, this approach reduces any potential endogeneity issue. Further, results of the Hausman tests carried out show that fixed effects estimator is preferred to a random effects estimator. Furthermore, as country-fixed effects capture variation of country specific effects within a country which do not change over time, fixed effects also arrest any selection biases which may arise due to over representation of poor countries in the disaster data distribution as a result of their higher vulnerability to disasters (McDermott et al, 2014). Year fixed effects capture the effects of time- varying factors common to all countries such as world business cycle, global technological advancement and world-wide economic and financial crises. In terms of the results of 'Testparm' test, time-fixed effects are needed to be included in the regression. Errors are clustered at country-level as natural disasters are not evenly distributed across countries and also to obtain robust standard errors as a remedial measure for heteroscedasticity. Given the constraints on availability and reliability of data, the analysis is restricted to the time period 1979 – 2011. The baseline model covers 147countries.

To show our original results are not driven by outliers at the lower or upper bounds of the credit and disaster data distribution, we repeat our regressions removing alternatively and jointly substantial amount of observations at the lower and upper bounds in the credit distribution and upper bound of the disaster distribution.

Robustness of results in the baseline model could be checked by adding more control variables that represent macro stability, magnitude of the government spending, foreign links, etc. which can be expected to have any influence on per capita credit, the dependent variable and independent variables in the model. By doing this we can overcome any omitted variable biases the baseline model suffers from, which are not taken care of by already included controls and, country and year fixed effects. The inclusion of additional control variables is done at different stages. Firstly, we add main control variables one by one to the baseline model and subsequent to each addition, an interaction term of that control with the disaster variable is included so that their impact on the baseline model can be observed clearly. These main control variables are inflation which control for macroeconomic stability of the country, government expenditure as a percentage of GDP and the trade share which reflects the degree of trade openness. Secondly, we control for other factors which seem to either stimulate or hinder private credit in connection with disasters, by using simple variant models of the baseline specification. Accordingly, we control for financial sector regulation using CPIA (Country Policy and Institutional Assessment) financial sector rating, non-life insurance premia volume as a share of GDP, lending interest rate, share of resource rent (including rent received on coal, oil gas, iron ore and minerals such as gold, silver, copper, etc. but not including rent on forestry) within the GDP, and share of forestry rent as a percentage of GDP and net official assistance received as a percentage of gross national income.

Results of our baseline model are given in Deliverable 5.1 and we restrict our concern to the marginal effect of natural disasters on private credit. As per the results, disasters show a significant (at 5% significance level) positive effect on contemporaneous credit, however, this positive effect is dampened down by higher income. It appears that disaster-agriculture interaction also yields a negative coefficient suggesting that the positive impact of disasters on credit is further mitigated by higher share of agriculture in the economy. However, as this interaction is less significant (only at 10% significance level), we ignore it for the time being.

In terms of the baseline model, in a low income country like Burkina Faso, one percentage point increase in the percentage of population affected by natural disasters will on average increase the contemporaneous per capita private credit by constant 2005 US dollars 8.33 [35.35-(4.669*In326)]. This impact is equivalent to an increase of per capita credit by 17.47 percent (8.33/48*100). However, in a high income country like Australia, when the disaster affected percentage of population is increased by one percentage point, the contemporaneous per capita credit is reduced on average by around constant 2005 US dollars 12.42 or by 0.06 percent. Notwithstanding the fact that both the countries have more or less similar values for average population affected (2.33 and 2.77 percent, respectively) due to natural disasters, when the same is increased by one percentage point, poor and rich countries will see a divergent impact on private credit depending on the magnitude of their prevailing per capita income and credit, as in the case of Burkina Faso and Australia.

Our findings can be depicted by way of a graph for clarity. Figure 29 shows how absolute change in per capita credit due to one percentage point increase in the percentage of population affected due to disasters in a single year will vary according to the per capita income using 2011 data for per capita income and credit. Figure 30 demonstrates how this change would be seen once the effect is quantified as a percentage of prevailing per capita credit. Despite the fact that all 147 countries contribute to construct the graph, only some countries are named to provide a general understanding on the distribution of disaster impact on credit across countries.

Although, our results seem to be consistent so far, we are still cautious as our model may be suffering from any potential simultaneity as the dependent variable, private credit may be reverse causing per capita income and the magnitude of the percentage of people affected. As we have used lagged per capita credit (lagged dependent variable) on the right hand side while using current per capita credit as the dependent variable, we may have already addressed this issue at least up to a certain extent. It is always desirable to check the validity of results of a model by employing different types of other estimators, especially, when there are more advanced estimators available which successfully address any lacunae present in the estimator already employed. As mentioned before, system GMM dynamic panel estimator is such an estimator which handles the problem of endogeneity in a more elegant and appropriate manner. So, our analysis is repeated using system GMM estimator and simultaneously, a simple ordinary least squares (OLS) and quantile regressions to see whether they yield consistent results to support the findings stem from our chosen fixed-effects estimator.

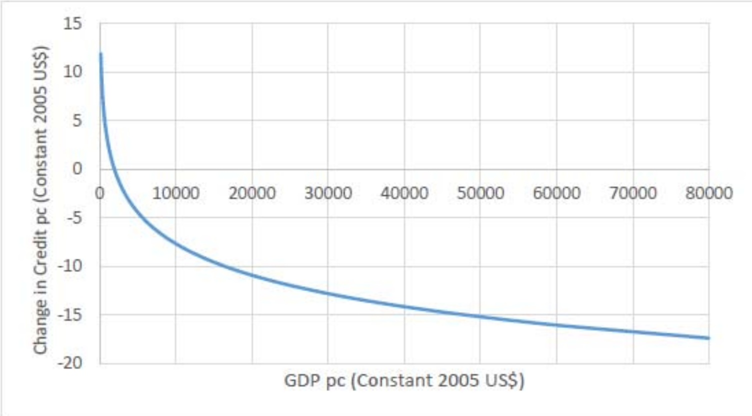


Figure 29. Nominal effect of natural disasters on per capita credit (using 2011 values).

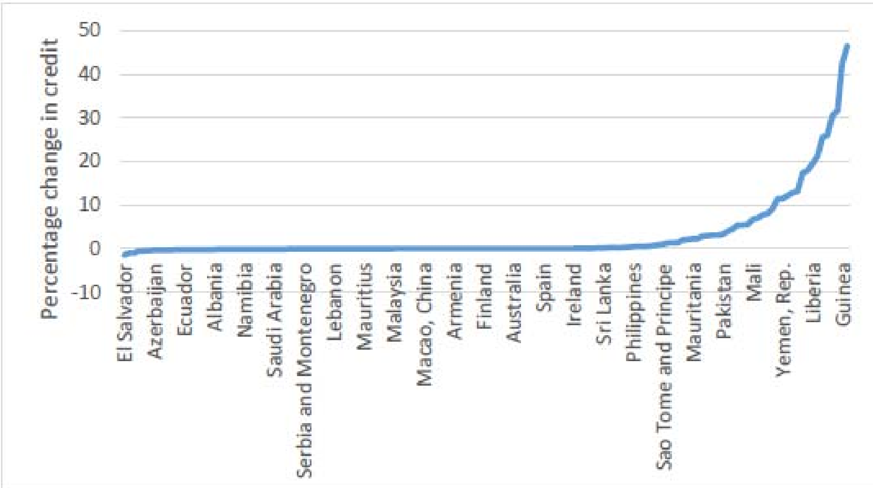


Figure 30. Percentage effect of natural disasters on per capita credit (using 2011 values).

In terms of our preliminary findings there appear to be significant positive impact of natural disasters on contemporaneous private credit which is mitigated by higher income. Our supplementary findings show that the significant positive impact of natural disasters on credit is further mitigated by higher agriculture dependency in the economy, anyhow at a lower significance level. These findings are robust to the inclusion of controls and across alternative estimators, FE, OLS, quantile and System GMM.

In terms of results of all the models we came across until now in this paper, we find a significant impact of natural disasters on financial development proxied by private credit. As already mentioned, private credit availability represents only the depth of financial institutions. Therefore, as a further robustness approach, we run our baseline model in fixed effects estimator once again, however, this time using other suitable candidates to represent financial development as the dependent variable. Accordingly, we use measures suggested by Levine et al (2013) in their 4x2 matrix. However, it is not feasible to run the model with some of these variables as there are no sufficient number of observations and even with measures with sufficient number of observations to run a regression model, all of them do not produce significant and reliable results mainly due to the under coverage of data across space and time. Most of these data are available only from year 2000 or 2003.

Table 2. Alternative estimation models with baseline specification.

	Dependent variable: Credit per capita		
	(1) Fixed Effects	(2) OLS	(3) System GMM
Disaster (% Population Affected)	35.35**	64.27***	58.49*
	(14.08)	(16.87)	(29.77)
Lagged Credit per capita	1.000***	1.027***	0.998***
	(0.0172)	(0.00714)	(0.0170)
GDP per capita (in logs)	654.0***	229.2***	784.1*
	(176.3)	(53.77)	(460.7)
Disaster * GDP per capita	-4.669**	-8.013***	-7.158**
	(1.807)	(2.019)	(3.553)
Share of Agriculture	15.64**	13.35***	7.512
	(7.006)	(3.588)	(33.28)
Disaster * Agriculture	-0.135*	-0.341***	-0.321
	(0.0763)	(0.113)	(0.208)
Polity2	-1.064	6.394**	29.41
	(5.273)	(2.698)	(20.19)
Observations	3,189	3,189	3,189
R-squared	0.958	0.992	
Number of Countries	147		147
Number of Instruments			109
Arellano-Bond Test AR(1)			0.302
Arellano-Bond Test AR(2)			0.049
Hansen Test			0.858

Notes: Annual data 1979-2011, except where lost due to lags. All models include a constant term, country and year fixed effects. Errors clustered at the country level. Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1 Lags used to instrument the endogenous variables in system GMM regression limited to 10.

It is not possible in any manner to plug all the different measures of financial development in our model as they are, given their nature and measurement units. To see the impact of natural disasters on various financial development indicators, it is necessary to employ proper estimation strategies on relevant variables for appropriate sub-samples with respect to space and time. For instance, exploring disaster effects on bank solvency, Klomp (2014) limits his sample to highest economic damage causing 170 severe disasters and time period from 1995 to 2010 in quantifying the impact of natural disasters on banks' distance to default.

Thus, it is obvious that all the indicators of financial development would not give rise to consistent results in our model. Nevertheless, as apparent from table 2 we find strongly consistent results for liquid assets to deposits and short term funding (%) which represents financial stability across alternative estimators. The indicators for which we get the sign correct are listed in further explained in the Deliverable.

Next we have documented the full economic impacts of climatic factors such as sea level rise when climate induced transportation disruptions are considered. The analysis provides updated estimates of the general equilibrium effects of land and capital loss and it produces a novel assessment of the full economic effects of climate change-induced disruptions to sea transport infrastructure. The analysis also includes a rigorous deterministic and probabilistic sensitivity analysis to stress the assumptions and inputs of the our model. Our results indicate that Global GDP is depressed, but the European GDP is less affected compared to the rest of the world. The global welfare loss is USD 61 billion. These losses are driven from the direct productivity losses in sea transport. We show that globally the welfare losses exceed the direct transportation cost changes by 30%, however the regional variation is substantial. Developed regions seem to be able to adjust more to the increases in transportation costs than developing regions. Our report concludes that climate-induced disruptions in sea transport effect significant changes to the global economy and should always be considered when estimating the consequences of climate change to the economy.

Another, potentially important, effect of SLR and other climate change impacts in coastal areas is their effects on sea transportation networks. Sea ports can be affected by climate change in several ways ((Peterson et al. 2008); (Becker et al. 2012); (Nursey-Bray and Miller 2012)). Climate change can affect transportation through sea level rise (SLR), increased heavy precipitation, increasingly severe storms, increased numbers of hot and cold days, et cetera. As identified by (Peterson et al. 2008) the locations of ports and airports could become inappropriate, creating a need for a non-trivial capital investment. Other problems such as storm surges might distort the operations of the sector through, for example, delays or destruction of freight when there is a need for alternative routes, i.e. rerouting that increases transportation times (UNCTAD, 20091; UNCTAD, 20101).

More than 80% of the international trade of goods is carried by sea, and the percentage is even higher for developing-country trade . Any distortion of the transportation sector would have effects not only for the industry itself, but also for other industries connected directly or indirectly to it, affecting both developed and developing countries.

In order to analyse the direct and indirect economic effects of coastal land and capital loss and climate-induced transportation disruptions, we use a computable general equilibrium model (CGE) based on the GTAP 6.2 model and the GTAP 8 database and make a link to the DIVA model.

The use of a computable general equilibrium model was chosen due to its ability to simulate changes in prices and quantities in an economy as a result of an exogenous shock which is in our case SLR. An important attribute of the CGE models is that they move away from the individual agent by looking at the whole economy and the interconnections of all agents (firms, households, etc), thus providing the economy-wide effects of SLR. The choice of the GTAP model is based on the fact that it is a trade CGE model fully equipped to analyse changes in the trade patterns of regions resulting from SLR.

First, we use DIVA projections of SLR-induced losses of land and capital as inputs in the GTAP model (figure 31). The DIVA projections are used to calculate exogenous changes (“shocks”) to regional endowments of land and capital. The absolute changes that are produced by DIVA, i.e., km2 of land lost and millions of USD of costs are translated into percentage decreases of total regional endowments. The percentage change of land endowment loss per region is calculated as the area of land that is annually lost by submergence in squared kilometres if it is unprotected and land below one-year flood level as a share of total agricultural land area in km2. Data on the amount of agricultural land per country are derived from FAO (FaoStat 2015). The assumption is that agriculture will absorb most of the flooding shock but the ability of this sector to adapt in order to reduce economic damages should not be disregarded (Yohe and Schlesinger 2002). The percentage-change shock to the capital endowment is equal to the percentage share of the expected sea-flood cost in regional GDP in the period of the event as estimated by the DIVA model. These percentage decreases of endowments are used as inputs ("shocks") in the GTAP model. The GTAP model computes a counterfactual equilibrium in which the economy adjusts to these losses.

Additionally, the outputs of DIVA are used as indicators of the relative vulnerability of regions to climate change and SLR-induced disruptions of sea transport networks. Transportation disruptions are simulated by a negative shock to the water transport specific technological change coefficient (i.e. productivity) for all regions (the parameter a in Eq. 1). Since there is no available information at this point on the changes of port functionality due to SLR, we use a reference point of 10% reduction in productivity (cf.(Tiwari and Itoh 2001)). We assume that the region-specific productivity changes are a function of the amount of land and capital loss due to SLR, derived from the DIVA model and from two additional scenarios based on (Hallegatte et al. 2013)

The regional aggregation in the model has been chosen in such a way to accurately represent international sea trade. The aggregation of the 13 regions is based on a combination of proximity, geophysical characteristics concerning SLR, port productivity in TEU's and economic activity. The regions include North and Latin America, North-West, North-East and South Europe, Ex-Soviet Union countries, Africa, West Asia, Central Asia, East Asia, China, Japan-Korea-Singapore, and Oceania.

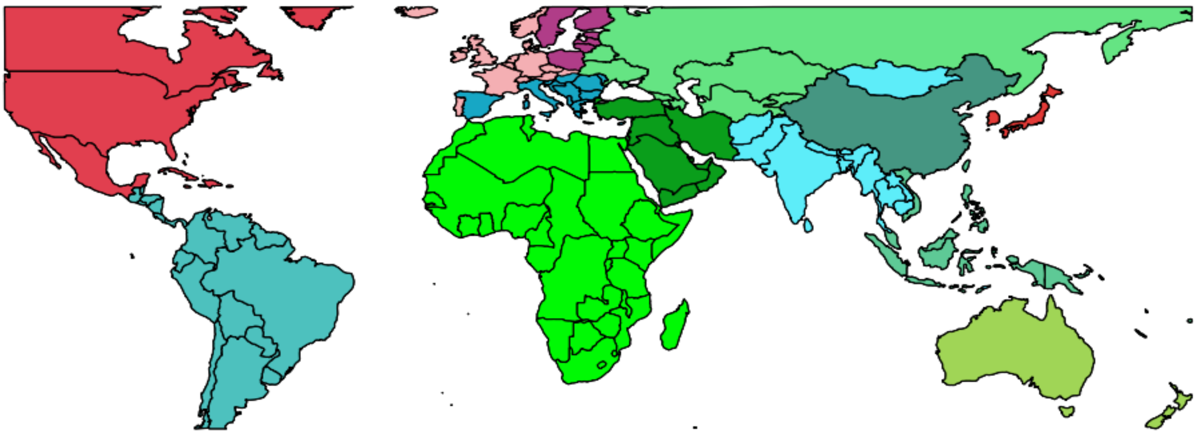


Figure 31. Regional aggregation of GTAP 8 data.

The GTAP sectors are aggregated into eight sectors, including agriculture, energy and energy production, transportation-intensive and non-transportation-intensive manufacturing industries, air, water, and other transport, and other services. We used an intuitive method to make a distinction between transportation-intensive and non-transportation-intensive industries, based on the available GTAP 8 data. For each of the 57 GTAP 8 sectors 57 we have calculated the proportion of transportation costs in total costs. Sectors that have a proportion of transportation costs in total costs of 1% or more are classified as transportation intensive (see table 3).

Table 3. Manufacturing industries classified as transportation intensive.

Industry	Percentage of transport costs in total costs
Food products nec	1%
Recreation and other services	1%
Construction	1%
Chemical, rubber, plastic prods	1%

Machinery and equipment nec	2%
Trade	4%
Transport equipment nec	5%
Business services nec	11%
Petroleum, coal products	25%

Table 4 presents the complete regional and sectoral aggregation of the GTAP data that was used in our study.

Table 4. Regional and sector aggregation.

Regional Aggregation			Sectoral Aggregation		
1	OCE	Australia, New Zealand	1	AGR	All Agriculture
2	EAS	East Asia	2	AIR	Air Transport
3	WAS	West Asia	3	ENY	Energy and energy production
4	NAM	North America	4	NTIND	Non Transportation Intensive industries
5	LAM	Latin America	5	SERV	Other Services
6	NEW	North West Europe	6	TIND	Transportation Intensive industries
7	NEE	North East Europe	7	OTR	Transport Not Elsewhere Classified
8	SEU	South Europe	8	SEA	Water Transport
9	CAS	Central Asia			
10	AFR	Africa			
11	EEF	Ex-Soviet countries			
12	JAK	Japan, Korea, Singapore			
13	CHN	China, Hong Kong			

We use one scenario to simulate the general equilibrium effects of regional-specific loss of land and capital due to SLR. We use eight different scenarios to simulate general equilibrium effects of the disruptions in the sea transport sector caused by SLR that also include losses of land and capital due to SLR.

Table 5 presents an overview of the scenarios and the source of information used in each of them. The Deliverable shows the inputs to the GTAP model for each scenario. We have shown that the calculated productivity losses in sea transport vary greatly between the scenarios. The LC_DIVA_L productivity shocks correlate negatively with those from all other scenarios. The LC_DIVA_C scenario correlates positively with the OECD scenarios, but the degree of correlation is not very high and not statistically significant based on the Spearman's pho. This means that not only the uncertainty on the global effects of climate change and SLR on the productivity of sea transport is high, but also the regional distribution of the productivity change. This should be taken into account when interpreting the results of our simulations in the next section.

Table 5. Overview of Scenarios.

Name of scenario	Scenario description	Source of productivity changes
L&C	Land and capital losses due to SLR	DIVA RCP 8.5 (J14) generated losses based on land loss due to submergence and annual flood costs
LC_Un10	Uniform reduction of productivity of sea transport by 10% to all regions	-

LC_Un05	Uniform reduction of productivity of sea transport by 5% to all regions	-
LC_Un20	Uniform reduction of productivity of sea transport by 20% to all regions	-
LC_DIVA_L	Global reduction of productivity of sea transport by 10%, regional variation scaled according productivity changes in sea transport proportional to DIVA estimates of land loss	DIVA RCP 8.5 (J14) generated losses based on land loss due to submergence
LC_DIVA_C	Global reduction of productivity of sea transport by 10%, regional variation scaled according to DIVA generated productivity changes in sea transport proportional to DIVA estimates of capital loss	DIVA RCP 8.5 (J14) generated losses based annual flood costs
LC_OECD_NA	Global reduction of productivity of sea transport by 10%, regional variation according to Mean Annual Property Losses due to flooding in sea ports without Adaptation	(Hallegatte et al. 2013), 2050 in the scenario with subsidence and optimistic sea-level rise (SLR-1)
LC_OECD_A	Global reduction of productivity of sea transport by 10%, regional variation according to Mean Annual Property Losses due to flooding in sea ports with Adaptation	(Hallegatte et al. 2013), 2050 in the scenario with subsidence and optimistic sea-level rise (SLR-1) with maintaining the defense standards (PD) by assuming that coastal defenses will be raised by the same amount as relative sea level rise
LC_OECD_DH	Global reduction of productivity of sea transport by 10%, regional variation according to the an indication of the height to which dikes need to be raised to implement adaptation strategy PL	(Hallegatte et al. 2013), 2050 in the scenario with subsidence and optimistic sea-level rise (SLR-1) with maintaining relative risk by increasing the dike hight (PL): assuming that, coastal defences will be raised by more than the level of relative sea level rise

Table 6. Percentage changes of GDP and HEV to initial regional GDP due to SLR induces land and capital losses.

	L&C			
	% Land loss	% Capital loss	Δ%GDP	HEV/GDPa
OCE	-0.001	-0.083	-0.03	-0.02
EAS	-0.005	-0.105	-0.05	-0.04
WAS	-0.000	-0.093	-0.05	-0.04
NAM	-0.002	-0.037	-0.01	-0.01
LAM	-0.001	-0.078	-0.03	-0.02
NWE	-0.002	-0.042	-0.02	-0.01
NEE	-0.001	-0.017	-0.01	-0.01
SEU	-0.007	-0.021	-0.01	-0.01
CAS	-0.003	-0.057	-0.03	-0.02
AFR	-0.002	-0.054	-0.02	-0.02
EEF	-0.003	-0.027	-0.01	-0.01
JAK	-0.003	-0.009	0.00	0.00
CHN	-3.3E-06	-0.053	-0.02	-0.02

Table 6 shows the percentage changes of GDP and HEV to initial regional GDP due to SLR induces land and capital losses based on the L&C scenario without any changes in the sea transport sector. The impacts of loss of productive recourses (i.e. land and capital only) are in line with the similar economic literature of SLR like (Bosello et al. 2012, Bosello, Roson, and Tol 2007). The GDP changes are benign and ranging from -0.004 in Japan-Korea-Singapore to -0.052 in West Asia. Furthermore, the HEV is also very small between -0.003 in Japan-Korea-Singapore and -0.04 in East Asia. Results seem to be disproportional to the imposed shock indicating the existence of mechanisms that propagate the initial negative effects of SLR in economies able to substitute the lost land and capital with alternative recourses.

Higher import prices of goods directly affect consumer prices around the globe, but they also affect production costs of firms that use imported goods as intermediate inputs in their production. In fact, because we assume increased transport costs in all global transport routes for all traded commodities, firms are affected by increased costs of imported intermediate goods from all source countries but on a different rate.

Higher domestic production costs lead to higher domestic and export (fob) prices. This, in turn, would lead to an additional increase in import (fob) prices, and so forth. This increase in prices is counteracted by behavioural changes of consumers and producers. They adjust their purchases of goods and services in the light of a changing pattern of prices. First, they will substitute between source countries, taking account of the higher transport margins. This will affect the pattern of trade.

Additionally, in the light of increased import prices, consumers and producers will, to the extent possible and according to their preferences, substitute imported goods for domestically produced varieties (saving on increased costs of transportation) and substitute transport-intensive goods for less transport-intensive goods, until the possibilities for beneficial *arbitrage* are exhausted and a new market equilibrium is established.

In the L&C scenario Asian regions seem to have the highest drop of imports from almost every region and imports in North America seem to be affected the least. The introduction of the 10% uniform drop in sea-port productivity affected most the imports in Latin America, Central Asia and China. Similar results we see in the LC_OECD_DH scenario. Last, the results are a bit different in the LC_DIVA_L scenario. Imports to Africa seems to be hit the most followed by Central Asia and Latin America.

Figure 32 shows a collective version of *cause to effects* for the LC_Un10, LC_DIVA_L and LC_OECD_DH scenarios making the comparison between countries and scenarios possible. Transport costs are a linear function of the exogenous shock in transportation productivity thus the graph can be interpreted as the relation between the imposed shock and the economy-wide effects of SLR measured by HEV. The relation between transportation costs and HEV seems to be linear in all scenarios. This is due to the construction of the GTAP model and the way HEV is defined in the model. Developed regions are clustered in the upper right quadrant indicating that they are the least affected in all cases. Oceania is an exception due to the high transportation costs this region faces. This can also be attributed to the distance of this region to the rest of the developed world in conjunction to the high imposed socks. Developing regions show more variation.

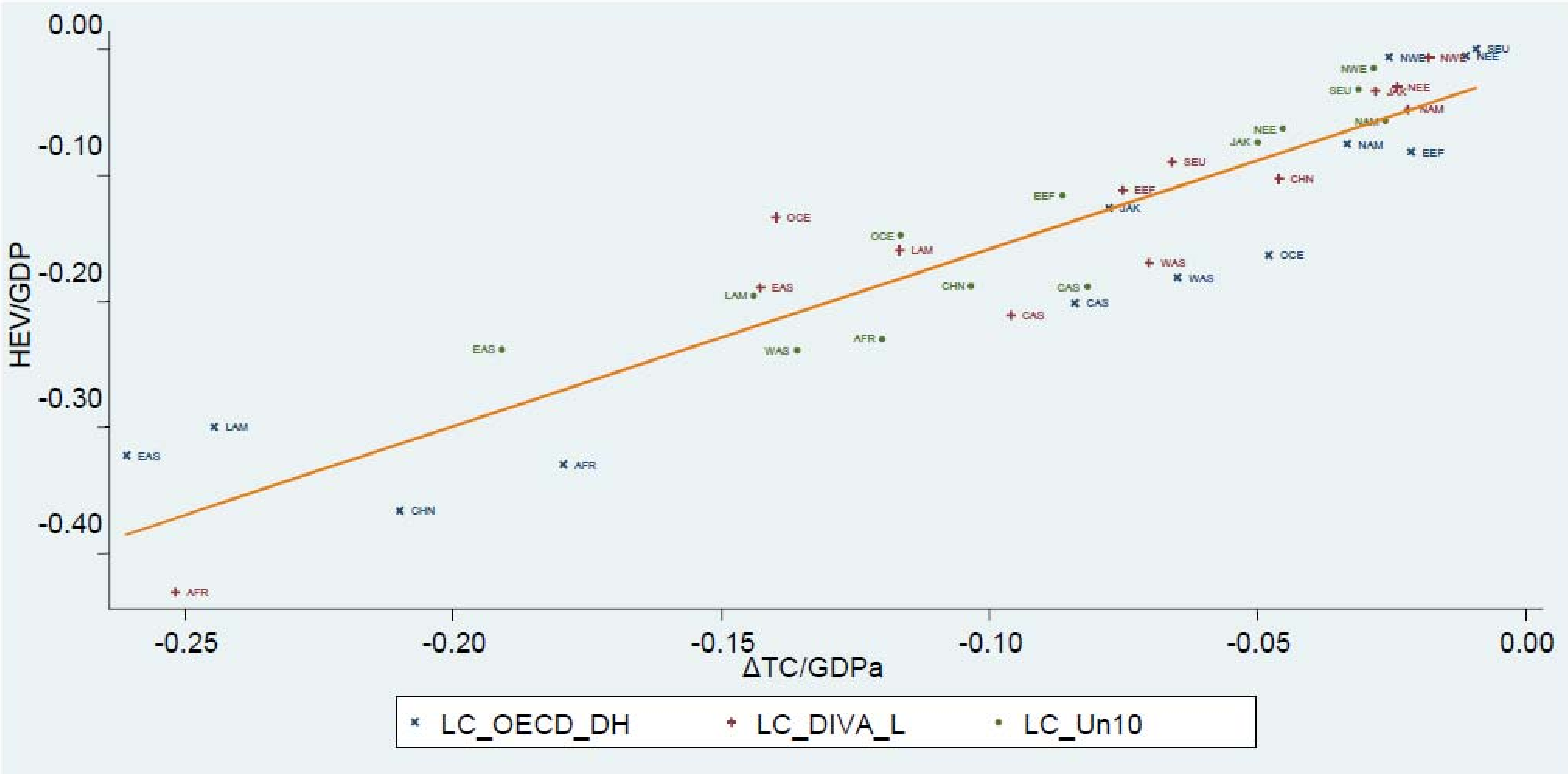


Figure 32. HEV to GDP as a function of changes in transportation prices to GDP.

Table 7 shows that the global welfare loss of the SLR-induced losses in the productivity of sea transport is USD 48 and circa 50 billion in the Un10 and the LC_DIVA_L respectively. In the LC_OECD_DH scenario the global welfare loss is the highest at USD 61 billion. Most of this loss (~85%) is due to direct productivity losses in sea transport. At the country level there are large differences, due to the various components of welfare loss. Although most countries experience a loss in allocative efficiency (an increase in the deadweight loss of taxation), North-West Europe and South Europe experience a gain in allocative efficiency. Deeper investigation of the simulation results shows that these gains are related to a high rate of taxation on sea transport services in European countries. The productivity losses in sea transport increase the use of resources in sea transport (more resources are needed for the same volume of sea transport); hence resources are pulled towards a high-taxed activity, decreasing the deadweight loss of taxation.

For such adaptation we should consider the substantial literature on what would constitute dangerous anthropogenic inference with the climate system (Dessai et al., 2004; Dietz, Hope, & Patmore, 2007; Gupta & van Asselt, 2006; Hansen, 2005; Knutti, Rogelj, Sedlácek, & Fischer, 2016; Kriegler, 2007; Leiserowitz, 2005; Lorenzoni, Pidgeon, & O'Connor, 2005; Mastrandrea & Schneider, 2004; New, Liverman, Schroder, & Anderson, 2011; O'Neill & Oppenheimer, 2002; Oppenheimer, 2005; Parry, Carter, & Hulme, 1996; Schneider, 2001; Shaw, 2015; Smith et al., 2009). This is not the place to review that literature. The natural sciences focus on what-if questions, predicting climate change and its impacts conditional on scenarios of greenhouse gas emissions and, occasionally, vulnerability to climate change. The social sciences also study so-what questions – including the question at what point a predicted impact of climate change would be deemed dangerous – but Arrow (1950) and Harsanyi (1955) showed that it would be an illusion to think a definition of dangerous could be universally agreed upon. We follow Weitzman (2009) and consider climate change as dangerous if it leads to a welfare impact equivalent to a total loss of income.

The impact estimates for global cooling are essentially uninformative. This is no surprise as there is one primary estimate only. Above 2.5°C of warming, the impact estimates are significantly different from zero. Focussing on the lower bounds of the confidence intervals, it is clear that there are substantial risks of global warming. At 8°C, the lower bound of the 99% confidential interval of the welfare loss would be equivalent to a 20% income loss.

The numbers from our analysis are striking. Below 3°C, the risks shown may essentially disappear. Above 3°C, however, risks rapidly escalate until everyone lives in a country where, on average, the welfare loss is equivalent to a total loss of income.

This work casts old data in a new light. Previous meta-analyses of the total impact of climate change focussed on best estimate of the average impact of climate change, or on the uncertainty about the global average impact, or on the distribution across countries of the average impact. Here, we combine uncertainty and distribution. The results show that the best guess of world average impacts are relatively small, but that the uncertainty is large and skewed towards negative surprises. Poorer countries are more vulnerable to climate change. The uncertainty about country-specific impact estimates is such that there is a 1% chance of a total loss in some countries at warming above 3°C. While economic growth would reduce vulnerability in general, this is not true for the tail of the distribution for warming above 3°C. There, vulnerability increases with economic growth. Thus, 3°C global warming appears as a critical threshold above which climate change is dangerous.

Table 7. GDP and HEV decomposition of main scenarios.

L&C	HEV decomposition						GDP decomposition						
	Allocative efficiency	Endowment Effect	Productivity Change	Terms of Trade	IS[1]	Total HEV	Government consumption	Private Consumption	Capital goods	Exports	Transport sales	Imports	Total difference
OCE	-78.5	-139	0	13.1	0.45	-204	-33	-137	-59	-120	-1	42	-307
EAS	-90.3	-433	0	41.8	-1.73	-483	-49	-307	-157	-403	-3	273	-647
WAS	-129	-765	0	54.7	-9.11	-849	-140	-502	-287	-445	-8	289	-1092
NAM	-334	-986	0	-10.6	-4.15	-1334	-165	-1089	-553	-407	-8	337	-1885
LAM	-162	-558	0	32.8	-1.98	-689	-107	-491	-155	-315	-3	117	-955
NWE	-423	-1039	0	1.93	3.07	-1457	-239	-1024	-652	-865	-50	771	-2060
NEE	-21.7	-48.1	0	-10.4	0.02	-80.1	-15	-55	-81	-12	-6	74	-94
SEU	-96.9	-249	0	-34	-4.73	-384	-61	-286	-352	-32	-7	277	-462
CAS	-71.8	-301	0	-6.21	0.76	-378	-44	-245	-251	-93	-3	171	-465
AFR	-57.8	-176	0	16.7	-0.71	-218	-32	-151	-48	-171	-2	78	-325
EEF	-35.5	-153	0	-2.13	0.92	-189	-27	-107	-124	-33	-4	80	-215
JAK	-57.3	-104	0	-96.9	11.3	-247	-35	-173	-382	135	-24	249	-229
CHN	-64.8	-642	0	-0.73	5.84	-702	-105	-284	-626	-209	-16	345	-894

1 IS: Investments/savings effect on HEV

Potential Impact and Main Dissemination Activities

The main area where the work in RISES-AM- can have a beneficial impact and has therefore been addressed in our dissemination activities is the management of coastal zones within a risk framework. The work done has supposed determining present and future impacts on vulnerable coastal areas. This has supposed advancing and therefore having an impact on regionalized projections for the physical and the socio-economic component. It has followed an impact assessment with improved models with respect to the state of the art. From here we have been able to determine or to start bounding the performance of conventional and innovative interventions. The final point has been the preparation of adaptation pathways considering in a comparative manner the present level of adaptation solutions with the additional adaptation that will be required under future climates and uncertainty.

In RISES-AM- we have developed adaptation pathways for a variety of coastal archetypes. Without adaptation to sea-level rise the socio-economic impact only could go up to 50 Trillion dollars in annual costs coming from flood and protection exclusively. We have also considered, at a global scale, the effect of rising dikes or building new ones to adapt to sea-level rise. This can reduce the total cost by 1 to 3 orders of magnitude (figure 33). This means that about 10% of the coast line worldwide can justify from an economic standpoint such a protection.

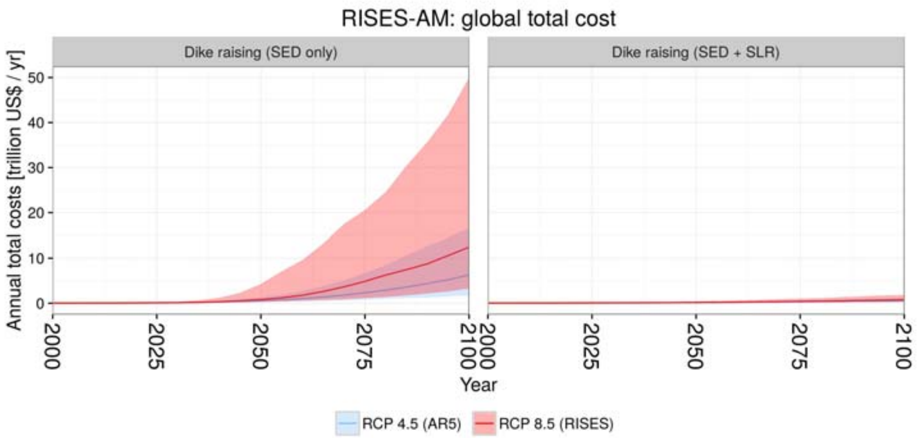


Figure 33. Global total cost (protection cost and seaflood cost) under RCP 4.5 (AR5) and RISES high end sea-level rise, without taking future sea-level rise into account in adaptation measures (left) and with taking future sea-level rise into account in adaptation measures (right). The shaded areas show the 5-95% range.

However, recognizing the limited sustainability of rigid approaches we have also explored more flexible solutions based on working with natural processes. For instance, we have explored the case of coastal wetlands, where provided there is enough room (in the riverine or marine domain), they are able to accommodate higher rates of relative sea-level rise due to enhanced vertical accretion. However, increased diking would have the adverse effect, making those wetlands unsustainable and leading to an increased rate of disappearance.

Planning for adaptation

Coastal adaptation involves decisions that have a long life time, long-term impact and are often costly. Exploring adaptation pathways can help decision makers to take the right decision at the right time without unwanted path-dependency. In the face of uncertainty, managers and planners are urged to develop robust adaptive plans. Such plans consist of short term actions and long term options. These plans should be successful under a range of possible futures or flexible to adapt to changing conditions and "surprises".

The essence is proactive planning for flexible adaptation over time, in response to how the future actually unfolds. Once a given action fails (that is, it reaches a barrier or adaptation tipping point), additional actions are needed to achieve objectives, and a series of pathways emerge; at predetermined trigger points the course can change while still achieving the objectives. By exploring different pathways and considering path-dependency of actions, an adaptive plan can be designed. The plan should be monitored for signals that indicate when the next step of pathway should be implemented or whether reassessment of the plan is needed.

The suggested actions go from traditional engineering to more nature-based solutions, linked to providing more space for natural coastal dynamics and making use of the natural functions provided by ecosystems. Most types of flexible coastal interventions, as required by an uncertain future climate, demand observations that can steer the adaptation pathway and the "distance" to an adaptation tipping point (figure 34).

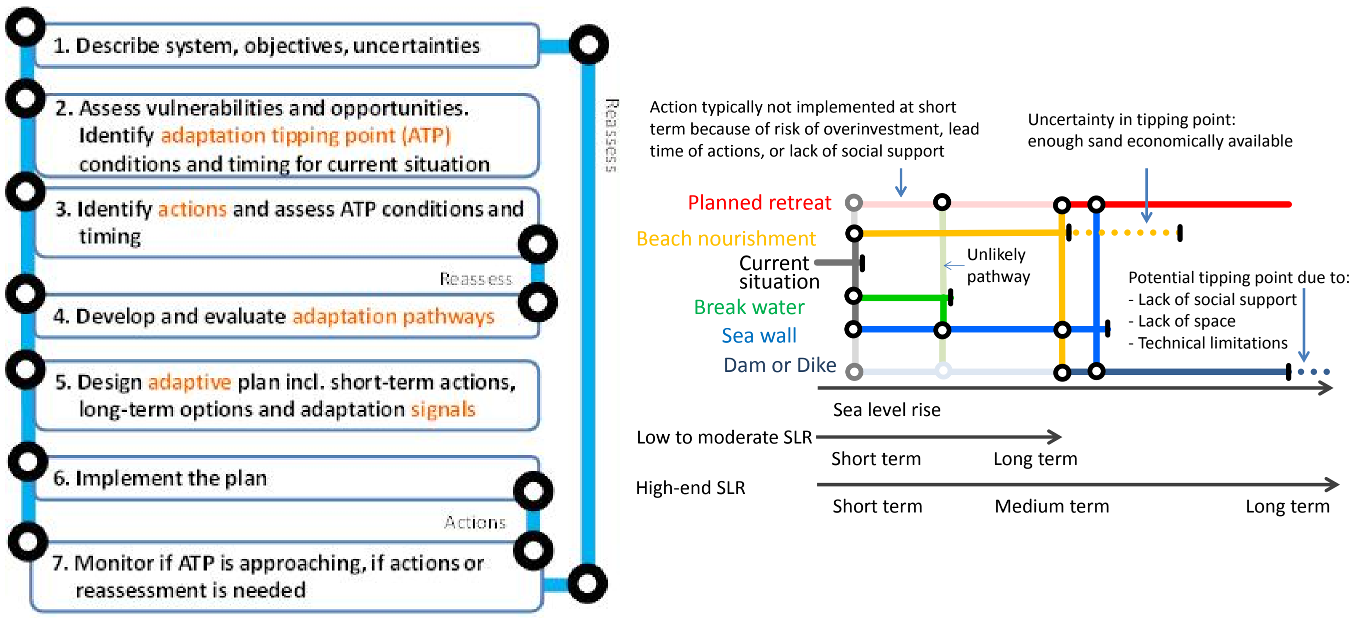


Figure 34. Steps in the Dynamic Adaptive Policy Pathways approach (Haasnoot et al. 2013) and a stylized example of an adaptation pathways map.

Another important are where the work of RISES-AM- is expected to have an impact is the definition of coastal boundaries. They represent borders, sometimes based on physical elements but often based on social and economic criteria that determine the present and future management on coastal areas. They also affect the calculation of hazards and vulnerabilities.

Delineating coastal zone boundaries is, thus, fraught with technical difficulties and suffering from social and legal inertia. Without revisiting these lines, however, the assessment of coastal impacts and risks under varying climates will lack a proper foundation. Coastal zone boundaries based on gradient levels require using the knowledge nowadays available from Earth Observations (satellite or airborne resources with unprecedented resolutions or submerged bathymetry capabilities).

Depending on the domain discretization or the coastal variable considered, the gradient may appear as a smooth variation (e.g. water level), a sharp variation (e.g. ecosystem transition) or a step function (e.g. public domain that passing over a one dimensional line goes from public to private character). For some classical variables (e.g. coastal zone elevation or infrastructure density) the gradient characterising the land water border must be within an interval to allow a reliable quantification. The same gradient approach may be applied to population density (figure 35).

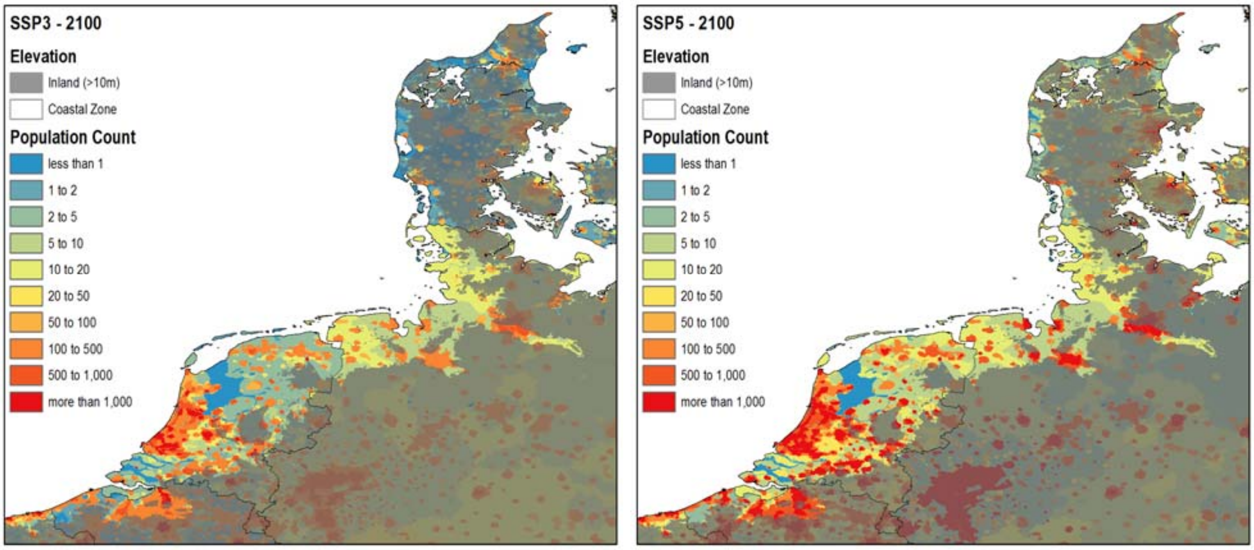


Figure 35. Illustration of a possible coastal zone definition based on a gradient in population density under future climates, according to recent calculations. SSP3 (regional rivalry) and SSP5 (fossil fuel development) correspond to Shared Socioeconomic Pathways with high socio-economic challenges for mitigation (O'Neill et al 2015).

Figure 36. Illustration of the complexity for defining the coastal zone in a river mouth and adjacent deltaic coast area corresponding to a delta in the Spanish Mediterranean. The green line indicates the "present" (2009) public domain limit while the purple line indicates a possible set back line (corresponding to the limit of the Service Protection Zone according to the Spanish Coastal Law)

Coastal zone boundaries near river and estuary areas are a particular although important case in socio-economic and ecological terms. Here, where many coastal megacities are located, the coastal zone concept should be related to the combined action of marine and riverine factors, as illustrated by the intersection of public domain areas where the river meets the sea (figure 36). These areas correspond to a hydraulic domain with the corresponding gradients associated to the limits of action of fresh and salt water. The lack of precise water-land boundaries and the different criteria applied by the river and coastal communities result sometimes in inconsistencies where defining gradient areas may become rather arbitrary. The land elevation gradient above a threshold would suggest as border a coastal mountain/hill, delimiting the socio-economic coastal zone. However in hydraulic and socio-economic terms the catchment area in the mountains should be included for water and sediment budget purposes and the same regarding the related economic assessment.

Establishing coastal zone boundaries for gradient regions requires a higher resolution and robustness than the corresponding definition associated with the value of any given variable. The present resolution of observations and modelling should however allow a relatively straightforward application illustrated in what follows by examples from the Catalan (Spanish Mediterranean) coast to maintain a consistent story line. The cases presented make reference to the geomorphic component, also looking for consistency, since this is the coastal component supporting the rest of natural and socio-economic functions. The boundary (and thus coastal zone width) evolution has been schematized for the geomorphic component representing the area for coastal gradient assessment. This schematization corresponds to a beach with an alongshore revetment or any other longitudinal barrier (see e.g. figure B6) where it is assumed that such a constraint will be maintained by human action regardless of climate and socio-economic evolution. The same type of behaviour is found for historical series of eroded areas as shown in figure 37, where the change in temporal gradient indicates a different system response and thus impact. Such differences in behaviour show the transition from one coastal state (S1) to a different one (S2), in this case representing the more rounded plan shape of the deltaic apex which results in smaller erosion rates. However, the continued, although slower, loss of land may lead to the eventual disappearance of the deltaic coastal fringe (under an energetic event) inducing again an accelerated loss of coastal plain (initiation of S3).

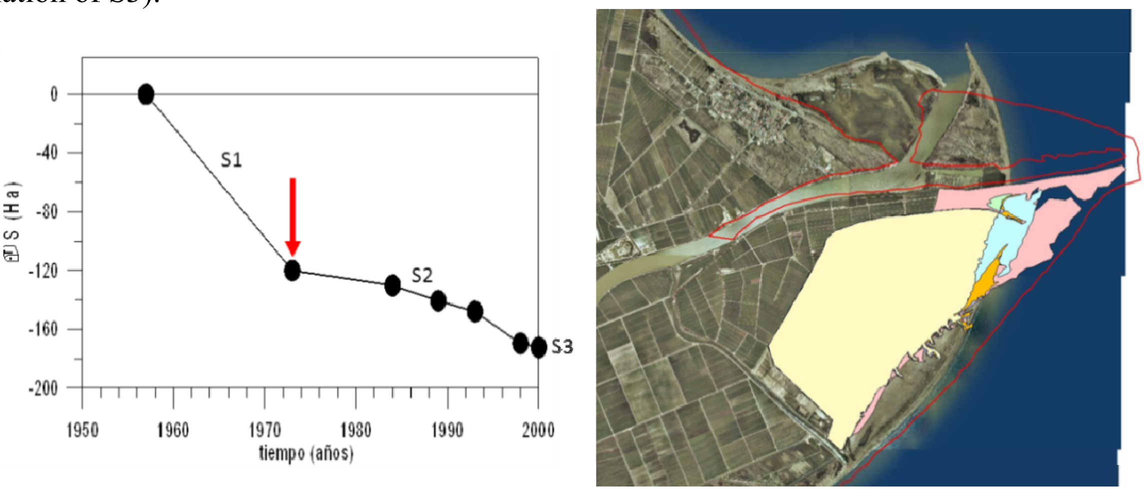


Figure 37. Loss of emerged deltaic territory for the Ebro Delta in the Spanish Mediterranean coast, as a function of time. The left picture shows three distinct slopes in the evolution rate corresponding (from S1 to S3) to the initial erosion of a coast line out of wave equilibrium (S1), to a rounded coast suffering a much slower erosion (S2) and the initiation of a new acceleration due to the progressive disappearance of the sandy coastal fringe (S3).

The need to have such a gradient region can be illustrated for the geomorphic component (figure B6) for a natural beach (figure 38a) with enough accommodation space and subjected to background erosion. Here the coastal fringe migrates landwards maintaining its gradient zone, i.e. the granular material body width. Although there is a net loss of emerged land, the beach is naturally rebuilt by coastal processes provided the rate of sea level rise is below a threshold. This reflects the natural resilience of coastal zones when they are not artificially limited. A neighbouring beach in the same coast where an alongshore revetment has been built, shows the progressive disappearance of the beach as erosion progresses (figure 38b). When the shoreline reaches the barrier, the system attains a first tipping point in which the loss of emerged surface has been prevented although the beach has nearly disappeared. Under present conditions and for a limited time interval, the system remains at this state but wave and current action will continue producing a gradient region that will affect the foundation of the revetment which, unless maintained, will fail, representing a second tipping point for the system. After the structural collapse the shoreline will retreat again (probably at larger rates), the emerged surface will decrease but the beach will be rebuilt to reach a width in equilibrium with governing conditions.

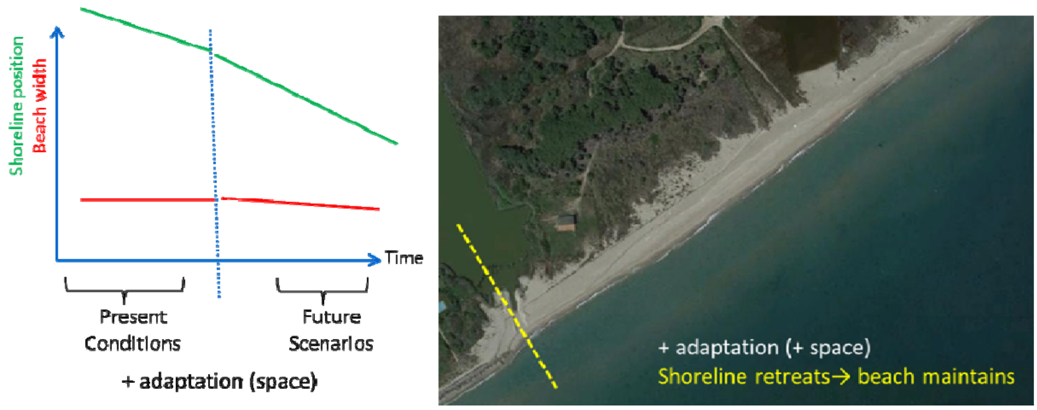


Figure 38a

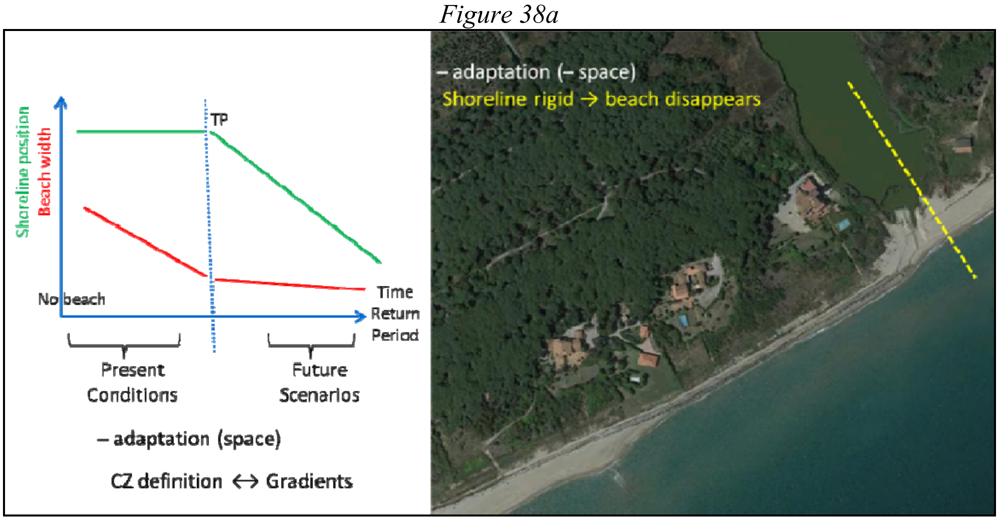


Figure 38b

Figure 38. Schematization of beach width evolution with time and shoreline position, showing how a dynamic beach (38a) subject to back-ground erosion evolves steadily maintaining the slope under present conditions and suffering acceleration under future conditions. The same beach with an alongshore barrier (38b) shows a progressive disappearance of the beach width under present conditions and the lack of a beach under future conditions if the barrier is artificially maintained (red line). If such a barrier is not maintained then a tipping point will be reached (TP) where the rate of shoreline retreat will be higher than for the same beach without the alongshore revetment. Both cases belong to a deltaic tract in the Spanish Mediterranean.

Such an approach to define the coastal area should facilitate the evolution form present coastal states to a future coastal system (Figure 39). Depending on the level of pressures and the resulting gradients the coastal zone may evolve toward collapse or transformation, indicated by tipping points such as for instance beach width or beach volume. In any case this type of approach illustrates the limited sustainability of conventional interventions and to enhance the impact of our project we have paid particular attention to the concept of Nature Based Solutions as explained below.

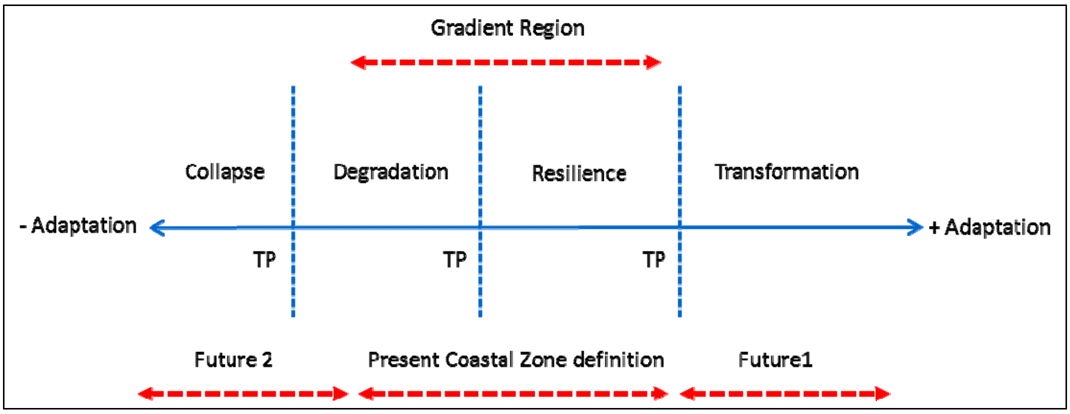


Figure 39. Schematization of the balance between degradation and resilience and how once the tipping point (TP) is reached the coast will move to a different state which can be taken to represent transformation (associated to more adaptation) or collapse (associated to less adaptation). Such an approach will be characterized in the central region (representing balanced adaptation) by a sequence of states between degradation and resilience.

Coastal zone definition

The project work has dealt with the types of solutions to be implemented in vulnerable coastal zones together with their comparative performance. This has required providing a robust definition of what is a coastal zone, a fuzzy concept not well quantified before. The same applies to Nature Based Solutions, whose transition from a word definition to an operational concept has also required significant work. From here we have prepared and exposed a number of policy opportunities to enhance coastal resilience in the face of climate change.

Coastal zone management and associated coastal adaptation to climate change (in particular sea-level rise) require a definition of what is to be managed or adapted. Hence, defining the coastal zone geographical concept is essential for reaching management and adaptation objectives. This concept has always been considered important in environmental management and governance, meaning that governing institutions need to fix territorial boundaries of the resource to be governed. For example, institutions governing a river basin should fit the watershed boundaries of the river basin. Spatial misfit often leads to negative externalities (conflicts on resources, properties, etc.) and other management failures, including legislative action.

From a functional standpoint the coastal zone fulfils a range of different functions such as flood protection, habitat generation and other ecosystem services; defining boundaries depends on which function is considered and at which time-scale. From an ecological point of view the coastal zone can be considered at the global scale as an ecotone, but is better defined as a hierarchy of ecosystems circumscribed by a variety of physical, biological or ecological gradients (Ray and Hayden, 1992). To give another example, from a flood risk perspective the coastal zone has been defined as the flood plain for flood events with a specific return period (Hoozeman et al 1993) or as a low elevation coastal zone (McGranahan et al 2007). In most cases the resulting coastal zone is a transitional boundary between land and sea, whose seaward and landward limits are normally defined from a terrestrial perspective.

This leads to a non-unique definition for this zone whose limits are either arbitrary or related to the dynamics and/or characteristics of the considered coastal subsystem (physical, ecological, socio-economic) and according to the users' needs. The resulting variable width, ranging from a few hundred meters to about 50 km can also be considered as a matter of flexibility (Atchia 1998) rather than imprecision. Based on the consensus that the coastal zone is the area where land and ocean interact, it is a matter of which part of this interaction is going to be analysed or managed which will determine the geographical ("physical" or "legal") definition of the coastal fringe.

Such definitions, often fuzzy in technical terms and static in legal terms should be appropriate for the various coastal archetypes found around the planet, so that the resulting interaction area includes the a) physical, b) ecologic and c) socio-economic components that converge in the coastal system. These approaches have been primarily employed by global studies where coastal flooding was one of the primary impacts. Local or regional scale studies, focusing on more direct impacts, have adopted a much narrower definition of the coastal zone (Kaiser et al 2011) and most consider only the landward side of the land-sea border fringe. This focus on the terrestrial part is essentially linked to the use of this delineation for land use planning and results in variations in the coastal domain extent (Gazeau et al 2004; Dennison 2008; LOICZ 2002). The seaward side limit legally extends to the territorial sea boundary, so as to include socio-economic activities in the water part of the coastal area. However both land and water sides are required for a coastal zone definition within a risk framework since both parts contribute to hazard, exposure and vulnerability when assessing risks.

The various coastal zone definitions (criteria and functions) are interdependent and thus cannot be managed in isolation, but require an integrated approach that considers all of these together, as articulated through the concept of Integrated Coastal Zone Management (ICZM). For example, protecting against coastal flood risks through hard structures may destroy ecologically important habitats through coastal squeeze and/or lead to coastal erosion in adjacent parts of the coast, as explained further below. Moreover, coastal zone boundaries are not static but evolve over time and space due to a range of natural and anthropogenic factors. These boundaries are closely related to climatic factors such as mean sea level, in the sense that any change in relative mean sea level will modify natural processes as well as human activities in the coastal zone. Potential changes in wave and surge climate, as expected under climate change, may modify the present level of equilibrium or lack of it, resulting in a forced shoreline evolution at a variety at time scales, commonly perceived as negative when compared to our "rigid" infrastructures at the coast, along which there may also be natural (e.g. capes) or artificial (e.g. National borders) boundaries that impose further constraints. The case of land claiming (e.g. megacities in China) moving the land-water border seawards, also illustrates this point.

The expected acceleration of changes (in physical and socio-economic conditions) under future climates will force revisiting the coastal zone concept to approach the conflict between anthropic uses or expectations and an inherently dynamic territory. Only with a flexible coastal zone definition, linked to a time scale and considering its projected evolution shall allow considering its full complexity and dynamics, and therefore advancing towards sustainability in a way that may be intercomparable around world coasts.

The coastal zone has been here characterized in RISES-AM- as a gradient region affecting a number of processes, while previous definitions make reference to a single variable (e.g. height below a threshold) or a single process (e.g. upper limit of wave run up). Historically these definitions have evolved regarding the land boundary, the sea boundary and the legal framework resulting mainly from physically-based criteria. Such definitions have served their purpose to maintain the coast, with important limitations and with different degrees of success since although our coasts are indeed managed they are often degrading (e.g. many Mediterranean touristic tracts), some are being realigned (e.g. re-naturalized areas in Germany, France or UK) and some are being split from their natural evolution features (e.g. "artificial" hard-engineered coasts in Europe and elsewhere requiring permanent maintenance). The expected increase in socio-economic activities and physical climatic factors require revisiting this coastal zone definition and surpassing present coastal zone management pitfalls.

Bringing these physically and economically based concepts to legal terms has identified a number of difficulties, illustrated by the use of straight baselines (reference lines dividing one region from another, such as the coastal zone public domain limits) that are static and include low tide elevations or fixed river mouth definitions and that cannot be used in general as a robust basis for determining the boundaries between land and ocean (see e.g. the UNCLOS, 1982 definition of territorial sea breadth). Baselines allow determining territories in land or water such as for instance the public domain in the emerged part and the territorial sea in the submerged part. The land boundary is normally linked to the low tide elevation and the upper limit of wave run up, but seldom considers the rising seas due to global warming (Houghton et al 2010). The sea boundary (territorial sea) extends up to 12 nautical miles from the baseline and in some cases until the 200 nautical miles (about 370 Km) limit of the exclusive economic zone.

Neither limit has been robustly defined nor have varied with policy requirements at each time or place, showing a wide dispersion in concept and extent (regarding the protection function it goes from 100m under the Spanish Shores Act to 3km under the Danish Planning Act, as an illustration). The seaward limit has also been linked to waste water limits or the variance of salinity in river mouth areas (Artioli et al 2005). The European directives and protocols recognizing this uncertainty allow some flexibility for countries and functions or policies. This leads to extending or reducing the coastal zone applying an ecosystem approach and economic/social criteria, which potentially can include the (negative) effects of climate change. Outside Europe, the position is very similar with the US Coastal Zone Management Act defining the coastal zone as an area of mutual marine and terrestrial influence and extending seaward to the extent necessary to control land processes. In many of these definitions (e.g. South Africa Integrated Coastal Management Act) the functionality of coastal protection and coastal access is also considered.

These limits or baselines need to be objectively defined to allow an efficient policy application. For that purpose, they require a dynamic evolution with climatic factors and socio-economic trends, since otherwise the coastal zone definition will hamper the development of adaptation pathways, as required in the face of climate change and other change drivers. The coastal zone needs the definition of upper and lower boundaries, reflecting the transition (in land) to a purely terrestrial ecosystem and the transition (at sea) to a pure marine ecosystem. Such a distinction becomes even more complex in river mouth areas where riverine processes also need a riparian limit. The same is true regarding the population or economic activity limits, which often elude an unambiguous definition but show (figure 40) gradients amenable to quantification.

The domain boundaries must be set in a consistent manner for hydraulic, ecologic and socio-economic "gradients" so as to allow a holistic assessment. Any proposed boundaries should encompass all components featuring a distinctive gradient and contributing to risk. The coastal zone boundaries are, thus, to be associated with characteristic gradient levels in physical variables and in ecosystem features or socio-economic uses/assets, where the functionality considered will condition the boundary location (e.g. the full river basin for freshwater management). The resilience or vulnerability levels of the coastal tract will then of course depend on the considered coastal domain.

Figure 40. Illustration of the coastal zone concept as a geotone (Left: Rio Janeiro coast showing a low-lying urbanized part backed by a mountain chain) and as an ecotone (Right: Ebro delta coast showing various habitats both natural and one anthropic). The fuzziness of the boundaries adds further complexity to the definition.

As a consequence, there is no comprehensive definition of the coastal zone neither in terms of extent nor in terms of partial delineations. Present boundaries are often straight lines and "freeze" dynamic concepts such as the low waterline into static positions. The probabilistic nature of, for instance, the upper limit of wave run up is again not properly analysed and included in the definition (although mentioned in some recent Coastal Acts such as for instance the Spanish one, BOE 2014), so that the coastal boundary is fixed at some arbitrary distance in-shore that goes from hundreds of meters to a few kilometres (Lavalle et al 2011). Although legally these static definitions allow an unambiguous application, from a physical standpoint it is quite obvious that there is a need to incorporate the natural variability and combination of variables that characterize complex coastal environments (including socio-economic activities) into this definition.

Considering the coastal zone as a gradient region (in physical or economic terms) or an ecotone (in ecological terms), there comes an automatic recognition of the transitional character of such an area. This definition must be linked to the key variables for each coastal function (e.g. salinity for ecology or agriculture, water depths or erosion rates for inundation, etc.). Based on present data availability and analysis capability, it should be feasible to apply such definitions based on a) the coastal functions considered, b) the time scales for the analysis and c) the main processes relevant for such scales and functions.

The gradient criterion should capture the region with higher risk levels as a function of physical or socio-economic factors. That zone, termed loosely as the littoral zone, can be associated to enhanced dynamics and, when prevented, to particularly high risk levels (figure 41). Under future conditions there will be a transition or tipping point that will accelerate "transitions", associated to a lower resilience and, thus, higher risk of the coastal system. This is due to the projected rapid change of sea level that will limit (under future climates) resilience capabilities of anthropic coastal tracts if not maintained by human action. Regarding ecologic or socio-economic factors, the same type of behaviour is expected, with tipping points due to a limiting coastal width below which the natural resilience will diminish much more rapidly.

The suggested coastal fringe delimitation, based on gradients, incorporates in a natural manner the energy level of coastal dynamics (e.g. high tidal range or wave storms versus micro tidal range and limited storms) and applies an ecosystemic approach to the natural and socio-economic components in terms of density of uses, represented e.g. by infrastructures or connecting lines. This type of definition will evolve naturally with changing physical and socio-economic scenarios, facilitating the assessment of coastal risks under future climates.

Figure 41. Present and projected (year 2100, assuming an average sea level scenario from RCP4.5) public domain baseline for the Barcelona littoral. The present limit has been associated to the promenade boundary while the future limit corresponds to the shoreline projected to the year 2100 assuming flooding and no shoreward migration. The geometric projection considering a given sea level rise leads to a line that should be considered as reference since the actual boundary will be conditioned by human responses (adaptation) which may counter this sea level induced changes partially or totally.

A holistic coastal zone definition integrating geomorphic, ecologic and economic criteria should be based on gradients for the more relevant variables (land elevation, population density….) and allow the inherent dynamic character of gradient regions to be explicitly considered when assessing coastal zone functions or services. Without such a definition, the shore will become an artificial line difficult to incorporate into sustainability analyses, particularly under high end climate scenarios where significant shifts in position are to be expected. Because of this, naturally resilient coastal zones may accept a narrower domain for decision making (since the impact of climate change will be bounded), provided it encompasses the main resilience mechanisms (e.g. back beach depositional areas).

Using gradients in natural or socio-economic variables should also help to incorporate climate into the coastal zone definition. Administratively established fixed boundaries that delineate public domain cannot incorporate the main processes controlling the gradient zone under varying climate. Such traditional definitions also fail to include the risk component associated with natural or socio-economic values, since they do account for all the space contributing to generate any given risk category.

The coastal zone definition proposed can become operational when applied to the three main components identified for the littoral fringe: geomorphic, ecologic and economic. The geomorphic component, supporting the ecologic and economic functions, can be characterized in a relatively straightforward manner using the gradients in topography and bathymetry but considering them as dynamic variables that will evolve with coastal morphodynamics and climate change. The ecologic component, associated to the natural services provided by the coastal system, can be characterized in terms of the composition of ecosystems in that area, looking for the transition indicated by salinity levels. In this respect salinity could also be considered as a proxy for determining the gradients and therefore the boundaries of the ecologic component. In a similar manner the economic component is associated to the anthropogenic uses and infrastructures located in the coastal fringe. It is therefore responsible for most of the vulnerability (damage) and can also explain the human related resilience of a given coastal zone that, because of its economic value, may justify continuous investment (even additional investment to cope with climatic variation) to sustain given coastal tracts. This economic component can be characterized by the gradients in population density or GDP density, so that the main core of activities in the coastal zone is included within the prescribed coastal domain.

Such an approach to defining coastal areas, based on gradients for the variables controlling the considered functionalities, should also facilitate the evolution from present coastal states to a future coastal system. Depending on the level of gradients, the coastal zone will evolve towards collapse or transformation, indicated by the exceedance of tipping points such as beach width for the protection function or salinity for agricultural uses.

Nature Based Solutions

Another impact point from the project work development has been the relative performance of various types of coastal interventions. In addition to the work done on conventional solutions here we shall expend a bit more the concept of Nature Based Solutions (NBS), due to their higher potential for impact/transfer.

Nature-based flood defences (NBFD) use natural dynamics and ecosystem services to reduce flood risk. They focus on preserving or restoring ecosystems such as marshes, mangroves, coral reefs and dunes in order to create natural barriers to protect the hinterland from flooding. They also draw on the potential of ecosystems to retain, store and discharge water. Ecosystems can be restored, enhanced, engineered or managed to successfully reduce flood risks on coastlines, in river basins and in estuaries throughout the world. Nature-based flood defences combine nature and flood protection, but they can also integrate other functions. These type of defenses fit the building with nature working method perfectly.

To achieve higher long term sustainability and to deal with future uncertainties, there is a Nature-based type of solutions which should be self-maintaining and adaptive to future conditions and therefore provide a longer term reduction of risks at more affordable costs.

The implementation of any type of NBS, inherently more flexible than conventional measures, is likely to benefit from a structured coastal adaptation plan, combining that flexibility with coastal land uses and dynamics, bounded by rigid coastal infrastructure and present socio-economic pressures. NBS will also require a monitoring effort to assess their performance and, because of their flexibility, to suggest critical thresholds or tipping points so that suitable corrective measures or maintenance interventions can be designed and implemented, preferably within an adaptation pathway with wide social support.

This can be illustrated by the projected change in global wetland areas under three different protection strategies for a high-end sea level rise scenario as considered RISES-AM- and a global population growth according to SSP-5 (figure 42). The differences in projected behaviour are due to the fact that protected coasts against flooding result in an enhanced wetland loss, while recovering coastal dynamics (fewer dikes in the plot) enhances the growth of wetlands and therefore promotes a more sustainable development of these NBS.

An illustration of how reintroducing sediment fluxes can promote accretion and thus resilience has been analysed and calculated for the case of the Ebro Delta, one of the pilot studies in RISES-AM-. Figure 43 shows an illustration due to an energetic storm with a return period in the order of decades that is an event happening every certain number of years and the accretion it produces in the deltaic fringe and associated deltaic plain for a sector of the Northern Hemidelta. The resulting effect is a natural input of sediment (positive impact) associated to a certain erosion of the shoreline plus an enhanced salinization of the affected fields (negative impact).

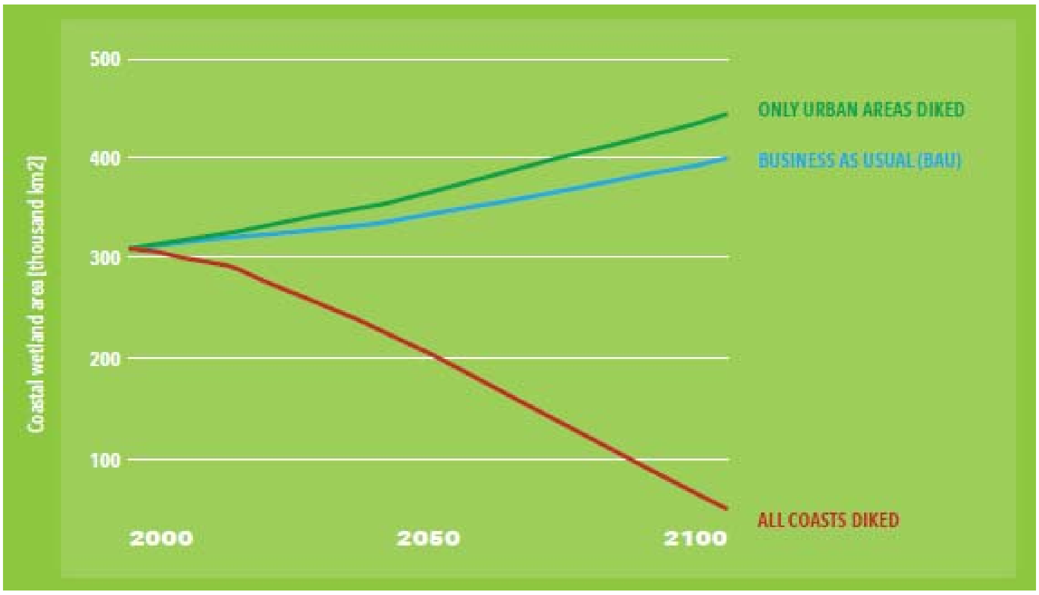


Figure 42. Projected change in global wetland area under three different protection strategies for the high end SLR scenario (RCP8.5 - J14) and a global population growth according to SSP5 (from GCF work).

The amount of overwash and thus sediment transport depends on the beach slope and berm levels (figure 44). The beach profile and berm do not remain static since they vary with the prevailing mete-oceanographic conditions in the short term and with subsidence and sea level rise at decadal scales. However for a given profile set of intervals it is possible to calculate run up and from that the corresponding overtopping. That requires calculating the probability distributions for driving factors and profile responses. It has been done (figure 45) for the time series available from 1958 till 2002. There it becomes apparent how for a certain number of years the run up associated to energetic storms was able to overwash the maximum crest level. In the picture we have shown the minimum, medium and maximum values of that berm level to account also for beach profile variability. The end result is that about two storms per year (in fact 1.84 for the selected period) are able to produce overwash and therefore supply sand but also enhance salinization to the studied coastal fringe sector.

This illustrates the capability of a natural mechanism to provide extra accretion without explicit energetic costs but at the price of an increase in local salinity levels and of course requiring a certain area of coastal fringe (see figure 43 or figure 44 for illustration) so that natural dynamics can come into play. Without that room for coastal dynamics this type of natural solution would not be able to promote vertical accretion. Moreover in the case of squeezed coastal fringes where the first line is already occupied by buildings or other types of infrastructures (railway lines, roads, etc) such a natural accretion mechanism would not be acceptable since the cost of natural flooding would exceed the benefits particularly because the input of salt water and sediment as it happens in many coastal villages would be moved back to the sea right after the storm.

Figure 43. Illustration of marine flooding and associated vertical accretion in the Ebro delta (from UPC work).

Coastal wetlands will substantially increase under high-end future scenarios (for instance, the 1.80m by 2100 considered in RISES-AM-) due to their ability to increase their vertical growth rate with increasing sea level rise, a fact well known from previous studies in local wetland areas. If accommodation space is available, or can be provided due to land planning changes, and enough sediment is available, then the coast will become wider with more capacity to damp incoming wave energy and the resulting coastal protection will improve. However, protecting the global coastal coastline with rigid works will result in a loss, up to 85%, of wetland areas until 2100, compared to their present extent.

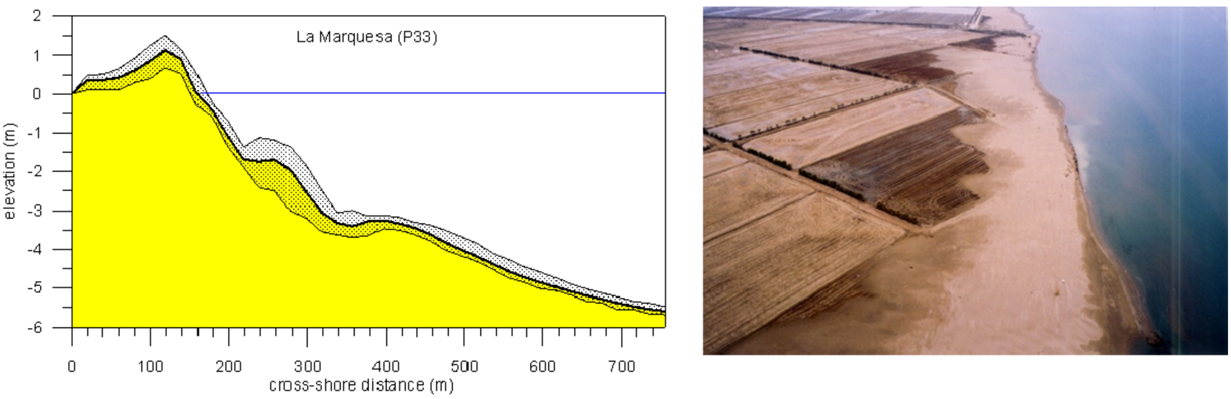


Figure 44. Set of profiles for a beach in the Northern Ebro delta (left), corresponding to the area where marine flooding (right) promotes natural accretion (from UPC work).

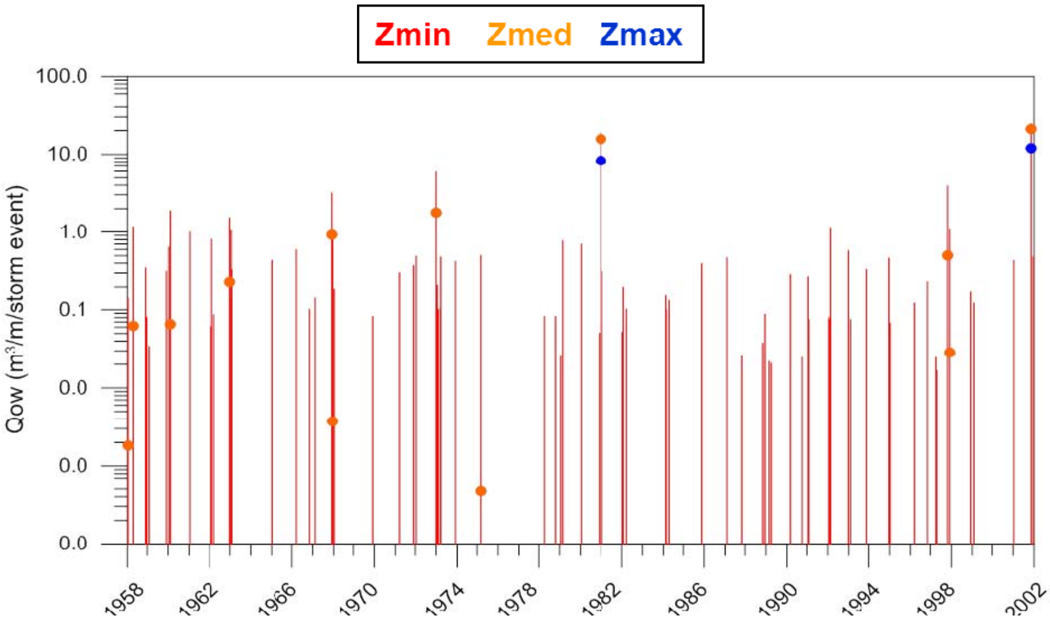


Figure 45. Evaluation of overwash volumes for the beach sector of figure C3, indicating by coloured dots the years when run-up exceeded the berm level from maximum to minimum. From UPC work.

The performance of Nature Based Solutions should always be put in context with that of conventional engineering interventions. Because of that we have structured the NBS solutions considered in our project in the following seven categories:

A. Conventional interventions:

1. Barriers such as a tidal barrage in the Liverpool – Mersey estuary for which the recommendation is to quantify the barrier effects affecting water, sediment and nutrient fluxes so as to assess the environmental impact and, if desired and needed, to circumvent partially these barrier effects.
2. Artificial nourishment with a "hold the line" approach resulting in varying efficiency for a number of archetypes and climatic conditions as, for instance, studied for the case of the Catalan, Dutch and Portuguese coasts.
3. Rigid barriers for low-lying coastal areas such as deltas (illustrated by the deltas of the Mekong and Ebro in our project) which result in increased subsidence and erosion, both for the vertical and horizontal dimensions, associated to increasing pumping demands to maintain salinity levels.

B. Transition towards NBS:

4. Smart artificial nourishment based on a proactive balance strategy and anticipating the effect of natural meteo-oceanographic and human factors to cope with present and short term future erosion. The long term sustainability, as studied for the sandy coast cases in our project will depend on costs and availability of the main requested elements (energy and sand).

C. NBS:

5. Reintroduction of water and sediment fluxes, such as considered in our project for the Ebro lower watershed. This reintroduction will lead to “raising” grounds and a reduction of salinization at the expense of a different water management policy.
6. Reduction of sediment mobility with local biota. This solution, analysed at a local scale for the Catalan coast and the Danube and Ebro cases, is particularly well suited for situations of sediment scarcity.
7. Increased room for natural dynamics in the river and sea fringe domains. This type of solution has been considered for river-sea dynamics for the Elbe case via the design of water retention areas. It has been considered for sea dynamics for the Catalan coast and the Croatian coast via set back lines.

Policy Implications and Barriers

The main synergies to support and help finding policy opportunities should be linked to an integrated assessment of a) available resources (e.g. volume of sand or freshwater), b) effectiveness of the proposed interventions (e.g. limited duration nourishments in a future with scarce energy) and c) resulting utilities (e.g. high value for urban coasts and relatively lower values for low density populated environments unless natural functions and cultural heritage are included).

This has resulted in a number of important questions to help steering policy making and the corresponding coastal zone decisions. It starts with the best way to manage the impacts of sea-level rise in an uncertain future. The recommended approach is based on establishing explicit risk levels which for developed coast normally are equal to present ones. This can be achieved by an adaptation pathway that proposes an order sequence of flexible interventions.

The second element to be considered is the timing that is when the proposed interventions should be implemented to maintain coastal risk levels at a desired or prescribed value. Based on the proposed adaptation pathways and the included signpost (indicators) they may appear for a warning e.g. actual or projected minimum beach width surpass for the measures to be implemented. The short term interventions should not mortgage the long term coastal development plans and adaptation options.

The third component is linked to the types of interventions that should be preferred for each coastal archetype. Such type depends on the vulnerability and exposure levels of each particular coastal zone and the type of policy action or adaptation selected (defend-adapt-retreat). In general terms it is recommended to favour Nature Based Solutions that should be able to save maintain up to a point under varying climates.

The fourth axis deals with the cause-effect relation for a given coastal area or problem. In more practical terms that means what should be the basis to define why a coastal area or problem should have higher urgency and receive therefore higher priority for interventions than others. The answer will depend on a) policy criteria, b) socio-economic constraints and preferences and c) technical feasibility conditions, from natural and anthropogenic environments. The solution may vary with time scale so that short term priorities may be different from long term ones.

The final element to be considered in this policy oriented summary is related to the main physical, social and economic factors controlling coastal risks. The main factors identified in this project are linked to the barriers in a) physical/technological system, b) economic/financial system and c) social / cultural system. The control factors will depend critically on whether these barriers are total (under present or future conditions) or can be circumvented.

The conclusion at local scales is that for the considered coastal archetypes at risk under climate change, the proposed set of interventions and adaptation pathways should serve to develop tailored made interventions and sequences so that the proposed solutions combine local policy objectives and sustainability criteria based on advanced scientific knowledge about the underline physical and socio-economic processes.

This adaptive planning is an efficient way to deal with uncertainties and long term implications for the short term action. It is therefore recommended to focus EU policy so that further content can be provided for these adaptation programs and in general for a risk framework to deal with coastal interventions at a variety of time and space scales. This will require removing their institutional barriers and enlarging the technological limits for such interventions, particularly for those which are less known nowadays and that can be collectively termed combinations of conventional plus Nature Based Solutions.

At the EU scale, there are no severe financial or technological limits to coastal adaptation towards the goal of reducing flood risk in the 21st century coastal flood risk can be maintained at or below today's levels, provided that large upfront investments can be mobilised where needed. It must be noted, however, that while risks can be kept constant, catastrophic consequences in the case of dike failure may increase substantially with continuing development behind higher and higher dikes.

Nevertheless, RISES-AM has identified that institutional barriers related to the implementation of innovative adaptation and social barriers, including resistance to change or social acceptance, constitute the major challenge to adaptation and are the most important drawbacks for implementing innovative adaptation options and can significantly influence the nature, timing, type and level of protection. (See case studies: Mersey Estuary, Ebro Delta, Elbe Estuary)

This concludes that building dikes in response to sea-level rise (rather than socio-economic conditions alone), most particularly if planned numerous decades in advance, is a highly effective adaptation strategy to reduce flood costs. Of course, building dikes may not be practical or desirable around every coast (e.g. disruption of sediment supply, viability, access). Alternative innovative solutions are available but multiple institutional barriers may exist.

Across all RCPs, the greatest total costs in Europe are projected to be in Denmark, followed by France. However, the higher end, as opposed to the lower end of sea-level rise, has the greatest uncertainty due to the greater range of results, due in some cases to defence initialisation and costs crossing a sensitivity threshold in the model.

This indicates that a step-change in the type of protection or in the planning of coastal protection may be required for higher levels of sea-level rise, where the consequences of inaction could have devastating results.

At a global scale, the impacts of sea-level rise on human settlements primarily occur via extreme sea-level events rather than as a direct consequence of mean sea-level rise (Wong et al. 2014). Extreme sea-levels occur during storms due to wind- and pressure-induced storm surges, potentially causing serious flooding as illustrated by Hurricane Sandy in New York in 2012 and Typhoon Haiyan in the Philippines in 2013. Under current conditions, on average 11 million people are subject to flooding annually (Muis et al., in review) with annual average sea flood costs of around US$ 11–40 billion per year (Hinkel et al. 2014). To better understand current and future risks, RISES-AM has developed the Global Tide and Surge Reanalysis (GTSR) dataset (Muis et al., 2016), which is the first global dataset of extreme sea-levels based on hydrodynamic modelling. The dataset provides estimates for various return periods. Figure 46 shows the height of the 100-year return period for present day conditions

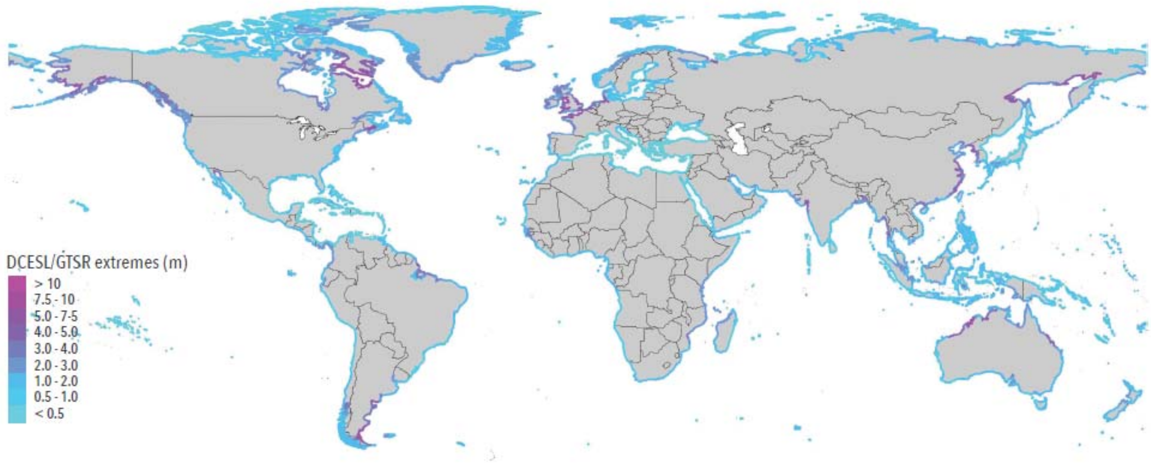


Figure 46. Extreme sea levels with a 100-year return period (present day conditions).

RISES-AM used the new high-end sea-level rise scenarios and the new extreme sea-level database for improving global estimates of sea-level rise impacts on human settlements. Following business-as-usual coastal zone management and (i.e. ignoring sea-level rise) could result in up to US$ 50 trillion in annual flood damage under the high-end scenario (RCP 8.5 – J14). Adapting to sea-level rise by building and raising defenses can reduce the total cost (damage and adaptation cost) by 1 to 3 orders of magnitude (figure 47). Our results show further that for 12% of the world's coastline it is economically robust to protect, i.e. protecting is cheaper than not protecting under all plausible combinations of sea-level rise and socio-economic scenarios (Lincke and Hinkel, in preparation). These 12% of coastline account for 89% of global coastal floodplain population and 94 % of assets in the global coastal floodplain.

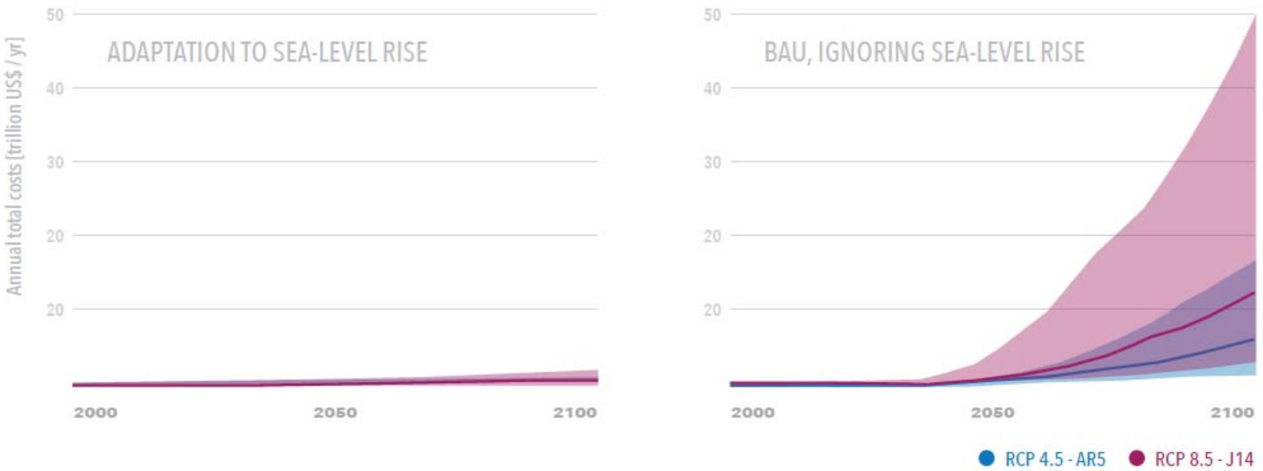


Figure 47. Global annual total cost of sea-level rise (protection cost and damage cost) under RCP 4.5 - AR5 and RISES-AM high end sea-level rise (RCP8.5 - J14) with adaptation (left) and without adaptation (right). The shaded areas show the 5-95% uncertainty range.

Transfer and dissemination

Dissemination activities during the project but mainly in year 3 have dealt with the enhanced interaction with the International Advisory Board (meetings in Southampton and in Barcelona) so as to promote the project approach and results in other countries/continents and also in the organization of ECCA-2017 Conference together with the parallel projects HELIX and IMPRESSIONS. During the final year we have produced 33 pier reviewed papers, 33 contributions to international conferences and held 10 meetings with stakeholders. There have also been 24 TV/Press reports dealing with climate change on coastal zones and mentioning the work done in RISES-AM-.

We have also started preparing a number of future presentations among which it is worthwhile mentioning the team contributions to the EGU and AGU meetings and the already mentioned ECCA-2017 conference in Glasgow. We have also in preparation papers dealing with SSP for coastal impact assessment in the Mediterranean, the analysis of the combined effect of extreme storms with sea level rise on coastal tracts for the considered case studies and a sensitivity analysis of exposure to various drivers.

We are also dealing with a more in depth analysis of uncertainties in coastal impacts and the resulting vulnerabilities and to show also the importance of the selected spatial scale. There is also another co-authored paper in preparation dealing with the benefits of adaptation for the Mediterranean basin. To further advance the regionalization of scenarios there are two papers in preparation dealing with storms and surges in the North-East Atlantic and the future wave conditions of North-West Europe in general.

Finally there is a set of more applied papers dealing with the combined traditional plus innovative interventions for the case studies and some additional work on the Black Sea based on the performed simulations and analysis within the project. The question of robustness for protection strategies under 21st Century sea-level rise and storminess is also been considered for a common paper at two scales. Finally it is worthwhile mentioning the extra effort on population dynamics and migration which has also received attention in ECCA-2017 with the suggestion of a session proposed by RISES-AM- partners and which will become a critical element in determine the resulting risk levels.

In RISES-AM- we have considered Nature Based Solutions and additional adaptation requirements versus conventional engineering and present adaptation in terms of their suitability for various coastal archetypes quantifying whenever possible the expected performance. We have also addressed the question of the technological, economic, social and institutional barriers that affect our present applications of Nature Based Solutions (NBS).

This research effort will help to advance the NBS concept, now often expressed in qualitative terms, towards an operational proposal for interventions that should work aligned with natural processes rather than opposing them. The developed work suggests that Nature Based Solutions should be:

- Less invasive and impacting that conventional approaches.
- Less energy demanding both for initial construction and for maintenance during the life of the intervention.
- More flexible and self-adaptable under a wider range of conditions.

Traditional interventions such as a rigid sea wall or soft but still conventional engineering based on artificial sand nourishment will become difficult to maintain under an accelerated rate of sea level rise compounded by a change in storminess (affecting not only wave height but also wave direction). The application of NBS as a natural way to cope with the uncertainty of future climates will mean a higher sustainability in the long run, in terms of impacts and costs.

Coastal wetlands, for example, are well known for their capacity to damp storm wave and surge action and may be created where enough accommodation space is available. Another example is the reintroduction of natural water and sediment fluxes into sediment starved deltas to slow down the vertical and horizontal erosion. A third example would be a combination of local retreat to recover the back beach as a buffer for dissipating wave energy and the generation of sand deposits with increased sediment fluxes from land.

The implementation of any type of NBS, inherently more flexible than conventional measures, is likely to benefit from a structured coastal adaptation plan, combining that flexibility with coastal land uses and dynamics, bounded by rigid coastal infrastructure and present socio-economic pressures. NBS will also require a monitoring effort to assess their performance and, because of their flexibility, to suggest critical thresholds or tipping points so that suitable corrective measures or maintenance interventions can be designed and implemented, preferably within an adaptation pathway with wide social support.

Our structured dissemination has led to a significant presentation of the RISES-AM- in front of scientific groups practitioners and decision makers (including also policy making on some of the occasions). As shown in the corresponding Deliverable the number of papers and book chapters with peer reviewing has been of 52, corresponding 10 to the year 2014, 9 to the year 2015 and 33 to the year 2016.

The number of communications has also been well spread throughout the project execution with 19 for the year 2014, 47 for the year 2015 and 33 for the year 2016. It is worthwhile mentioning that we have already sent 5 communications for the next year related to the work in RISES-AM- and we have 14 papers in preparation for this coming year.

Regarding the number of meetings with stakeholders and the organization of the corresponding workshops the total number in the duration of the RISES-AM- project has been 46, of which 22 were organized the first year to start promoting the RISES-AM- approach and tools, 14 in 2015 and 10 in 2016. This was supplemented by general presentations of the RISES-AM- project which have continued even until the present moment, after the official ending date of the project (e.g. TV report in the Spanish official channel first week of December about RISES-AM-). In specific terms there have been three TV/Newspaper presentations in 2013, 28 in 2014, 19 in 2015 and 24 in 2016, excluding the last mentioned one.

Special mention deserves the work done by the RISES-AM- team for the ECCA Conferences. We have contributed to the last edition in Copenhagen and we are now preparing a set of sessions and individual contributions to the ECCA-2017 in Glasgow. The work here corresponds to the research and application advances obtained during the project and make reference to a) regionalized projections (WP2), b) impact assessment with and without additional (WP3 and WP4), c) adaptation pathways that incorporate the general structure (WP1) and the economic implications (WP5). Since the evaluation is not yet make public there will be no further description of the individual papers or sessions. Only to remark that this work for climate adaptation has been done in cooperation with the parallel projects HELIX and IMPRESSIONS.

Finally the work in RISES-AM- has involved presentations and joint communications with stakeholders and decision makers so that the corresponding policy makers would take note this of the novel approach and interventions proposed in our project. This has been done at the level of study cases, teaming up with national representatives in the countries involved. From an international point of view we have used the International Transfer and Advisory Board and make connections also through other projects, such as for instance Hydralab+, where the component of adaptive interventions for coastal evolution under future climates is clearly included or RISC-KIT, where the tools are pretty similar but the analysis is carried out for present climate. RISES-AM- has also produced material to launch new national and international projects. The various partners have submitted various proposals, in some cases in cooperation with their coastal representatives. Some of the partners are also cooperating to launch or have already launched parallel projects with various linkages to RISES-AM-. For instance there has been a project on the economic implications led by the GCF partner. Another project dealing with the incorporation of satellite information or assessing coastal impacts has also been approved and is led by the UPC partner. All these activities illustrate the potential of the approach and tools considered and developed during the project.

References

The detailed list of references has not been here included for the sake of brevity. They can be found in the corresponding Deliverables and the list of papers produced during the project duration.

Address of project public website and relevant contact details

The RISES-AM- website is the following: http://www.risesam.eu

The RISES-AM- tweeter account is the following: @rises_am_

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C Use and dissemination of foreground

NOTE I: Completed and submitted to EC through SESAM application.

NOTE II: The most complete list of publications and dissemination activities is summarized in Deliverable 6.3.

D Report on societal implications

NOTE: Completed and submitted to EC through SESAM application.