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METHODOLOGICAL CHALLENGES AND STRATEGIES TO INCORPORATE CLIMATE CHANGE INTO FLOOD RISK ANALYSIS OF SPANISH COASTAL CITIES

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ABSTRACT

Flooding of coastal cities may arise from a combination of coastal and inland flooding, which requires understanding complex correlations and dependencies between multiple agents (precipitation, storm surge, tide...), and conducting joint analysis of future changes due to climate change. In this work we explore some of the intrinsic variabilities of some of the multiple drivers usually associated to the climate change: increased intensity of storms (wind, precipitation, waves, etc.) and concomitant sea level rise. Mean sea level rise alone will already increase the probability of coastal inundation relative to fixed elevations from a combination of such flood agents. In addition, vulnerability of coastal cities is aggravated by the concentration of population and economic activity, with a continued upward trend in projection. The above flood risk drivers pose an inevitable challenge to coastal management. Coastal cities must adapt to future flood risk conditions, which requires knowledge-based long term planning. In this work we discuss some of the practical challenges encountered and the strategies and methods that can be adopted to incorporate climate change into flood risk analysis of Spanish coastal cities. We focus on the following aspects: (1) The characterization of the joint behavior of the inland and marine agents at the coast, and the evaluation of their hydrodynamic interactions; and (2) The derivation of local-scale projections of the required surface variables from the output of global climate models, and the assessment of their uncertainty.

Keywords: Flood risk, coastal cities, climate change, Spain

1 INTRODUCTION

Floods are the most common natural hazard worldwide. According to the global EM-DAT database, they represented nearly half of all weather-related disasters in the period 1995-2015 and affected more than 2 billion people (CRED and UNISDR, 2015). In Spain, 43.3 % of the insurance claims from extraordinary events in the period 1971-2017 were related to floods, representing 61.7 % of the total compensatory payments (6 billion €) (CCS, 2018).

Global warming is expected to increase the risk of floods worldwide, particularly in low-lying coastal areas, through changes in sea level and storminess (IPCC, 2014). Projected increases in extreme high coastal water levels along the European coastline are likely to be mostly the result of increases in local relative mean sea, although increases in the meteorologically driven surge component can also play a substantial role (EEA, 2017). According to the pan-European assessment of future extreme sea levels conducted by Vousdoukas et al. (2017), 5 million Europeans currently under threat of a 100-year sea level could be annually at risk from coastal flooding under high-end warming by 2100. Without adaptation, up to 1.5 million people in Europe are expected to be flooded annually by the end of the century, with annual coastal flooding damages reaching 0.86 % of Europe's Gross Domestic Product (Vousdoukas et al., 2018).

The concentration of population, their properties and services in coastal areas contributes to high flood risk. With more than 7000 km of coastline, Spain has a high overall vulnerability to flooding and erosion (Policy Research Corporation, 2009). Within the past 40 years, large stretches of coast, particularly along the Mediterranean, have become largely artificial, with new beach developments, tourism resorts, marinas and harbors. It has been suggested that the observed increase in economic losses caused by flood events on this coast is in fact primarily a result of an increase in vulnerability and exposure during periods of economic growth and legal laxity, rather than an increase in natural hazard activity (Pérez-Morales, 2018). This upward trend in vulnerability is almost certain to continue due to the increase in tourism flows to the coast, Spain being the second world destination by international tourist arrivals and receipts (WTO, 2018).

In this work we discuss the practical challenges encountered and the methods that can be adopted to incorporate climate change into flood risk analysis of Spanish coastal cities. The temporal horizon extends to

2100. The ultimate aim is to guide the resilient and sustainable development of Spanish coastal cities under changing climatic conditions and increased human pressures.

2 CLIMATE CHANGE ON THE SPANISH COAST

Here we adopt the working hypothesis that global warming is changing the magnitude and frequency of extreme sea level events worldwide. In spite of the lack of full scientific certainty, the precautionary principle should be adopted given the potential serious and irreversible consequences. This requires that we predict long-term climate change and understand and quantify the uncertainties affecting the predictions.

The change in the extreme sea level events has been mainly attributed to the observed rise of the mean sea level (MSL) (Menéndez and Woodworth, 2010), which increases the probability of coastal inundation relative to fixed elevations from a combination of marine, atmospheric and inland flood agents (storm surge, tides, river discharge, precipitation, etc.). However, the projected changes in such agents can also play a role in future extreme water levels. In the following, we give a brief overview of the observed changes and projections of these agents on the Spanish continental coast. For this purpose, we distinguish two regions: the Atlantic region (northern and western coast) and the Mediterranean region (southern and eastern coast). A summary is provided in Table 1.

In the previous 60 years, MSL rise has been in the order of 2 mm/year in the Spanish coast. At the end of the century, local MSL is estimated to rise around 0.5 m, with small differences depending on the location along the coast and Representative Concentration Pathway (RCP) scenarios considered (Losada et al., 2014). A multidecadal analysis has shown that depth changes caused by MSL rise, together with other associated mechanisms such as increased surface water temperatures, can also alter tide properties (Diez-Minguito et al., 2018). The observed tidal range variations along the Spanish coast have been low in recent years (in the order of 0.1 mm/year), except for some stretches of coastline such as the Gulf of Cádiz, where a decrease of nearly 3 mm/year has been observed. Global projections indicate that only minor changes of tidal amplitudes are anticipated in this century along the Spanish coast, although local oceanographic and terrestrial factors could exacerbate such changes at bays and estuaries (Schindelegger et al., 2018).

Table 1. Local MSL, tidal range, storm surge, waves and river discharge at the Spanish coast: past observed trends (in a period of the order of 60 years) and projections for 2100 under RCP8.5 scenario. Variation ranges along the coast are indicated in square brackets. Note: S_{50} is the 50-year storm surge height, P is the wave energy flux, H_{s12} is the significant wave height exceeded for 12 hours per year, Max H_s is the annual maxima H_s, H_{s50} is the 50-year return period of H_s, Q is the river discharge, and Q_{100} is the 100-year river discharge.

	SPANISH ATLANTIC COAST		**SPANISH MEDITERRANEAN COAST**	
	OBSERVATIONS	**PROJECTIONS**	**OBSERVATIONS**	**PROJECTIONS**
MSL	[+1.8, +2.9] mm/year	[+55, +65] cm	[+2, +10] mm/year (from 1990 onwards)	[+55, +65] cm
TIDAL RANGE	[-0.2, -0.11] mm/year	~2 cm variations for 0.5 m increase MSL	[-0.05, +0.1] mm/year	~2 cm variations for 0.5 m increase MSL
SURGE	S_{50}: -0.05 cm/year (W coast) +0.05 cm/year (N coast)	S_{50}: [-4, 0] cm	S_{50}: -0.05 cm/year	S_{50}: [-4, 0] cm
WAVES	Mean P: [+0.05, +0.15] W/m/year H_{s12}: [+0.4, +1.4] cm/year	Mean H_s: -0.2 m Max H_s: +0.5 m	Mean P: [-0.05, 0] W/m/year H_{s12}: [-0.6, -0.4] cm/year	Median H_s: ±10% H_{s50}: ±20%
RIVER DISCHARGE	Decreasing trend in extreme Q	Q_{100}: [-5, +25] %	Decreasing trend in extreme Q	Q_{100}: [-5, +40] %

Storm surges and wind waves can also be significant contributors to extreme sea levels. Past observations show a slight decrease of extreme surge levels along the Spanish coast (except for the Cantabrian coast), and projections suggest that surge levels will probably be relatively stable this century, or continue this slight decreasing trend (Losada et al., 2014; Marcos et al. 2011). A decrease in mean significant wave height (H_s) is projected across most of the European coast. However, projections show a potential increase in extreme waves in the Atlantic coast (Bricheno and Wolf, 2018). A general decrease of the median H_s is predicted in along most of the Spanish Mediterranean coast, but future projections disagree on both the sign and magnitude of the changes in extreme waves (Casas-Prat and Sierra, 2013). According to the precautionary principle and in lack of better knowledge, the worst case hypothesis of an intensification should be adopted.

Water levels are also dependent on river discharge in estuarine locations. A decreasing trend in magnitude and frequency of extreme river discharges was found by Mediero et al. (2014). The overall freshwater input to estuarine areas in Spain is projected to decrease (Diez-Minguito et al. 2018), whereas extreme river discharges might increase. An average increase of 11% is projected in the 100-year discharge by the end of the century (relative to 1971–2000, with RCP8.5) in the Iberian Peninsula (Paprotny and Morales-Nápoles, 2017). These changes will require new water resources management approaches to increase resiliency to both water excess and water scarcity.

With or without changes in climate itself, the concentration of population, infrastructure and economic activity developed around the coast all contribute to high flood risk (Jongman et al., 2012). The upward trend in vulnerability observed on the Spanish coast (Pérez-Morales, 2015) is almost certain to continue due to the continuing growth of coastal cities (Neumann et al., 2015). Globally, population density in flood-prone coastal zones is expected to grow by 25% by 2050 (Aerts et al., 2014). In addition to residents' groups (second home owners and permanent residents), the increase in tourism flows to the coast also needs to be taken into account. Although there is no reliable data on coastal tourism alone, it is generally considered to be one of the fastest growing forms of tourism in recent decades (UNEP, 2009). Deltas and coasts in areas like the Mediterranean might have already entered a persistent destruction phase due to the human-induced changes in hydrodynamic conditions and sediment supply (Anthony et al., 2014), which will be exacerbated by pressures associated to climate change.

3 INCORPORATION OF CLIMATE CHANGE INTO COASTAL FLOOD RISK ASSESSMENTS

The changes described in the previous section pose an inevitable challenge to Spanish coastal cities, and highlights the need for adequate models to evaluate flood risks and inform climate change adaptation planning. This is however far from straightforward, given the complexity of coastal systems, the limitations of climate and impact models and the uncertainty of future socioeconomic development. The intertwined competences of the state, regional and local administrations over the Spanish coastal areas also complicates the adoption of integrated management strategies.

In the following we discuss some of the practical challenges encountered and the strategies and methods that can be adopted to incorporate climate change into flood risk analysis of Spanish coastal cities. We focus on the following aspects: (1) the characterization of the joint behavior of the inland and marine flood agents at the coast; and (2) the derivation of local-scale projections from global climate models (GCMs) and the quantification of their uncertainty.

3.1 Joint behavior of the marine and inland flood agents at the coast

Most of Spanish coastal towns and cities are located on estuaries and coastal river reaches. Extreme water levels in these areas depend on the interaction between marine dynamics, defined by agents such as the tide or the storm surge, and inland dynamics, mainly governed by the river discharge. A given water level can thus result from different combinations of these dynamics, which makes the estimation of the exceedance probabilities much more complex than in a typical univariate problem. The simultaneous occurrence of high waves, storm surge and river discharge, associated with the passage of a storm, can in fact be the cause of the highest water levels at these locations. Some examples of compound flood events (surge-discharge or surge-precipitation) occurred in Spain can be found in Paprotny et al. (2018).

The case of the river Mandeo, as it passes though the town of Betanzos, in Northwest Spain (Figure 1) is used to illustrate importance of considering marine dynamics on the estimation of extreme water levels in coastal river reaches. For a representative example of the interplay between inland and marine forcings in Mediterranean coast, the reader is referred to previous works in Playa Vera in Andalusia (García et al., 2013). The river Mandeo flows into the inner part of the estuary of Betanzos, with tidal ranges between 1.5 m and 4.5 m, and maximum storm surges of approximately 0.5 m. The area is classified as high potential flood risk of fluvial and coastal origin by the regional authorities, since it is vulnerable to flooding from both high sea levels and high precipitation. Water depth frequency distributions calculated at different points along the river are shown in Figure 2. Two different depth frequency distributions are calculated. They consider both coastal and inland dynamics, but differ in the way coastal dynamics are defined. In the first case, coastal dynamics are defined by the tidal range and the storm surge, whereas in the second case the contribution of the storm surge is neglected, and the sea level only depends on the tidal range. Details of methodology followed to estimate return period water levels are given in Bermúdez et al. (submitted). As shown in Figure 2, neglecting the storm surge contribution results in a significant underestimation of the inundation depth at points close to the sea. The influence of the sea level decreases as we move away from the river mouth, but it is still a relevant contributor to extreme water levels up to control point P5 (Figure 1). This corroborates the influence of this parameter on the water depth in this area.

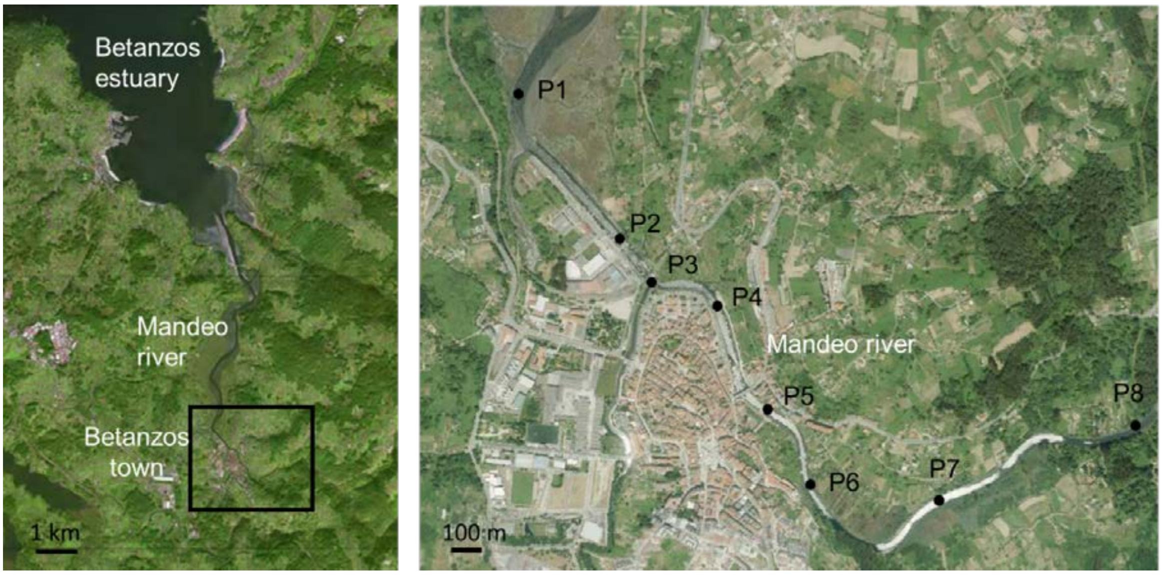

Figure 1. Aerial images of the estuary and town of Betanzos. Location of control points (P1 to P8) along the river Mandeo.

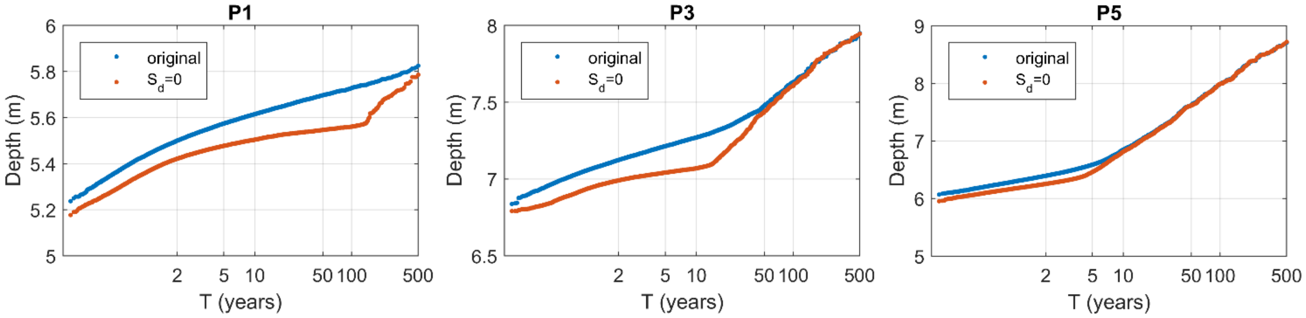

Figure 2. Depth frequency distribution obtained at points P1, P3 and P5 with the original simulation and the simulation that neglects the storm surge (S_d=0).

To determine the probability of a critical water level taking place, it is thus necessary to assess the joint probability distribution function of extreme total water events, considering multiple simultaneous components. This in turn requires information about the individual components (i.e., the flood agents) and their interactions. In order to characterize the space-time variability of the agents, and the hydrodynamic interactions between them, integrated hydrologic-hydraulic-coastal modelling frameworks are needed. Such frameworks must enable the combined modelling of fluvial flows, tides, surges and waves at the appropriate temporal and spatial resolutions. A compromise between resolving finer spatial structure or high-frequency temporal variability is frequently made, due to the limitations of the available data or the modelling methods (Qu and Hetland, 2019). In the above example of the river Mandeo and the town of Betanzos, daily time series of the main flood drivers (in this case the tide, storm surge and river discharge) are downscaled to a higher time resolution and then simulated in a high resolution 2D flood inundation model. The downscaled tidal level and surge are used as the downstream boundary condition, while the river hydrograph is imposed at the upstream inlet boundary in the 2D inundation model. This model is applied to understand the interaction between the different sources of flooding and to provide detailed estimates of flood inundation and hazard (Figure 3). In this case, morphology is assumed to remain static during the flooding process. However, morphological changes could also be incorporated in the method if erosional impacts are expected to exert a relevant influence on flood risks (Pollard et al, 2018).

In order to fully explore the combinations of flood agents that can occur, it is necessary to use a probabilistic framework and perform a high number of model runs. This is computationally costly for complex hydrodynamic models, such as the ones described above, especially when high spatial and temporal resolutions are required. A strategy that has proven successful in many recent studies is the development of computationally more efficient surrogate models (or metamodels) based on artificial intelligence methods (Razavi et al., 2012). A recent example of how this strategy can be applied to develop a rapid flood inundation model of a coastal urban area is described in Bermúdez et al. (2019). In this case, least squares support vector machine regression is used to predict flood hazard, resulting in comparable predictions to a physically-based inundation model, but with a significantly lower computing time. The combined used of a physical model, capable of reproducing the physics of the combined forcings, and a fast surrogate model which emulates its responses, is well suited to analyzing coastal flood systems.

Figure 3. Inundation maps for the return period of 2.3 years (from Sopelana et al. 2018).

3.2 Local-scale projections and their uncertainty

The methods described in the previous section can rely on long-term instrumental records, as well as new climate data sources such as model simulations, model-based reanalyses and remote sensors, to improve our knowledge of the flood system. However, the non-stationarity inherent in natural systems, as well as changes induced by human activity, need to be considered in order to estimate future extreme total water level event frequencies. Present statistics, based on historical records, may not be representative of future conditions. For example, large-shifts in the climate system (sometimes called “tipping points”) have the potential to generate outcomes that are difficult to anticipate and may have high consequences (Jay et al., 2018).

Future climate projections based on RCP scenarios simulated by Global Climate Models (GCMs) are typically used for local impact analysis studies. Downscaling techniques are applied to address the scale mismatch between the GCMs and the small-scale required for impact analysis, or to derive variables that are not directly available from GCMs. Downscaled precipitation for the catchment of Betanzos, used as illustrative example throughout the paper, is shown in Figure 4. These data, together with changes in temperature, humidity and other relevant variables, can be fed into a hydrological model to assess impacts on streamflow.

However, impact analysis following this top-down approach (i.e., from climate change scenarios to impact models) is not without limitations. In addition to the uncertainty associated with future scenarios given by IPCC, GCMs are simplifications or the climate system, and their skill in simulating extremes is limited due to the parameterization of climate processes and properties. Downscaling techniques can only partly circumvent the problem (IPCC, 2012), since they still depend heavily on the GCM data that is fed in. GCM projections and downscaling methods must preserve the intervariable consistency of the meteorological conditions that lead to flood events, which is still a key open question (Keller et al. 2018). Impact analysis typically employ multi-model and multi-scenario ensembles, where each member of the ensemble is assumed to be equally likely, to account to some extent for the uncertainty in projected impacts that stems from the above factors. In many cases, highly variable impacts, which may differ in magnitude and direction among ensemble members, are obtained. By way of example, the rainfall projections for the catchment of Betanzos, which consider only one RCP scenario and a single statistical downscaling method, show a wide spread among GCMs (Figure 4). These large uncertainties and the difficulty of assigning probabilities to the different outcomes hampers the development of robust strategies for adapting to climate change. However, this should not be used as a reason for postponing the adoption of adaptation measures; the precautionary principle must prevail.

Although top-down approaches currently prevail in the literature, bottom-up frameworks could be better suited for climate impact studies. These scenario-neutral approaches explore the system responses to plausible changes in climate conditions, which can go beyond the bounds projected by GCMs. The combinations of drivers under which the system performs satisfactory or not can be identified, and then the likelihood of such combinations can be explored working backwards (Zscheischler et al., 2018). Examples of how this approach can be used in water resource system management can be found in Culley et al. (2016) or Wilby and Dessai (2010). These studies provide evidence of how significant progress can be made in adaptation planning without climate change projections.

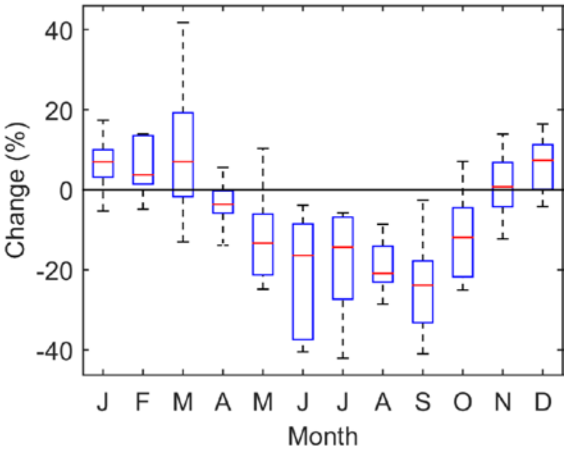

Figure 4. Changes in mean monthly maximum daily precipitation based on GCMs of RCP85 (from Bermúdez et al. 2018).

4 CONCLUSIONS

Projected changes in climate and sea levels, together with the urban growth in coastal flood-prone areas, pose an inevitable challenge to Spanish coastal cities. There is an urgent need to develop robust methods and strategies to incorporate climate change into flood risk analysis.

In this work we first emphasize the need to properly characterize the joint behavior of the inland and marine flood agents at the coast, and to evaluate their hydrodynamic interactions. To reproduce the physics of the combined forcings, covering all possible combinations of flood agents, complex integrated hydrologic-hydraulic-coastal models need to be applied in a probabilistic framework. We then discuss top-down and bottom-up approaches for climate change impact analysis. The latter frameworks explore the system responses to plausible changes in climate conditions without relying on uncertain GCM-based climate change projections, and are potentially more suitable for climate change adaptation.

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