3.6 Hydrological risk: wave action, storm surges and coastal flooding

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3.6.1 Overview of coastal flood risk

Coastal flooding is one of the most significant risks to life and infrastructure both globally and for Europe, with wide-ranging social, economic and environmental impacts. For example, in the United Kingdom alone, it is estimated that GBP 150 billion (EUR 177 billion) of assets and 4 million people are currently at risk from coastal flooding (Environment Agency, 2009). In Europe, long-term investment in operational flood warning systems has largely ensured that fatalities due to coastal flooding are avoided; however, the damage to infrastructure and clean-up costs are still significant. For example, during storm Xaver (4-8 December 2013) which brought the highest ever observed water levels to many European coastlines, there was no loss of life due to coastal flooding (although there were 15 fatalities directly associated with falling trees and vehicles).

Coastal flooding is one of the most significant risks to life and infrastructure both globally and for Europe, with wide-ranging social, economic and environmental impacts. For example, in the United Kingdom alone, it is estimated that GBP 150 billion (EUR 177 billion) of assets and 4 million people are currently at risk from coastal flooding (Environment Agency, 2009). In Europe, long-term investment in operational flood warning systems has largely ensured that fatalities due to coastal flooding are avoided; however, the damage to infrastructure and clean-up costs are still significant. For example, during storm Xaver (4-8 December 2013) which brought the highest ever observed water levels to many European coastlines, there was no loss of life due to coastal flooding (although there were 15 fatalities directly associated with falling trees and vehicles).

In contrast to European weather systems, tropical cyclones can cause storm surges of up to 10 metres, which continue to cause devastating loss of life in parts of South-East Asia. In 1970, a devastating storm surge resulted in approximately a quarter of a million deaths in Bangladesh. Over the past decade, there has been considerable activity in the development of crucial flood warning systems for vulnerable tropical areas such as Bangladesh (DMB, 2010; WMO, 2010), resulting in the saving of tens of thousands of lives. However, despite the improving availability of coastal warning systems, tropical cyclones continue to cause havoc when this is a lack of preparedness. On 8 November 2013, Typhoon Haiyan (known as typhoon Yolanda in the Philippines) caused catastrophic damage throughout the Philippines, with the majority of the death toll (estimated to be more than 6 000 people) attributable to the storm surge that struck Tacloban City.

Coastal flood risk is growing because of long-term mean sea-level rise and possible future changes in storminess (Church et al., 2013), as well as continued population growth and development in flood-exposed areas (Hallegatte et al., 2013). Irrespective of any future change in storm climate (which would affect storm surges and waves), mean sea-level rises will result in more instances of extreme sea-level

Coastal flooding is caused by a combination of high tides, storm surges and wave conditions. Development on floodplains increases the risk as do coastal erosion and sea-level rise.
Coastal flooding occurs when a combination of high tide, storm surges and wave conditions is sufficiently severe to overtop or breach coastal defences and cause inundation of low-lying areas. Extreme high waters around Europe are normally caused by a combination of high tides and severe weather events (with the exception of the Mediterranean Sea where tides are small). Extra-tropical cyclones (the prevailing European weather systems) produce storm surges that can increase tidal levels by 3-4 metres in exceptional cases. The still water level (defined as the sea level before short-period waves are taken into account) can be further elevated at the coast by wave set-up caused by wave breaking. Storms then also produce large wind and swell waves, which can overtop coastal defences/beach- and cause flooding and erosion. A further factor that drives coastal flood risk is socioeconomic change (Thorne et al., 2007). Changes in land use and increasing asset values in floodplain areas have led to increased exposure to flooding (Horsburgh et al., 2010). Changes in coastal morphology can also influence flood pathways and thus flood risk (Thorne et al., 2007; Nicholls et al., 2015). As erosion is expected to dominate coastal morphological change in the future because of mean sea-level rises, this will add to the overall flood risk.

Waves and storms are a significant feature of global climate and have been included in many assessments of climate, including the latest assessment (AR5) of the Intergovernmental Panel on Climate Change (IPCC, 2013). Recently, recognition of the central role of waves in atmosphere–ocean interactions has led to an initiative to include wave models more directly into climate model projections (Cavalieri et al., 2012; Hemer et al., 2012). The largest waves in European waters are found on the Atlantic boundaries, where waves can propagate over large fetches from the Atlantic Ocean. Many factors affect the height of waves in European waters, but for the Atlantic margin, the persistence and strength of westerly winds are particularly important (Wolf and Woolf, 2006), as are the intensity and frequency of storms. Waves are affected by currents and water depth and are locally modified by coastal geometry and man-made structures. Waves decrease in height in shallow water as a result of energy dissipation by bottom friction and wave breaking; this reduction in wave energy at a particular location may reduce over time, if the sea level rises, unless the coastal morphology in areas of mobile sediment can adapt at a similar rate (Woof and Wolf, 2013). Extreme waves represent a hazard for any offshore operation or construction. Hazards may be due to, for example, large individual or significant wave heights, steep waves, crossing seas, or rapidly developing sea states (Toffoli et al., 2005). At the coast, wave overtopping or the impact of the waves on structures may become important. On longer timescales, changes in coastal wave climate may cause changes in the sedimentation and erosion patterns that in the long run will have impacts on sediment and shoreline dynamics (Wong et al., 2014). As sea levels rise and the rate of rise accelerates, low-lying coastal regions may be inundated, allowing waves to penetrate further inland, thus causing further damage.

### 3.6.2 Natural variability of waves, storm surges and mean sea level

All components of sea level display considerable natural variability, which influences the frequency of flooding on all timescales. Natural variability in the wave, storm surge and mean sea-level components ranges from variability associated with stochastic processes, to those displaying seasonal and longer period changes associated with regional climate (e.g. the quasi-decadal cycle known as the North Atlantic Oscillation - NAO). Europe experienced an unusual sequence of extreme storms over the winter of 2013-2014, resulting in some of the most significant coastal flooding since the catastrophic North Sea storm surge of 1953 (Matthews et al., 2014; Haigh et al., 2016).

Sea-level change at any particular location depends on many regional and local processes as well as global climate drivers, so regional sea-level change will differ from the global average. The fifth assessment report (AR5) of the IPCC concluded that it is very likely that the average rate of global averaged sea-level rise was 1.7 mm per year between 1901 and 2010 (IPCC, 2013). For the more recent period 1993-2010, this had risen to 3.2 mm per year, with consistency between tide-gauge and satellite altimeter data. It is likely that similarly high rates occurred between 1920 and 1950. Although there is a great deal of local variability in the measured values, mean sea levels around Europe (from tide gauge records) mostly exhibit
20th century rises that are consistent with the global mean value, although the central estimate around the United Kingdom is slightly lower than that of the global value (Woodworth et al., 2009). There is high confidence that the rate of observed sea-level rise increased from the 19th to the 20th century (Bindoff et al., 2007; Woodworth et al., 2011) and there is evidence of a slow long-term acceleration in the rate of sea-level rise throughout the 20th century (Church and White, 2011).

All components of sea level exhibit natural variability. There is no convincing evidence of observed changes in European storminess. Changes in extreme levels are driven by mean sea-level change.

Whether the faster rate of increase in sea level during the period from the mid-1990s reflects an increase in the longer-term trend or decadal variability is still not clear. For planning and engineering purposes, it is sea level with respect to the local land level that is of primary interest; furthermore, the Earth itself is moving as it recovers from ice loading during the most recent ice age. A key process that affects vertical land motion is the viscoelastic response of the solid Earth to deglaciation, termed glacial isostatic adjustment (GIA). An accurate understanding of regional sea-level change is a particular area that involves combining the global models of eustatic sea-level change (i.e. sea-level rise due to volume changes as well as geological changes to ocean basins) with local models of GIA modified localised effects at the coast (e.g. Smith et al., 2012). A further complication is that sea-level change is affected by large-scale gravitational adjustment in response to polar ice melt. Mitrovica et al. (2001) showed how rapid melting of major ice sources gives rise to spatial changes in the Earth’s gravity field (as well as to the volume of water in the oceans); their model predicts a fall in relative sea level close to the source of melting as the gravitational interaction between ice and ocean is reduced, but a correspondingly larger rise in sea level further from the melt source.

Storm surges are the large-scale increases in sea level due to a storm. They can increase sea levels by 3-4 metres in European coastal seas and may last from hours to days and span hundreds of square kilometres. They are caused by wind stress at the sea surface and the horizontal gradient of atmospheric pressure (Pugh and Woodworth, 2014), although the magnitude of any particular storm surge is influenced by many factors, including the intensity and track of the weather system, bathymetry and coastal topography. The same factors control storm surges caused by mid-latitude weather systems (extra-tropical cyclones) and tropical cyclones (hurricanes). In regions of high tidal range, storm surges represent the greatest threat when they coincide with tidal high water: most operational forecasting centres now systematically refer to the combination of a storm surge and tidal high water as a storm tide.

In a strongly tidal region such as the European shelf, it is important to understand the interaction between storm surges and tides. Such interactions have been extensively studied (e.g. Rossiter, 1961; Prandle and Wolf, 1978). The dominant mechanism for tide-surge interaction is increased water levels as a result of meteorological forcing that induce a phase shift in the tidal signal (Horsburgh and Wilson, 2007); many properties of a non-tidal residual time series (i.e. the time series of sea-level observations minus tidal predictions) are simply artefacts of small changes to the timing of predicted high water. The most useful measure of storm surges is the skew surge, which is the difference between the maximum observed sea level and the maximum predicted tidal level, regardless of their timing during the tidal cycle (de Vries et al., 1995). Hence, each tidal cycle has one predicted high water value and one associated skew surge value. The advantage of using the skew surge is that it is a simple and unambiguous measure of the storm surge. Williams et al. (2016) have now shown that the magnitude of high water exerts no influence on the size of the most extreme skew surges. This is the first systematic proof that any storm surge can occur on any tide, which is essential to understand worst-case scenarios. The lack of surge generation dependency on water depth emphasises the dominant natural variability of weather systems. Weak seasonal relationships between skew surges and tidal high waters have been identified, and the inclusion of these in statistical methods will improve the estimates of extreme sea levels.

Storm surges are, of course, generated by storms, and there has been much
recent research aimed at understanding past and future changes in storminess over Europe due to the changes in mid-latitude storms over the North-East Atlantic. Trends in severe wind storms around the United Kingdom are difficult to identify, owing to the low numbers of such storms, their decadal variability and the unreliability of direct wind speed observations (Wang et al., 2009).

Wang et al.'s analysis shows that storminess conditions in this region have undergone profound decadal or longer timescale fluctuations, with considerable seasonal and regional differences. The most notable differences are seen between winter and summer, and between the North Sea area and other parts of the region. Over the last century the number of winter storms has decreased and then increased again. The observational evidence indicates that the strength of mid-latitude sea-level pressure (SLP) gradients and associated westerly circulation has increased in the northern hemisphere, especially during winter, since at least the late 1970s (Woolf and Wolf, 2013). The behaviour of North Atlantic storm tracks is key to understanding present and future changes in storminess. Future climate model projections have a large variability between models and a low signal-to-noise ratio for Europe compared with other mid-latitude regions (Hawkins and Sutton, 2009). Woolings (2010) identifies future European climate as particularly uncertain because (1) the spread between the predictions of current climate models is still considerable and (2) Europe is particularly strongly affected by several processes, which are known to be poorly represented in models, such as the small-scale structure of storms. Some of this variability seems to be related to the large-scale atmospheric patterns such as the NAO, which is related to the SLP difference between Iceland and the Azores. However, it is not clear that this relationship will persist into the future.

Wave climate in the North-East Atlantic and in European seas is to a large extent determined by the large-scale atmospheric circulation, the statistics of large-scale extra-tropical storms and smaller scale regional and local wind systems. Natural climate variability or anthropogenic changes in such factors will affect the wind climate, which results in corresponding changes to the wave climate. Changes in local wind climate will affect the wind sea, while changes in remote storm statistics will have an effect on the swell component of the wave climate. For the North-East Atlantic, Wolf and Woolf (2006) performed a number of sensitivity experiments with a numerical wind–wave model. By using synthetic wind fields, varying the strength of the prevailing westerly winds and the frequency and intensity of storms, as well as the location of storm tracks and the storm propagation speed, they found that variations in the strength of the westerly winds was most effective at changing mean and maximum significant wave height, while variations in other parameters had little effect on the mean wave height. Intensity, track and storm propagation speed, however, significantly affected maximum wave height. Generally, in all European Shelf seas and in the North-East Atlantic, pronounced seasonal variability in wave climate is seen with the highest waves in autumn and winter (e.g. Dodet et al., 2010; Arkhipkin et al., 2014).

Based on the assessment of literature analysing data from in situ measurements, satellite altimeter observations and wave model hindcasts, the IPCC AR5 concluded that it is likely that mean significant wave heights have increased in regions of the North Atlantic over the past half-century and that it is likely that these trends largely reflect natural variations in wind forcing (Church et al., 2013). For the North Sea and Baltic Sea, recent work is summarised in Huthnance et al. (2016) and Hünicke et al. (2015), indicating that wave height in these seas varies substantially on inter-annual and decadal timescales but does so far not show significant long-term trends. Using 20 years of buoy data for the Bay of Biscay, Dupuis et al. (2006) reported a tendency towards decreasing wave heights, which is consistent with the findings published in Dodet et al. (2010). For the Mediterranean Sea, Lionello and Sanna (2005) reported decreasing mean winter values of significant wave height in the period 1958–2001, while for the Black Sea, Arkhipkin et al. (2014) reported no significant change in corresponding storm activity.

The IPCC (2013) confirms that at most locations mean sea level is the dominant driver of observed changes in sea-level extremes, although large-scale modes of variability such as the NAO may also be important. There is evidence of increases in extreme water levels over the past 100-200 years around many parts of the global coastline, including Europe (e.g. Menendez and Woodworth, 2010). While changes in storminess could contribute to changes in sea-level extremes,
there is little or no evidence for either systematic long-term changes in storminess or any detectable change in storm surges (IPCC, 2012). The scientific consensus is that any changes in extreme sea levels at most locations are caused by the observed rise in mean sea level (e.g. Woodworth and Blackman, 2004; Menendez and Woodworth, 2010; Wahl and Chambers, 2016).

3.6.3 Datasets for coastal flood hazard analysis

The importance of having long time series data for assessing the statistics of extremes is well known (e.g. Weisse et al., 2009). A long time series of wave observations (at least 10 years and, ideally, 30 years) is required to describe the wave climate (Wolf et al., 2011). Such knowledge is required to characterise coastal vulnerability and to plan coastal management strategies. We know that there is also a large amount of inter-annual and inter-decadal variability, which can obscure any observation of long-term trends. There are few long-term wave datasets for European waters. One example is the United Kingdom Met Office Marine Automatic Weather Station (MAWS) system, which consists of various met-ocean recording systems, some of which have been maintained for several decades. A review by Hawkes et al. (2001) assessed the data available and led to the establishment of the CEFAS Wavenet network (n.d.).

Data collected from the Seven Stones Light Vessel since 1962 led to the earliest observation of an increase in wave height in the North Atlantic (Bacon and Carter, 1991). This observation has since been validated and extended using altimeter wave data and models and attributed largely to changes observed in the North Atlantic atmospheric circulation patterns, principally the NAO (Woolf et al., 2002, 2003; Wolf and Woolf, 2006). Owing to the lack of long-term datasets, numerical models are often used to extend the time series, and many global and regional wave hind-casts and reanalyses are now available (e.g. ERA-Interim, ERA-20C from the European Centre for Medium-range Weather Forecasts (ECMWF, n.d.).

Datasets covering more than 30 years of wave observations are essential for flood hazard analysis. All coastal European countries store sea-level data. There are fewer wave datasets but satellite data are increasingly useful.

Long time series are increasingly available from satellite observations, although these are less reliable in the coastal zone. Improved algorithms now allow these data to be used closer to the coast (e.g. Gommenginger et al., 2010). Long time series data can also be generated using proxy data from time series of other variables (e.g. SLP data can be used as a proxy for storminess or can be generated from long hindcasts of dynamical models). Projections of future impacts that the relationships between proxy variables will remain the same in a future climate or may be made by running dynamic models into the future. Local impact models are highly dependent on the accuracy of projections of storminess in global climate models (where storminess may be defined as a measure of the frequency and intensity of storms).

Sea-level data from most European nations are archived and made available through their national data repositories. For instance, the British Oceanographic Data Centre is responsible for the remote monitoring and retrieval of sea-level data from the tide gauge network. These are then processed and quality controlled prior to being made available for scientific use. Several other European nations offer a similar facility (e.g. Système d’Observation du Niveau des Eaux Littorales, SONEL, in France and National Oceanographic Data Committee, NODC, of the Netherlands). For long-term sea-level analysis, a global record of sea levels is available from the Permanent Service for Mean Sea Level, which is responsible for the collection, publication, analysis and interpretation of sea-level data from the global network of tide gauges (PSMSL, 2017).

In order to better understand historical magnitudes and footprints of coastal flooding events for the United Kingdom, a systematic database of extreme sea level and coastal flooding has been compiled, covering the past 100 years (Haigh et al., 2015; www.surgewatch.org). Using records from tide gauges, all sea levels that reached or exceed the 1 in 5 year return level were identified. These were attributed to 96 distinct storms, the dates of
which were used as a chronological base from which to investigate whether historical documentation exists for a concurrent coastal flood. For each event, the database contains information about the storm that generated that event, the sea levels recorded during the event, and the occurrence and severity of coastal flooding that resulted. This database is continuously updated. Similar databases for Europe-wide flooding could be conceived and created.

3.6.4 Future climate projections of waves, storm surges and mean sea level

The IPCC (2013) has projected global sea-level rise for the period 2081-2100, compared with 1986-2005, to be 0.29–0.82 metres. The precise range varies with the assumed Representative Concentration Pathway (RCP) scenario, which describes the radiative imbalance in Earth’s atmosphere due to greenhouse gas emissions. Unlike in the previous IPCC report, these projections now include a contribution from changes in ice-sheet outflow, for which the central projection is 0.11 metres (it should be noted that there is only medium confidence in the range of projected contributions from models of ice sheet dynamics). Nevertheless, these new projections are broadly similar to those in the earlier AR4 assessment (IPCC, 2007). It is very likely that the rate of global mean sea-level rise during the 21st century will exceed the rate observed during the period 1970-2010 for all RCP scenarios. Regional patterns of sea-level change in the 21st century still differ between models. However, about 70% of the global coastlines are projected to experience a sea-level change within 20% of the global mean sea-level change.

Some studies use simple statistical, so-called ‘semi-empirical’, models that relate 20th-century (e.g. Rahmstorf, 2007) or earlier (e.g. Vermeer and Rahmstorf, 2009; Grinsted et al., 2010) temperature or radiative forcing (Jevrejeva et al., 2010) with sea-level rise, in order to extrapolate future global mean sea level. These models are motivated by evidence in the palaeo record of a connection between global mean sea level and temperature over glacial/interglacial timescales. These models result in wider ranges, and typically larger, projections of sea-level rise than those obtained from physical process-based models. For example, Rahmstorf (2007) has projected sea-level rise by 2100 under a range of climate scenarios to be between 0.50 and 1.40 metres, and Vermeer and Rahmstorf (2009) suggested the higher range of 0.75 to 1.90 metres. Church et al. (2011) note that these models may overestimate future sea levels because of the exclusion of key non-linear processes and climate feedback mechanisms. In addition, future rates of sea-level rise may correlate less well with global mean temperature if ice sheet dynamics play an increased role in the future. Many national authorities have introduced high-end scenarios to aid contingency planning, the value of which justifies the numerous assumptions made. For the United Kingdom (Lowe et al., 2009), this low-probability but high-impact value was estimated to be 1.9 metres, which is consistent with physical constraints on glacier movement (Pfeffer et al., 2008); this value also encompasses the majority of semi-empirical model projections. For comparison, Katsman et al. (2011) used an alternative method to develop a high-end scenario of a 0.40- to 1.05-metre sea-level rise (excluding land subsidence) on the coast of the Netherlands by 2100. More recently, Jevrejeva et al. (2014) obtained a probability density function of the global sea level in 2100, suggesting that there is a 5% or smaller probability of a global sea-level rise greater than 1.8 metres; this low probability upper limit combined expert opinion and process studies and also indicates that other lines of evidence are needed to justify any larger sea-level rise this century. It is very likely that global mean sea-level rise will continue beyond 2100, even if greenhouse gas concentrations are stabilised immediately (which is unlikely). Contributions to sea-level rise from ice sheets are expected to continue beyond 2100, but glacier contributions will decrease as the amount of glacial ice diminishes. Some models suggest sea-level rises of between 1 metre and 3 metres in response to carbon dioxide (CO₂) concentrations above 700 parts per million. Studies of the last interglacial period (e.g. Kopp et al., 2009) indicate a very high probability of a sea-level rise of 2 metres over 1 000 years, and cannot rule out values in excess of 4 metres.

Overall there is low confidence in
future storm surge and wave height projections because of the lack of consistency between models, and limitations in the model capability to simulate extreme winds (IPCC, 2012). Numerous studies have used regional climate model forcing to drive storm surge and wave models to infer changes in extreme sea level for the Mediterranean (Conte and Lionello, 2013; Jordà et al., 2012; Marcos et al., 2011), North Sea (Debernard and Roed, 2008; Gaslikova et al., 2013; Howard et al., 2010; Worth et al., 2006), as well as the Atlantic coast of Europe (Lowe et al., 2001; Lowe et al., 2009; Lowe et al., 2010; Marcos et al., 2012) and Baltic Sea (Gräwe and Burchard, 2012; Meier, 2006; Meier et al., 2004), while the first pan-European study was by Vousdoukas et al. (2016a). Some of these studies suggested increasing levels of storm surge along parts of northern Europe.

While extreme sea levels could change in the future, both as a result of changes in atmospheric storminess and of mean sea-level rise, it is very likely that mean sea-level rise will continue to be the dominant control on upwards trends in extreme future coastal water levels. Vousdoukas et al. (2017; 2016a) concluded that that by the end of this century the 100-year extreme sea-level along Europe’s coastlines is on average projected to increase by 57 cm for RCP4.5 and 81 cm for RCP8.5. The North Sea region is projected to face the highest increase in ESLs, amounting to nearly 1 m under RCP8.5 by 2100, followed by the Baltic Sea and Atlantic coasts of the UK and Ireland. Mean sea-level rise is shown to be the main driver of the projected rise in extreme sea-level, with increasing dominance towards the end of the century and for the high-concentration pathway. Changes in storm surges and waves enhance the effects of sea-level rise along the majority of northern European coasts, locally with contributions up to 40%. In southern Europe, episodic extreme events tend to stay stable, except along the Portuguese coast and the Gulf of Cadiz where reductions in surge and wave extremes offset sea-level rise by 20-30%.

**Global mean sea level will rise between 0.3 metres and 0.8 metres this century. Larger rises are possible. There is low confidence in storm surge and wave projections due to climate model limitations.**

Regarding possible future wave climate changes, the IPCC AR5 notes low confidence in projections of future storm activity and hence in projections of wind waves (Church et al., 2013). For the Baltic Sea, Groll et al. (2017) found changes in the wave climate towards higher significant wave height for most regions that were consistent across their ensemble simulations. They noted that these changes result not only from higher wind speeds but also from a shift towards more westerly winds. In a comparable study for the North Sea, Groll et al. (2014) found a robust signal in eastern areas, where wave height was projected to increase towards the end of the 21st century in most of the analysed projections. For the west European Shelf, Zacharioudaki et al. (2011) found an increase in mean and extreme winter significant wave height south-west of the United Kingdom and the west of France. Elsewhere, decreases were found. This is consistent with the results provided by Charles et al. (2012), Menetaschi (2017) and Perez et al. (2015) who projected a general decrease in wave heights in the Bay of Biscay and Atlantic Europe by the end of the 21st century. Zacharioudaki et al. (2011) further emphasised that swell and wind sea may show different developments. For the north-west Mediterranean Sea, Casas-Prat and Sierra (2013) found some increase in mean and extreme projected wave heights, but noted that these changes were very much dependent on changes in wave direction and thus on wind direction in the global models that were not uniform. The findings are consistent with those for the Mediterranean Sea reported by Lionello et al. (2008, 2010), who projected a shift in the wave height distribution towards lower values. Similar changes are reported in Perez et al. (2015), who further noted that the decreases were larger for long-term and high-emissions scenarios.

The effect of sea-level rise on tides remains an open scientific question, since previous studies are not reaching consensus. There is observational evidence of changes in tidal constituents in the 20th century (Mawdsley et al., 2015) however the significance of the driving processes remains yet unresolved (Woodworth, 2010). Regional modelling efforts have shown that sea-level rises exceeding 2 m can
affect tidal amplitudes and phases (Pickering et al., 2012). For smaller sea level rises (~1 m) some studies find significant tidal changes (Arns et al., 2015; Idier et al., 2017; Pelling and Green, 2014) whilst others report negligible effects (Lowe et al., 2001; Sterl et al., 2009; Vousdoukas et al., 2017).

### 3.6.5 Tools and methods for assessing coastal flood hazard

Downscaling from global to regional climate change projections is vital for the study of meaningful local impacts (Wolf et al., 2015). Downscaling is generally taken to refer to the generation of locally relevant data from the output of Global Circulation Models (GCMs). The aim is to use global-scale projections, using accepted greenhouse gas emissions scenarios, to generate regionally specific and useful forecasts, with increased spatial and temporal resolution, and including processes that are not resolved in the coarser resolution model. Downscaling can be done in several ways: (1) using process models, (2) using empirical/statistical relationships, and (3) using hybrid methods (e.g. pattern recognition). Nesting an RCM into an existing GCM is an example of the first method, termed dynamical downscaling. An RCM is a dynamic model that gives higher resolution results than a GCM. Downscaling can also be done using statistical regression. This aims to capture the essential relationships (often calibrated using relationships in the current climate) between the global model and local variables.

Extreme events are linked to coastal flooding and for that reason inundation maps are a crucial element for coastal management and engineering practices (Ferreira et al., 2006), and evaluation of adaptation options (Cooper and Pile, 2014; Hinkel et al., 2010). The most common and simple way to obtain inundation maps is the static inundation approach considering all areas with elevation lower than the forcing water level, extensively used for studies of different scales (Hinkel et al., 2014; Hinkel et al., 2010; Vousdoukas et al., 2012b).

**Statistical or dynamical downscaling methods can be used to derive local information from global climate models. Reducing uncertainties and connecting physical models to decision tools will assist coastal management.**

However, given the high complexity of coastal flooding processes, several recent studies showed that the static approach resulted in substantial overestimation of the flood extent compared to dedicated hydraulic models, especially in flatter terrains (Breilh et al., 2013; Gallien, 2016; Ramirez et al., 2016; Seenath et al., 2016; Vousdoukas et al., 2016b).

Intermediate approaches have been developed which are capable of reducing the computational cost by taking into consideration either only water mass conservation (Breilh et al., 2013), or aspects of flooding hydrodynamics (Dottori et al., 2016), or the presence of obstacles (Perini et al., 2016; Sekovski et al., 2015). More elaborate and more computationally intensive are dynamic models like LISFLOOD-FP (Bates et al., 2010), which despite being originally developed for simulating river flow processes, have been proven to be reliable also for coastal flooding applications, such as the reproduction of storm surge events (Ramirez et al., 2016; Smith et al., 2012) and the evaluation of future scenarios of sea level rise (Purvis et al., 2008). Finally, process-based models specialized for coastal hydro- and morpho-dynamics (Lesser et al., 2004; McCall et al., 2010; Roelvink et al., 2009; Vousdoukas et al., 2012a) would appear as the optimal option, however they come with the disadvantages of (i) increased computational costs, which are almost prohibitive for large scale application; and (ii) the fact that they require information about the nearshore topography in detail which is often not available.

Outputs from climate models of various resolutions are often used to force hydrodynamic impacts models such as wave and storm surge models (leading to models of coastal impacts such as flooding and erosion). Issues for these model couplings are (1) quantification of model accuracy for past events and (2) understanding the uncertainty for future projections. This uncertainty consists of (1) uncertainty in greenhouse gas emissions,
Innovation

There are a number of priority knowledge gaps that need to be addressed to improve the ability of the scientific community to assess the hazard-related risk associated with sea-level extremes, storm surges and waves. First, we require an improved understanding of the processes controlling time mean regional sea-level rise, in order to provide accurate regional projections. This implies a more sophisticated combination of ocean and solid Earth models, as well as sustained and accurate monitoring of sea level so as to better analyse regional variability. Sea-level projections also demand improved modelling of physical processes that couple the ocean and the cryosphere in order to explore the plausibility of rates of sea-level rise outside that suggested by the current models.

(2) uncertainty in climate model projections of sea level and storms and (3) uncertainty in the surge and wave models. As models improve, the model uncertainty may be reduced but there remains uncertainty in the emissions and some of the model physics. Increasingly, the outputs of physical models such as those described above are combined with socioeconomic data to provide a set of decision tools that allow coastal managers to assess and mitigate risk.

These so-called ‘broad-scale assessment tools’ (e.g. Gouldby et al., 2008) connect marine science to engineering and economics and are now widely used in national analyses of coastal flood hazard, helping to define the scale of the problem and the potential mitigations.

3.6.6 Conclusions and key messages

Partnership

There is a need for improved multidisciplinary connections between oceanographers, coastal engineers and coastal planners to deliver decision tools based on sound physical and economic models.

Knowledge

Flood severity analysis would benefit from a community-wide European database and analysis of historic storm events that resulted in coastal flooding, building on the model of Haigh et al. (2015).

Improved process understanding of regional sea-level change is essential, as are improvements to the representation of weather systems in climate models. Multidisciplinarity is needed to deliver economic planning tools.

To better understand the possibility of changes to future storminess and, therefore, storm surges and waves, requires improved high-resolution modelling of mid-latitude weather systems in climate models. This would lead to a more complete assessment of future changes in the wave and storm surge climate with reduced uncertainty.
REFERENCES CHAPTER 3 - SECTION II

3.4 Hydrological risk: floods


3.6 Hydrological risk: wave action, storm surges and coastal flooding


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