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

***Kevin Horsburgh**, Inigo Losada, Michail Vousdoukas, Ralf Weisse, Judith Wolf*

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 GPB 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). However, the financial impact of the severe coastal flooding was estimated by Credit Suisse to be more than EUR 1.5 billion.

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 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 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 thresholds being reached.

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/beaches 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 (Cavaleri 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 (Woolf 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 19^{th} to the 20^{th} 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 20^{th} 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). Woollings (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 ranging, 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 the 21st century. The thermal expansion of the ocean as a result of increased temperatures takes place over centuries to millennia; therefore, thermal expansion 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 (CO_2) 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 Røed, 2008; Gaslikova et al., 2013; Howard et al., 2010; Woth 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), Mentaschi (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 as flooded all the 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 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,

(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).

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.

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

Alfieri, L, Feyen L, Salamon P, Thielen J, Bianchi A, Dottori F, Burek P (2016) Modelling the socioeconomic impact of river floods in Europe. Natural Hazards and Earth System Sciences 16, 1401–1411.

Alfieri, L., Burek, P., Dutra, E., Krzeminski, B., Muraro, D., Thielen, J., Pappenberger, F., 2013. GloFAS — global ensemble streamflow forecasting and flood early warning. Hydrology and Earth System Sciences 17, 1161-1175.

Alfieri, L., Burek, P., Feyen, L., Forzieri, G., 2015. Global warming increases the frequency of river floods in Europe. Hydrology and Earth System Sciences 19, 2247-2260.

Alfieri, L., Salamon, P., Pappenberger, F., Wetterhall, F., Thielen, J. (2012) Operational early warning systems for water-related hazards in Europe. Environmental Science and Policy 21, 35-49.

Alfieri, L., Velasco, D., Thielen, J., (2011). Flash flood detection through a multi-stage probabilistic warning system for heavy precipitation events. Advances in Geosciences 29, 69–75.

Alvarez-Garreton, C., Ryu, D., Western, A., W., Su, C.-H., Crow, W. T., Robertson, D. E., Leahy, C. 2015. Improving operational flood ensemble prediction by the assimilation of satellite soil moisture: comparison between lumped and semi-distributed schemes. Hydrology and Earth System Sciences 19, 1659-1676.

Apel, H., Aronica G.T., Kreibich H., Thieken, H.A., 2008. Flood risk analyses—How detailed do we need to be?. Natural Hazards 49 (1), 79–98.

Arnal, L., Ramos, M.H., Coughlan, E., Cloke, H.L., Stephens, E., Wetterhall, F., Andel, S.J., F. Pappenberger undefined, 2016. Willingness-to-pay for a probabilistic flood forecast: a risk-based decision-making game. Hydrology and Earth System Sciences 20, 3109–3128.

Ballard, S.P., Li, Z., Simonin, D.and Caron, J.F., 2016. Performance of 4D-Var NWP-based nowcasting of precipitation at the Met Office for summer 2012. Quarterly Journal of the Royal Meteorological Society 142, 472–487.

Berenguer M., Corral C., Sánchez Diezma, R., Sempere Torres, D., 2005. Hydrological validation of a radar-based nowcasting technique. Journal of Hydrometeorology 6, 532–549.

Blöschl, G., Zehe, E., 2005. On hydrological predictability. Hydrological Processes 19, 3923–3929.

Boudou, M., Danière B., Lang M., 2016. Assessing changes in urban flood vulnerability through mapping land use from historical information. Hydrology and Earth System Sciences 20, 161–173.

Brauer, C.C., Teuling, A.J., Overeem, A., Velde, Y., Hazenberg P., Warmerdam, P.M.M., Uijlenhoet, R., 2011. Anatomy of extraordinary rainfall and flash flood in a Dutch lowland catchment. Hydrology and Earth System Sciences 15, 1991-2005.

Bubeck, P., Botzen, W.J.W., Aerts, H J.C.J., 2012. A Review of Risk Perceptions and Other Factors that Influence Flood. Mitigation Behavior. Risk Analysis 32, 1481–1495.

CCC, 2017. Adaptation sub committee of the Committee on Climate Change, UK. www.theccc.org.uk

Chen, A.S., Leandro, J., Djordjevic, S., 2016. Modelling sewer discharge via displacement of manhole covers during flood events using 1D/2D SIPSON/P-DWave dual drainage simulations. Urban Water Journal 13(8), 830-840.

Cloke, H.L., Pappenberger, F., 2009. Ensemble flood forecasting: a review. Journal of Hydrology 375, 3–4.

Cloke, H.L., Wetterhall F., He Y., Freer J.E., Pappenberger, F. undefined, 2013. Modelling climate impact on floods with ensemble climate projections. Quarterly Journal of the Royal Meteorological Society 139 (671 part B), pp. 282-297.

Cole, S.J., Moore, R.J., Aldridge, T.A., Gunawan, O., Balmforth, H., Hunter, N., Mooney, J., Lee, D., Fenwick, K., Price, D., Demeritt, D., 2016. Natural Hazards Partnership Surface Water Flooding Hazard Impact Model: Phase 2 Final Report.

Collenteur, R.A., Moel H., Jongman, B., Di Baldassarre, G., 2015. The failed-levee effect : Do societies learn from flood disasters ?. Natural Hazards 76 (1), 373–388.

Collier, C.G., 2007. Flash flood forecasting: What are the limits of predictability?. Quarterly Journal of the Royal Meteorological Society 133, 3–23.

Copernicus Emergency Management Service—Mapping, 2017. http://emergency.copernicus.eu/mapping, [accessed 24 April, 2017].

Coughlan de Perez, E., van den Hurk, B., van Aalst, M. K., Amuron, I., Bamanya, D., Hauser, T., Jongma, B., Lopez, A., Mason, S., Mendler de Suarez, J., Pappenberger, F., Rueth, A., Stephens, E., Suarez, P., Wagemaker, J., Zsoter, E., 2016. Action-based flood forecasting for triggering humanitarian action. Hydrology and Earth System Sciences 20, 3549-3560.

Crochemore, L., Ramos, M., Pappenberger, F., Andel, S., Wood, A., 2016. An experiment on risk-based decision-making in water management using monthly probabilistic forecasts. Bulletin of the American Meteorological Society 97 (4), 541–551.

Dale, M., Wicks, J., Mylne, K. Pappenberger, F., Laeger, S., Taylor, S., 2014. Probabilistic flood forecasting and decision-making: An innovative risk-based approach. Natural Hazards 70(1), 159-172.

Dartmouth Flood Observatory. http://www.dartmouth.edu/~floods/, [accessed 24 April, 2017].

Daupras, F., Antoine, J. M., Becerra, S., Peltier, A., 2015. Analysis of the robustness of the French flood warning system: a study based on the 2009 flood of the Garonne River. Natural Hazards 75(1), 215-241.

de Moel, H., Jongman, B., Kreibich, H,, Merz, B., Penning Rowsell, E., Ward, P., 2015. Flood risk assessments at difference spatial scapes. Mitigation and Adaptation Strategies for Global Change 20(6) 865-890.

Demeritt, D., Nobert, S., Cloke, HL., Pappenberger, F., 2013. The European Flood Alert System and the communication, perception, and use of ensemble predictions for operational flood risk management. Hydrological Processes 27(1), 147–157.

Di Baldassarre, G., Viglione, A., Carr, G., Kuil, L., Yan, K., Brandimarte, L., Blöschl, G., 2015. Debates—Perspectives on socio-hydrology: Capturing feedbacks between physical and social processes. Water Resources Research 51, 4770–4781.

Dittrich, R., Wreford, A., Butler, A., Moran, D., 2016. The impact of flood action groups on the uptake of flood management measures. Climatic Change 138(3), 471-489.

Dottori, F., Salamon., P., Bianchi., A., Alfieri, L., Hirpa, F.A., Feyen, L., 2016. Development and evaluation of a framework for global flood hazard mapping. Advances in Water Resources 94, 87-102.

EEA, 2017. Climate change adaptation and disaster risk reduction in Europe — Synergies for the knowledge base and policies, forthcoming

EFAS, 2016. European Flood Awareness System (EFAS). European Commission Joint Research Centre. https://www.efas.eu/, [accessed 16 April, 2017].

Emerton, R.E., Stephens, E. M., Pappenberger, F., Pagano, T. C., Weerts, A.H., Wood, A.W., Salamon, P., Brown, J. D., Hjerdt, N., Donnelly, C., Baugh, C., Cloke, H.L., 2016. Continental and global scale flood forecasting systems. Wiley Interdisciplinary Reviews: Water 3 (3), 391-418.

Environment Agency, 2015. Public dialogues on flood risk communication. Final Report — SC120010/R1. Environment Agency, Bristol, UK.

European Commission, 2007. Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risks. Official Journal of the European Union, L 288/27, 6.11.2007, 27–34.

FFC, n.d. Flood forecasting centre. http://www.ffc-environment-agency.metoffice.gov.uk/, [accessed 16 April, 2017].

Garcia Pintado, J., Mason, D., Dance, S. L., Cloke, H., Neal, J. C., Freer, J., Bates, P. D., 2015. Satellite-supported flood forecasting in river networks: a real case study. Journal of Hydrology 523, 706-724.

Garde Hansen, J., McEwen, L., Holmes, A., Jones, O. 2016. Sustainable flood memory: Remembering as resilience. Memory Studies, 1-22.

Gaume, E., Bain, V., Bernardara, P., Newinger, O., Barbuc, M., Bateman, A., Blaskovicová, L., Blöschl, g., Borga, M., Dumitrescu, A., Daliakopoulos, I., Garcia, J., Irimescu, A., Kohnova, S., Koutroulis, A., Marchi, L., Matreata, S., Medina, V., Preciso, E., Sempere Torres, D., Stancalie, G., Szolgay, J., Tsanis, I., Velasco, D., Viglione, A., 2009. A compilation of data on European flash floods, Journal of Hydrology 367(1–2), 70–78.

Gersonius, B., Ashley, R., Pathirana, A, Zevenbergen, C., 2013. Climate change uncertainty: building flexibility into water and flood risk infrastructure. Climatic Change 116(2), 411-423.

GloFAS, 2017. Emergency Management Service - Global Flood Awareness System. European Commission Copernicus. www.globalfloods.eu, [accessed 16 April, 2017].

Hall, J., Arheimer, B., Borga, M., Brazdil, R., Claps, P., Kiss, A., Kjeldsen, T.R., Kriauciuniene, J., Kundzewicz, Z.W., Lang, M., Llasat, M.C., Macdonald, N., McIntyre, N., Mediero, L., Merz, B., Merz, R., Molnar, P., Montanari, A., Neuhold, C., Parajka, J., Perdigao, R.A.P., Plavcova, L., Rogger, M., Salinas, J.L., Sauquet, E., Schaer, C., Szolgay, J., Viglione, A., Bloeschl, G., 2014. Understanding flood regime changes in Europe: a state-of-the-art assessment. Hydrology and Earth System Sciences 18(7), 2735-2772.

Hirabayashi, Y., Mahendran, R., Koirala, S., Konoshima, L., Yamazaki, D., Watanabe, S., Kim, H., Kanae, S., 2013. Global flood risk under climate change. Nature Climate Change 3, 816–821.

HM Government (2016). National Flood Resilience Review. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/551137/national-flood-resilience-review.pdf [accessed 06 April, 2016].

Huntingford, C., Marsh, T., Scaife, A.A., Kendon E.J., Hannaford, J., Kay, A.L., Lockwood M., Prudhomme, C., Reynard, N.S., Parry, S., Lowe, J.A., Screen, J.A., Ward, H.C., Roberts, M., Stott, P.A., Bell, V.A., Bailey, M., Jenkins A., Legg, T., Otto, F.E.L., Massey, N., Schaller, N., Slingo, J., Allen, M.R., 2014. Potential influences on the United Kingdom's floods of winter 2013/14. Nature Climate Change 4, 769-777.

Hydrologic Ensemble Prediction Experiment, n.d. www.hepex.org, [accessed 24 April, 2017].

Javelle, P., Demargne, J., Defrance, D., Pansu, J. and Arnaud, P., 2014. Evaluating flash-flood warnings at ungauged locations using post-event surveys: a case study with the AIGA warning system. Hydrological Sciences Journal, 59 (7), 1390–1402.

Kendon, E J., Ban, N., Roberts, N.M., Fowler, H.J., Roberts, M.J., Chan, S.C., Evans, J.P., Fosser, G., Wilkinson, J.M., 2016 Do convection-permitting regional climate models improve projections of future precipitation change?. Bulletin of the American Meteorological Society.

Klinger, C, Landeg, O., Murray, V., 2014. Power Outages, Extreme Events and Health: a Systematic Review of the Literature from 2011-2012. PLOS Currents, 6.

Kumar, P., 2011. Typology of hydrologic predictability. Water Resources Research 47(4), W00H05.

Landeg, O., Lawson, J., 2014. Effective flood resilience in health providers: Flooding at a major NHS Blood and Transplant Facility. in Chemical Hazards & Poisons Report, Public Health England, Sep, Iss.24.

Lavers, D. A., Allan, R. P., Wood, E. F., Villarini, G., Brayshaw, D. J., Wade, A. J., 2011. Winter floods in Britain are connected to atmospheric rivers. Geophysics Research Letters 38, L23803.

Le Coz, J., Patalano, A., Collins, D., Guillén, N.F., García, C. M., Smart, G.M., Bind, J., Chiaverini, A., Le Boursicaud, R., Dramais, G., Braud, I., 2016. Crowdsourced data for flood hydrology: Feedback from recent citizen science projects in Argentina, France and New Zealand. Journal of Hydrology 541, B, pp. 766-777.

Liechti, K., Zappa, M., Fundel, F., Germann, U., 2013. Probabilistic evaluation of ensemble discharge nowcasts in two nested Alpine basins prone to flash floods. Hydrological Processes 27, 5–17.

Liguori, S., Rico Ramirez, M.A., Schellart, A.N.A., Saul A. J., 2012. Using probabilistic radar rainfall nowcasts and NWP forecasts for flow prediction in urban catchments. Atmospheric Research 103, 80–95.

Macdonald, D., Dixon, A., Newell, A., Hallaways, A., 2012. Groundwater flooding within an urbanised flood plain. Journal of Flood Risk Management 5(1): 68-80.

Marchi, L., Borga, M., Preciso, E., Sangati, M., Gaume, E., Bain, V., Delrieu, G., Bonnifait, L., Pogačnik, N., 2009. Comprehensive post-event survey of a flash flood in Western Slovenia: observation strategy and lessons learned. Hydrological Processes 23, 3761–3770.

McCarthy, S., Tunstall, S., Parker, D., Faulkner, H., Howe, J., 2007. Risk communication in emergency response to a simulated extreme flood. Environmental Hazards 7 (3), 179-192.

Merz, B., Kreibich, H., Schwarze, R.,Thieken, A., 2010. Assessment of economic flood damage. Natural Hazards Earth System Sciences 10, 1697–1724.

Michaels, S., 2015. Probabilistic forecasting and the reshaping of flood risk management. Journal of Natural Resources Policy Research 7 (1), 41-51.
Muchan, K., Lewis, M., Hannaford, J. Parry, S., 2015. The winter storms of 2013/2014 in the UK: hydrological responses and impacts. Weather 70, 55–61.
Pagano, T.C., Pappenberger, F., Wood, A.W., Ramos, M.H., Persson, A., Anderson, B., 2016. Automation and human expertise in operational river forecasting. WIRES Water 3 (5), 692-705.
Pagano, T.C., Wood, A.W., Ramos, M.H., Cloke, H.L., Pappenberger, F., Clark, M. P., Cranston, M., Kavetski, D., Mathevet, T., Sorooshian, S. Verkade, J.S., 2014. Challenges of Operational River Forecasting. Journal of Hydrometeorology 15, 1692–1707.
Palla, A., Colli, M., Candela, A., Aronica, G.T. Lanza, L.G., 2016. Pluvial flooding in urban areas: the role of surface drainage efficiency. Journal of Flood Risk Management.
Pappenberger, F., Beven, K. J., 2006. Ignorance is bliss: Or seven reasons not to use uncertainty analysis. Water Resources Research 42, W05302.
Pappenberger, F., Cloke, H. L., Parker, D. J., Wetterhall, F., Richardson, D.S., Thielen, J., 2015. The monetary benefit of early flood warnings in Europe. Environmental Science and Policy 51, 278-291.
Pappenberger, F., Dutra, E, Wetterhall F., Cloke H.L., (2012) Deriving global flood hazard maps of fluvial floods through a physical model cascade. Hydrology and Earth System Sciences 16 (11), 4143-4156.
Pappenberger, F., Stephens, E., Thielen, J., Salamon, P., Demeritt, D., van Andel, S. J., Wetterhall, F., Alfieri, L., 2013. Visualizing probabilistic flood forecast information: expert preferences and perceptions of best practice in uncertainty communication. Hydrological Processes 27, 132–146.
Peña, J.C., Schulte, L., Badoux, A., Barriendos, M., Barrera Escoda, A., 2015) Influence of solar forcing, climate variability and modes of low-frequency atmospheric variability on summer floods in Switzerland. Hydrology and Earth System Sciences 19, 3807-3827.
Perks, M.T., Russell, A.J., Large, A.R.G., (2016). Technical Note: Advances in flash flood monitoring using unmanned aerial vehicles (UAVs). Hydrology and Earth System Sciences 20, 4005-4015.
Ramos, M.H., Mathevet, T., Thielen, J., Pappenberger, F., 2010. Communicating uncertainty in hydro-meteorological forecasts: mission impossible?. Meteorological Applications 17(2), 223-235.
Ramos, M.H., van Andel, S.J., Pappenberger, F., 2013. Do probabilistic forecasts lead to better decisions?. Hydrology and Earth System Sciences 9 (17), 2219-2232.
Revilla Romero, B., Hirpa. F,A,, Thielen del Pozo, J., Salamon, P., Brakenridge, R., Pappenberger, F., De Groeve T., 2015. On the Use of Global Flood Forecasts and Satellite-Derived Inundation Maps for Flood Monitoring in Data-Sparse Regions. Remote Sensing 7 (11), 15702-15728.
Rodríguez Rincón, J.P., Pedrozo Acuña, A., Breña Naranjo, J.A., 2015. Propagation of hydro-meteorological uncertainty in a model cascade framework to inundation prediction. Hydrology and Earth System Sciences 19, 2981-2998.
Romanowicz, R., Beven, K.J., 2003. Bayesian estimation of flood inundation probabilities as conditioned on event inundation maps. Water Resources Research 39 (3), 1073.
Rufat, S., Tate, E, Burton, C.G., Maroof, A.S., 2015. Social vulnerability to floods: Review of case studies and implications for measurement. International Journal of Disaster Risk Reduction 14 (4), 470–486
Sampson, C.C., Fewtrell, T.J., O'Loughlin, F., Pappenberger, F., Bates, P.B., Freer, J. E., Cloke, H.L., 2014. The impact of uncertain precipitation data on insurance loss estimates using a flood catastrophe model. Hydrology and Earth System Sciences 18, 2305-2324.
Schröter, K., Kunz, M., Elmer, F., Mühr, B., Merz, B., 2015. What made the June 2013 flood in Germany an exceptional event? A hydro-meteorological evaluation. Hydrology and Earth System Sciences 19, 309-327.
Scussolini, P., Aerts, J.C.J.H., Jongman, B., Bouwer, L.M., Winsemius, H.C., de Moel, H.,Ward, P.J., 2016. FLOPROS: an evolving global database of flood protection standards. Natural Hazards and Earth System Sciences 16, 1049-1061.
Slater, L.J., Singer, M.B., Kirchner, J.W., 2015. Hydrologic versus geomorphic drivers of trends in flood hazard, Geophysical Research Letters 42, 370376.
Stephens, E., Cloke, H., 2014. Improving flood forecasts for better flood preparedness in the UK (and beyond). Geographical Journal 180 (4). pp. 310-316.
Stephens, E., Day, J.J., Pappenberger, F., Cloke, H., 2015. Precipitation and floodiness. Geophysical Research Letters 42 (23), 10316-10323.
Thieken, A. H., Kreibich, H., Muller, M. Merz, B., 2007. Coping with floods: preparedness, response and recovery of flood-affected residents in Germany in 2002. Hydrological Sciences Journal 52(5), 1016-1037.
Thielen del Pozo, J., Salamon, P., Burek, P., Pappenberger, F., Eklund, C., Sprokkereef, E., Hazlinger, M., Padilla Garcia, M., Garcia Sanchez, R., 2017. Handbook of hydrometeorological forecasting. Forthcoming.
Thielen del Pozo, J., Thiemig, V., Pappenberger, F., Revilla-Romero, B., Salamon, P., De Groeve, T., Hirpa, F., 2015. The benefit of continental flood early warning systems to reduce the impact of flood disasters: An assessment for Europe and an outlook for Africa. JRC Science for Policy Report. EUR 27533 EN.
Thiemig, V., Bisselink, B., Pappenberger, F., Thielen, J., 2015. A pan-African medium-range ensemble flood forecast system. Hydrology and Earth System Sciences 19, 3365-3385.
UNISDR, 2015. Sendai Framework for Disaster Risk Reduction 2015-2030. UNISDR, Geneva, Switzerland.
Versini, P.A.., Berenguer, M., Corral, C., Sempere Torres, D., 2014. An operational flood warning system for poorly gauged basins: demonstration in the Guadalhorce basin (Spain). Natural Hazards 71(3), 1355-1378.
Vigicrues, 2017. Service central d'hydrométéorologie et d'appui à la prévision des inondations (Schapi). https://www.vigicrues.gouv.fr/, [accessed 16 April, 2017] (in French).
Vormoor, K., Lawrence, D., Heistermann, M., and Bronstert, A., 2015. Climate change impacts on the seasonality and generation processes of floods — projections and uncertainties for catchments with mixed snowmelt/rainfall regimes. Hydrology and Earth System Sciences 19, 913-931.

Walker, D., Forsythe, N., Parkin, G., Gowing J., (2016). Filling the observational void: scientific value and quantitative validation of hydrometeorological data from a community-based monitoring programme. Journal of Hydrology 538, 713-725.
Ward, P.J., Jongman, B., Weiland, F.S., Bouwman, A., van Beek, R., Bierkens, M.F.P., Ligtvoet, W., Winsemius, H.C., 2013. Assessing flood risk at the global scale: model setup, results, and sensitivity. Environmental Research Letters 8, 044019,
Watson, D., Adams, M., 2010. Design for Flooding: Architecture, Landscape and Urban Design for Resilience to Climate Change. John Wiley & Sons.
Winsemius, H.C., Van Beek, L.P.H., Jongman, B., Ward, P.J., Bouwmanal, A., 2013. A framework for global river flood risk assessments. Hydrology and Earth System Sciences 17(5), 1871–1892.
Younis, J., Ramos, M. H., Thielen, J., 2008. EFAS forecasts for the March-April 2006 flood in the Czech part of the Elbe River Basin — a case study. Atmospheric Science Letters, 9 (2), 88-94.
Zsótér, E., Pappenberger, F., Smith, P., Emerton, R.E., Dutra, E., Wetterhall, F., Richardson, D., Bogner, K., Balsamo, G., 2016. Building a Multimodel Flood Prediction System with the TIGGE Archive. Journal of Hydrometeorology.

3.5 Hydrological risk: landslides

Jakob, M., 2000. The impacts of logging on landslide activity at Clayoquot Sound, British Columbia. CATENA 38 (4), 279-300.
Van der Linden, P., Mitchell, J.F.B., (Eds.), 2009: ENSEMBLES: Climate Change and its Impacts: Summary of research and results from the ENSEMBLES project. 160pp.
Cannon, S. H., Gartner, J. E., 2005. Wildfire-related debris flow from a hazards perspective. In: Debris-flow Hazards and Related Phenomena. Springer Praxis Books. Springer Berlin Heidelberg, pp. 363-385.
Shakesby, R., Doerr, S., 2006. Wildfire as a hydrological and geomorphological agent. Earth-Science Reviews 74 (3-4), 269-307.
European Commission, 2006. Proposal for a Directive of the European Parliament and of the Council establishing a framework for the protection of soil and amending Directive 2004/35/EC. COM/2006/0232 final - COD 2006/0086.
Baum, R.L., Godt, J.W., 2010. Early warning of rainfall-induced shallow landslides and debris flows in the USA. Landslides 7, 259–272.
Berger, M., Moreno, J., Johannessen, J.A., Levelt, P.F., Hanssen, R.F., 2012. ESA's sentinel missions in support of Earth system science. Remote Sensing of Environment 120, 84-90.
Bishop, A.W., Hutchinson, J. N., Penman, A.D.M., Evans, H.E., 1969. Geotechnical investigation into the causes and circumstances of the disaster of 21 October 1966. In: A selection of technical reports submitted to the Aberfan Tribunal. HMSO, London, UK, pp. 1-80.
Blikra, L. H., 2008. The Åknes rockslide: Monitoring, threshold values and early-warning. In: Landslides and Engineering Slopes: From the Past to the Future. Proceedings of the 10th International Symposium on Landslides and Engineering Slopes, Xi'an, China.
Blikra, L.H., 2012. The Åknes rockslide, Norway. In: Clague, J. J., Stead, D. (eds), Landslides: types, mechanisms and modeling. Cambridge University Press, Cambridge, pp. 323-335.
Casagli, N., Catani, F., Del Ventisette, C., Luzi, G., 2010. Monitoring, prediction, and early warning using ground-based radar interferometry. Landslides 7, 291–301.
Catani, F., Tofani, V., Lagomarsino, D., 2016. Spatial patterns of landslide dimension: A tool for magnitude mapping. Geomorphology 273, 361–373.
Cloutier, C., Agliardi, F., Crosta, G.B., Frattini, P., Froese, C., Jaboyedoff, M., Locat, J., Michoud, C., Marui, H., 2015. The First International Workshop on Warning criteria for Active Slides: technical issues, problems and solutions for managing early warning systems. Landslides 12, 205–212.
Corominas, J., Van Westen, C., Frattini, P., Cascini, L., Malet, J.-P., Fotopoulou, S., Catani, F., Van Den Eeckhaut, M., Mavrouli, O., Agliardi, F., Pitilakis, K., Winter, M.G., Pastor, M., Ferlisi, S., Tofani, V., Hervás, J., Smith, J.T., 2014. Recommendations for the quantitative analysis of landslide risk. Bulletin of Engineering Geology and the Environment 73 (2), 209–263.
Crosta, G.B., Agliardi, F., 2003. Failure forecast for large rock slides by surface displacement measurements. Canadian Geotechnical Journal 40, 176–191.
Dai, F.C., Lee, C.F., Ngai, Y.Y., 2002. Landslide risk assessment and management: an overview. Engineering Geology 64 (1), 65-87.
Dash, N., Gladwin, H., 2007. Evacuation Decision Making and Behavioral Responses: Individual and Household. Natural Hazards Review 8, 69–77.
Federico, A., Popescu, M., Elia, G., Fidelibus, C., Internò, G., Murianni, A., 2012. Prediction of time to slope failure: a general framework. Environmental Earth Sciences 66 (1), 245–256.
Fell, R., 1994. Landslide risk assessment and acceptable risk. Canadian Geotechnical Journal 31, 261 – 272.
Fell, R., Hartford, D., 1997. Landslide risk management. In: Cruden, D., Fell, R. (Eds.), Landslide Risk Assessment. Balkema, Rotterdam, pp. 51 – 109.
Froese, C., Moreno, F., 2014. Structure and components for the emergency response and warning system on Turtle Mountain. Natural Hazards 70, 1689–1712.
Gili, J., Corominas, J., Riuz, J., 2000. Using global positioning system techniques in landslide monitoring. Engineering Geology 55, 167–192.
Guzzetti, F., Ardizzone, F., Cardinali, M., Galli, M., Rossi, M., Valigi, D., 2009. Landslide volumes and landslide mobilization rates in Umbria, central Italy. Earth and Planetary Science Letters 279 (3), 222–229.
Guzzetti, F., Carrara, A., Cardinali, M., Reichenbach, P., 1999. Landslide hazard evaluation: a review of current techniques and their application in a multi–scale study. Central Italy. Geomorphology 31, 181–216.
Guzzetti, F., Peruccacci, S., Rossi, M., Stark, C.P., 2008. The rainfall intensity–duration control of shallow landslides and debris flows: an update. Landslides 5, 3–17.
Guzzetti, F., Mondini, A.C., Cardinali, M., Fiorucci, F., Santangelo, M., Chang, K.-T., 2012. Landslide inventory maps: New tools for an old problem. Earth-Science Reviews 112 (1-2), 42–66.
Guzzetti, F., Reichenbach, P., Cardinali, M., Galli, M., Ardizzone, F., 2005. Probabilistic landslide hazard assessment at the basin scale. Geomorphology 72 (1), 272–299.

Hungr, O., Leroueil, S., Picarelli, L., 2014. The Varnes classification of landslide types — an update. Landslides 11 (2), 167–194
Hutchinson, J.N., 1988. General Report: Morphological and geotechnical parameters of landslides in relation to geology and hydrogeology. In: Proceedings 5th International Symposium on Landslides, Lausanne, Switzerland.
Intrieri, E., Gigli, G., Casagli, N., Nadim, F., 2013. Landslide Early Warning System: toolbox and general concepts. Natural Hazards and Earth System Sciences 13, 85–90.
Intrieri, E., Gigli, G., Mugnai, F., Fanti, R., Casagli, N., 2012. Design and implementation of a landslide early warning system. Engineering Geology 147-148, 124–136.
IPCC, 2012. Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.K. Plattner, S.K. Allen, M. Tignor, P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK, and New York, NY, USA.
Jaedicke, C., van den Eeckhaut, M., Nadim, F., Hervás, J., Kalsnes, B., Vangelsten B.V., Smith, J.T., Tofani, V., Ciurean, R., Winter, M.G., Sverdrup-Thygeson, K., Syre, E., Smebye, H., 2013. Identification of landslide hazard and risk hotspots in Europe. Bulletin of Engineering Geology and the Environment 73 (2), 325-339.
Jakob, M., Owen, T., Simpson, T., 2012. A regional real-time debris-flow warning system for the District of North Vancouver, Canada. Landslides 9, 165–178.
Larsen, I.J., Montgomery, D.R., Korup, O., 2010. Landslide erosion controlled by hill-slope material. Nature Geoscience 3, 247–251.
Marchi, L., Arattano, M., Deganutti, A.M., 2002. Ten years of debris flows monitoring in the Moscardo Torrent (Italian Alps). Geomorphology 46, 1–17.
Michoud, C., Bazin, S., Blikra, L.H., Derron, M.H., Jaboyedoff, M., 2013. Experiences from site-specific landslide early warning systems. Natural Hazards and Earth System Sciences 13, 2659-2673.
Petley, D.N., 2010. Document On the impact of climate change and population growth on the occurrence of fatal landslides in South, East and SE Asia. Quarterly Journal of Engineering Geology and Hydrogeology 43(4), 487-496.
Rossi, M., Guzzetti, F., Reichenbach, P., Mondini, A.C., Peruccacci, S., 2010. Optimal landslide susceptibility zonation based on multiple forecasts. Geomorphology 114(3), 129–142.
Rouyet, L., Kristensen, L., Derron, M.H., Michoud, C., Blikra, L.H., Jaboyedoff, M., Lauknes, T.R., 2016. Evidence of rock slope breathing using Ground-Based InSAR. Geomorphology.
Sättele, M., Bründl, M., Straub, D., 2016. Quantifying the effectiveness of early warning systems for natural hazards, Natural Hazards and Earth System Sciences 16, 149-166.
IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
Tofani, V., Segoni, S., Agostini, A., Catani, F., Casagli, N., 2013. Technical NB: Use of remote sensing for landslide studies in Europe. Natural Hazards and Earth System Sciences 13, 299–309.
Tinti, S., Pagnoni, G., Zaniboni, F., 2006. The landslides and tsunamis of the 30th of December 2002 in Stromboli analysed through numerical simulations. Bulletin of Volcanology 68 (5), 462–479.
Nations, United, 2015. World population prospects. The 2015 revision. Dept. Economics and Social Affairs. undefined undefined, undefined.
Witt, A., Malamud, B.D., Rossi, M., Guzzetti, F., Peruccacci, S., 2010. Temporal correlations and clustering of landslides. Earth Surface Process and Landforms 35 (10), 1138–1156.

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

Arkhipkin, V.S., Gippius, F.N., Koltermann, K.P., Surkova, G.V., 2014. Wind waves in the Black Sea. Results of a hindcast study. Natural Hazards and Earth System Sciences 14 (11), 2883–2897.
Arns, A., Wahl, T., Dangendorf, S., Jensen, J., 2015. The impact of sea level rise on storm surge water levels in the northern part of the German Bight. Coastal Engineering 96, 118-131.
Bacon, S., Carter, D.J.T., 1991. Wave climate changes in the North Atlantic and North Sea. International Journal of Climatology 11, 545–558.
Bates, P.D., Horritt, M.S., Fewtrell, T.J., 2010. A simple inertial formulation of the shallow water equations for efficient two-dimensional flood inundation modelling. Journal of Hydrology 387, 33-45.
Bengal and the Arabian Sea, Tropical Cyclone Programme, Report No TCP21.
Bindoff, N.L., J. Willebrand, V. Artale, A, Cazenave, J. Gregory, S. Gulev, K. Hanawa, C. Le Quéré, S. Levitus, Y. Nojiri, C.K. Shum, L.D. Talley and A. Unnikrishnan, 2007. Observations: Oceanic Climate Change and Sea Level. In: Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, Miller, H.L., (Eds.). Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, USA, pp. 385-432.
Breilh, J.F., Chaumillon, E., Bertin, X., Gravelle, M., 2013. Assessment of static flood modeling techniques: application to contrasting marshes flooded during Xynthia (western France). Natural Hazards and Earth System Sciences 13, 1595-1612.
Casas Prat, M., Sierra, J.P., 2013. Projected future wave climate in the NW Mediterranean Sea. Journal of Geophysical Research Oceans 118 (7), 3548–3568.
Cavaleri, L., Fox-Kemper, B., Hemer, M., 2012. Wind Waves in the Coupled Climate System. Bulletin of the American Meteorological Society 93, 1651–1661.
CEFAS, n.d. WaveNet, Cefas' strategic wave monitoring network for the United Kingdom. www.cefas.co.uk/cefas-data-hub/wavenet/, [accessed 07 April, 2016].
Charles, E.D., Idier, D., Delecluse, P., Deque, M., Le Cozannet, G., 2012. Climate change impact on waves in the Bay of Biscay. France. Ocean Dynamics 62, 831–848.

Church, J.A., Gregory, J.M., White, N.J., Platten, S.M., J.X, Mitrovica, 2011. Understanding and projecting sea level change. Oceanography 24 (2), 130–143.

Church, J.A., P.U. Clark, A. Cazenave, J.M. Gregory, S. Jevrejeva, A. Levermann, M.A. Merrifield, G.A. Milne, R.S. Nerem, P.D. Nunn, A.J. Payne, W.T. Pfeffer, D. Stammer, A.S. Unnikrishnan, 2013. Sea Level Change. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK and New York, USA, pp. 1137–1216.

Church, J.A., White, N., 2011. Sea-Level Rise from the Late 19th to the Early 21st Century. Surveys in Geophysics 32 (4-5), 585–602.

Conte, D., Lionello, P., 2013. Characteristics of large positive and negative surges in the Mediterranean Sea and their attenuation in future climate scenarios. Global and Planetary Change 111, 159-173.

Cooper, J.A.G., Pile, J., 2014. The adaptation-resistance spectrum: A classification of contemporary adaptation approaches to climate-related coastal change. Ocean & Coastal Management 94, 90-98.

De Vries, H., Breton, M., de Mulder, T., Krestenitis, Y., Ozer, J., Proctor, R., Ruddick, K., Salomon, J. C.,Voorrips, A., 1995. A comparison of 2-D storm surge models applied to three shallow European seas. Environmental Software 10(1), 23–42.

Debernard, J.B., Røed, L.P., 2008. Future wind, wave and storm surge climate in the Northern Seas: a revisit. Tellus A 60, 427-438.

Disaster Management Bureau of the Government of the People's Republic of Bangladesh, 2010. National Plan for Disaster Management 2010-2015. Government of the People's Republic of Bangladesh.

Dodet, G., Bertin, X., Taborda, R., 2010. Wave climate variability in the North-East Atlantic Ocean over the last six decades. Ocean Modelling 31 (3-4), 120-131.

Dottori, F., Martina, M.L.V., Figueiredo, R., 2016. A methodology for flood susceptibility and vulnerability analysis in complex flood scenarios. Journal of Flood Risk Management, n/a-n/a.

Dupuis, H., Michel, D., Sottolichio, A., 2006. Wave climate evolution in the Bay of Biscay over two decades. Journal of Marine Systems 63 (3-4), 105-114.

ECMWF, n.d. Browse reanalysis datasets.http://www.ecmwf.int/en/research/climate-reanalysis/browse-reanalysis-datasets, [accessed 17 April, 2017].

Environment Agency, 2009. Flooding in England: A National Assessment of Flood Risk. Environemnt Agency report. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/292928/geho0609bqds-e-e.pdf [accessed 07 April, 2016].

Ferreira, Ó., Garcia, T., Matias, A., Taborda, R., Dias, J.A., 2006. An integrated method for the determination of set-back lines for coastal erosion hazards on sandy shores. Continental Shelf Research 26, 1030-1044.

Gallien, T.W., 2016. Validated coastal flood modeling at Imperial Beach, California: Comparing total water level, empirical and numerical overtopping methodologies. Coastal Engineering 111, 95-104.

Gaslikova, L., Grabemann, I., Groll, N., 2013. Changes in North Sea storm surge conditions for four transient future climate realizations. Natural Hazards 66, 1501-1518.

Gommenginger, C., Thibaut, P., Fenoglio-Marc, L., Quartly, G., Deng, X. Gómez Enri, J. Challenor, P., Gao., Y., 2010. Retracking altimeter waveforms near the coasts — A review of retracking methods and some applications to coastal waveforms. In: Vignudelli, S., Kostianoy. A., Cipollini, P., Benveniste, J. (eds), Coastal Altimetry. Springer, Dordrecht, Netherlands.

Gouldby B., Sayers P., Mulet Marti J., Hassan M., Benwell D., 2008. A methodology for regional-scale flood risk assessment. Proceedings of the Institution of Civil Engineers-Water Management 161, (3), 169–182.

Gräwe, U., Burchard, H., 2012. Storm surges in the Western Baltic Sea: the present and a possible future. Climate Dynamics 39, 165-183.

Grinsted, A., Moore, A.J., Jevrejeva, S., 2010. Reconstructing sea level from paleo and projected temperatures 200 to 2100 AD. Climate Dynamics 34(4), 461-472.

Groll N., Grabemann I., Hünicke B., Meese ,M., 2017. Baltic Sea wave conditions under climate change scenarios. Boreal Environment Research 22, 1–12.

Groll, N., Grabemann, I., Gaslikova, L., 2014. North Sea wave conditions. An analysis of four transient future climate realizations. Ocean Dynamics 64 (1), 1-12.

Haigh, I.D., Wadey, M.P., Gallo, S.L, Loehr, H., Nicholls, R.J., Horsburgh, K., Brown, J.M, Bradshaw, E., 2015. A user-friendly database of coastal flooding in the United Kingdom 1915-2014. Scientific Data 2, 150021.

Haigh, I.D., Wadey, M.P., Wahl, T., Ozsoy, O., Nicholls, R.J,. Brown, J.M, Horsburgh, K., Gouldby, B., 2016. Spatial footprint and temporal clustering analysis of extreme sea level and storm surge events around the coastline of the UK. Scientific Data 3, 160107.

Hallegatte, S., Green, C., Nicholls, R. J., Corfee Morlot, J., 2013. Future flood losses in major coastal cities. Nature Climate Change, 3, 802–806.

Hawkes, P.J., Atkins, R., Brampton, A.H., Fortune, D., Garbett, R., Gouldby, B.P., 2001. WAVENET: Nearshore Wave Recording Network for England and Wales: Feasibility Study. HR Wallingford Report TR 122.

Hemer, M.A., Wang, X.L., Weisse, R., Swail, V.R., 2012. Advancing wind-waves climate science: The COWCLIP project. Bulletin of the American Meteorological Society 93, 791–796.

Hinkel, J., Lincke, D., Vafeidis, A.T., Perrette, M., Nicholls, R.J., Tol, R.S.J., Marzeion, B., Fettweis, X., Ionescu, C., Levermann, A., 2014. Coastal flood damage and adaptation costs under 21st century sea-level rise. Proceedings of the National Academy of Sciences 111, 3292-3297.

Hinkel, J., Nicholls, R., Vafeidis, A., Tol, R.J., Avagianou, T., 2010. Assessing risk of and adaptation to sea-level rise in the European Union: an application of DIVA. Mitigation and Adaptation Strategies for Global Change 15, 703-719.

Horsburgh, K., Ball, T., Donovan, B., Westbrook, G., 2010. Coastal flooding in MCCIP Annual Report Card 2010-11. MCCIP Science Review. Available from: www.mccip.org.uk/arc.

Howard, T., Lowe, J., Horsburgh, K., 2010. Interpreting Century-Scale Changes in Southern North Sea Storm Surge Climate Derived from Coupled Model Simulations. Journal of Climate 23, 6234-6247.

Hünicke, B., Zorita, E., Soomere, T., Madsen, K.S.; Johansson, M., Suursaar, Ü., 2015. Recent Change-Sea Level and Wind Waves. In: The BACC II Author Team (eds.), Second Assessment of Climate Change for the Baltic Sea Basin. Springer, Berlin, pp. 155-185.

Huthnance, J., Weisse, R., Wahl, T., Thomas, H., Pietrzak, J., Souza, A.J., Van Heteren, S., Schmelzer, N., van Beusekom, J., Colijn, F., Haigh, I., Hjøllo, S., Holfort, J., Kent, E.C., Kühn, W., Loewe, P., Lorkowski, I., Mork, K.A., Pätsch, J., Quante, M., Salt, L., Siddorn, J., Smyth, T., Sterl, A., Woodworth, P. (2016). Recent change - North Sea. In: Quante, M. and Colijn, F. (Ed.), North Sea region climate change assessment. Springer, Switzerland, pp. 85-136.

Idier, D., Paris, F., Cozannet, G.L., Boulahya, F., Dumas, F., 2017. Sea-level rise impacts on the tides of the European Shelf. Continental Shelf Research 137, 56-71.

IPCC, 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment

IPCC, 2012. Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.K. Plattner, S.K. Allen, M. Tignor, P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK, and New York, NY, USA.

IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jevrejeva, S., Grinsted, A., Moore, J., 2014. Upper limit for sea level projections by 2100. Environmental Research Letters 9, 104008.

Jevrejeva, S., Moore, J.C., Grinsted, A., 2010. How will sea level respond to changes in natural and anthropogenic forcings by 2100?. Geophysical Research Letters 37, 07703.

Jordà, G., Gomis, D., Álvarez-Fanjul, E., Somot, S., 2012. Atmospheric contribution to Mediterranean and nearby Atlantic sea level variability under different climate change scenarios. Global and Planetary Change 80–81, 198-214.

Katsman, C.A., Sterl, A., Beersma, J.J., Brink, H.W., Church, J.A., Hazeleger, W., Kopp, R.E., Kroon, D., Kwadijk, J., Lammersen, R., Lowe, J., Oppenheimer, M., Plag, H.P., Ridley, J., Storch, H., Vaughan, D.G., Vellinga, P., Vermeersen, L.L.A., Wal, R.S.W., Weisse, R., 2011. Exploring high-end scenarios for local sea level rise to develop flood protection strategies for a low-lying delta — the Netherlands as an example. Climate Dynamics 109 (3-4), 617–645.

Kopp, R.E., Simons, F.J., Mitrovica, J.X., Maloof, A.C., Oppenheimer, M., 2009. Probabilistic assessment of sea level during the last interglacial stage. Nature 462, 863–867.

Lesser, G.R., Roelvink, J.A., van Kester, J.A.T.M., Stelling, G.S., 2004. Development and validation of a three-dimensional morphological model. Coastal Engineering 51, 883-915.

Lionello, P., Cogo, S., Galati, M.B., Sanna, A., 2008. The Mediterranean surface wave climate inferred from future scenario simulations. Global and Planetary Change 63, 152–162.

Lionello, P., Galati, M.B., Elvini, E., 2010. Extreme storm surge and wind wave climate scenario simulations at the Venetian littoral. Physics and Chemistry of the Earth Parts 40, 86–92.

Lionello, P., Sanna, A., 2005. Mediterranean wave climate variability and its links with NAO and Indian Monsoon. Climate Dynamics 25 (6), 611–623.

Lowe, J.A., Gregory, J.M., Flather, R.A., 2001. Changes in the occurrence of storm surges around the United Kingdom under a future climate scenario using a dynamic storm surge model driven by the Hadley Centre climate models. Climate Dynamics 18, 179-188.

Lowe, J.A., Howard, T., Pardaens, A., Tinker, J., Holt, J., Wakelin, S., Milne, G., Leake, J., Wolf, J., Horsburgh, K., Reeder, T., Jenkins, G., Ridley, J., Dye, S., Bradley, S., 2009. UK Climate Projections science report: Marine and coastal projections. Met Office Hadley Centre, Exeter, UK.

Lowe, J.A., Howard, T.P., Pardaens, A., Tinker, J., Holt, J., Wakelin, S., Milne, G., Leake, J., Wolf, J., Horsburgh, K., Reeder, T., Jenkins, G., Ridley, J., Dye, S., Bradley, S., 2009. UK Climate Projections science report: Marine and coastal projections. Met Office Hadley Centre, Exeter, UK.

Lowe, J.A., Woodworth, P.L., Knutson, T., McDonald, R.E., McInnes, K.L., Woth, K., Von Storch, H., Wolf, J., Swail, V., Bernier, N., Gulev, S., Horsburgh, K.J., Unnikrishnan, A.S., Hunter, J.R. & Weisse, R. (2010) Past and future changes in extreme sea levels and waves. In: Church, J.A, Woodworth, P. L., Aarup, T.,Wilson, W. S. (eds), Understanding Sea Level Rise and Variability. Wiley-Blackwell, London, pp. 326-361.

Lowe, J.A., Woodworth, P.L., Knutson, T., McDonald, R.E., McInnes, K.L., Woth, K., von Storch, H., Wolf, J., Swail, V., Bernier, N.B., Gulev, S., Horsburgh, K.J., Unnikrishnan, A.S., Hunter, J.R., Weisse, R., 2010. Past and Future Changes in Extreme Sea Levels and Waves, Understanding Sea-Level Rise and Variability. Wiley-Blackwell, pp. 326-375.

M. Tignor, H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Marcos, M., Chust, G., Jorda, G., Caballero, A., 2012. Effect of sea level extremes on the western Basque coast during the 21st century. Climate Research 51, 237-248.

Marcos, M., Jordà, G., Gomis, D., Pérez, B., 2011. Changes in storm surges in southern Europe from a regional model under climate change scenarios. Global and Planetary Change 77, 116-128.

Matthews, T., Murphy, C., Wilby, R. L., Harrigan, S., 2014. Stormiest winter on record for Ireland and UK. Nature Climate Change 4, 738–740.

Mawdsley, R.J., Haigh, I.D., Wells, N.C., 2015. Global secular changes in different tidal high water, low water and range levels. Earth's Future 3, 66-81.

McCall, R.T., Van Thiel de Vries, J.S.M., Plant, N.G., Van Dongeren, A.R., Roelvink, J.A., Thompson, D.M., Reniers, A.J.H.M., 2010. Two-dimensional time dependent hurricane overwash and erosion modeling at Santa Rosa Island. Coastal Engineering 57, 668-683.

Meier, H.E.M., 2006. Baltic Sea climate in the late twenty-first century: a dynamical downscaling approach using two global models and two emission scenarios. Climate Dynamics 27, 39-68.

Meier, H.E.M., Broman, B., KjellstrÃ¶m, E., 2004. Simulated sea level in past and future climates of the Baltic Sea. Climate Research 27, 59-75.

Menendez, M., Woodworth, P.L., 2010. Changes in extreme high water levels based on a quasi-global tide-gauge dataset. Journal of Geophysical Research 115, C10011.

Mitrovica, J.X., Tamisea, M.E., Davis, J.L. and Milne, G.A., 2001. Recent mass balance of polar ice sheets inferred from patterns of global sea-level change. Nature 409, 1026- 1029.

Nicholls, R.J., French, J., Burningham, H., Van Maanen, B., Payo, A., Sutherland, J., Walkden, M., Thornhill, G., Brown, J., Luxford, F., Simm, J., Reeve, D.E., Hall, J. W., Souza, A., Stansby, P.K., Amoudry, L.O., Rogers, B.D., Ellis, M., Whitehouse, R., Horrillo-Caraballo, J.M., Karunarathna, H.U., Pan, S., Plater, A., Dix, J., Barnes, J., Heron, E., 2015. Improving Decadal Coastal Geomorphic Predictions: An Overview of the ICOASST Project. In: Proceedings of the Coastal Sediments, San Diego, USA.

Pelling, H.E., Mattias Green, J.A., 2014. Impact of flood defences and sea-level rise on the European Shelf tidal regime. Continental Shelf Research 85, 96-105.

Perez, J., Menendez, M., Camus, P., Mendez, F.J., Losada, I.J., 2015. Statistical multi-model climate projections of surface ocean waves in Europe. Ocean Modelling 96, 161–170.

Perini, L., Calabrese, L., Salerno, G., Ciavola, P., Armaroli, C., 2016. Evaluation of coastal vulnerability to flooding: comparison of two different methodologies adopted by the Emilia-Romagna region (Italy). Natural Hazards and Earth System Sciences 16, 181-194.

Pfeffer, W.T., Harper, J.T., O'Neel, S., 2008. Kinematic constraints on glacier contributions to 21st century sea level rise. Science 321, 1340–1343.

Pickering, M.D., Wells, N.C., Horsburgh, K.J., Green, J.A.M., 2012. The impact of future sea-level rise on the European Shelf tides. Continental Shelf Research 35, 1-15.

Prandle, D., Wolf, J., 1978. The interaction of surge and tide in the North Sea and River Thames. Geophysical Journal of the Royal Astronomical Society 55, 203–216.

PSMSL, 2017. Permanent Service for Mean Sea Level. http://www.psmsl.org/, [accessed 17 April, 2017].

Pugh, D., Woodworth, P., 2014. Sea-Level Science: Understanding Tides, Surges, Tsunamis and Mean Sea-Level Changes. Cambridge University Press, Cambridge.

Purvis, M.J., Bates, P.D., Hayes, C.M., 2008. A probabilistic methodology to estimate future coastal flood risk due to sea level rise. Coastal Engineering 55, 1062-1073.

Rahmstorf, S., 2007. A semi-empirical approach to projecting future sea-level rise. Science 315 (5810), 368–370.

Ramirez, J.A., Lichter, M., Coulthard, T.J., Skinner, C., 2016. Hyper-resolution mapping of regional storm surge and tide flooding: comparison of static and dynamic models. Natural Hazards 82, 571-590.

Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt,

Roelvink, D., Reniers, A., Dongeren, A.v., Vries, J.v.T.d., McCall, R., Lescinski, J., 2009. Modelling storm impacts on beaches, dunes and barrier islands. Coastal Engineering 56, 1133-1152.

Rossiter, J.R., 1961. Interaction between tide and surge in the Thames. Geophysical Journal of the Royal Astronomical Society 6, 29–53.

Seenath, A., Wilson, M., Miller, K., 2016. Hydrodynamic versus GIS modelling for coastal flood vulnerability assessment: Which is better for guiding coastal management? Ocean & Coastal Management 120, 99-109.

Sekovski, I., Armaroli, C., Calabrese, L., Mancini, F., Stecchi, F., Perini, L., 2015. Coupling scenarios of urban growth and flood hazards along the Emilia-Romagna coast (Italy). Natural Hazards and Earth System Sciences 15, 2331-2346.

Smith, D.E., Hunt, N., Firth, C.R., Jordan, J.T., Fretwell, P.T., Harman, M., Murdy, J., Orford, J.D., Burnside, N.G., 2012. Patterns of Holocene relative sea level change in the North of Britain and Ireland. Quaternary Science Reviews 54 (26), 58–76.

Smith, R.A.E., Bates, P.D., Hayes, C., 2012. Evaluation of a coastal flood inundation model using hard and soft data. Environmental Modelling & Software 30, 35-46.

Sterl, A., van den Brink, H., de Vries, H., Haarsma, R., van Meijgaard, E., 2009. An ensemble study of extreme storm surge related water levels in the North Sea in a changing climate. Ocean Science 5, 369-378.

Thorne, C.R., Evans, E.P., Penning-Roswell, E.C., 2007. Future Flooding and Coastal Erosion risks. Thomas Telford Ltd, London, UK.

Toffoli, A., Lefèvre, J.M., Bitner-Gregersen, E., Monbaliu, J., 2005. Towards the identification of warning criteria: Analysis of a ship accident database. Applied Ocean Research 27 (6), 281–291.

Vermeer, M., Rahmstorf, S., 2009. Global sea level linked to global temperature. Proceedings of the National Academy of Sciences 106 (51), 21527–21532.

Vousdoukas, M.I., Ferreira, O., Almeida, L.P., Pacheco, A., 2012a. Toward reliable storm-hazard forecasts: XBeach calibration and its potential application in an operational early-warning system. Ocean Dynamics 62, 1001-1015.

Vousdoukas, M.I., Mentaschi, L., Voukouvalas, E., Verlaan, M., Feyen, L., 2017. Extreme sea levels on the rise along Europe's coasts. Earth's Future submitted after minor revision.

Vousdoukas, M.I., Voukouvalas, E., Annunziato, A., Giardino, A., Feyen, L., 2016a. Projections of extreme storm surge levels along Europe. Climate Dynamics 47, 3171–3190.

Vousdoukas, M.I., Voukouvalas, E., Mentaschi, L., Dottori, F., Giardino, A., Bouziotas, D., Bianchi, A., Salamon, P., Feyen, L., 2016b. Developments in large-scale coastal flood hazard mapping. Natural Hazards and Earth System Science 16, 1841-1853.

Vousdoukas, M.I., Wziatek, D., Almeida, L.P., 2012b. Coastal vulnerability assessment based on video wave run-up observations at a mesotidal, steep-sloped beach. Ocean Dynamics 62, 123-137.

Wahl, T., Chambers, D.P., 2016. Climate controls multidecadal variability in U. S. extreme sea level records. Journal of Geophysical Research: Oceans 121, 1274–1290.

Wang, X.L., Zwiers, F.W., Swail, V.R., Feng, Y., 2009. Trends and variability of storminess in the Northeast Atlantic region, 1874–2007. Climate Dynamics 33, 1179–1195.

Weisse, R., Storch, H., Callies, U., Chrastansky, A., Feser, F., Grabemann, I., Günther, H., Pluess, A., Stoye, T., Tellkamp, J., Winterfeldt, J., Woth, K., 2009. Regional meteorological-marine reanalysis and climate change projections: results for northern Europe and

potential for coastal and offshore applications. Bulletin of the American Meteorological Society 90 (6), 849–860.
Williams, J., Horsburgh, K.J., Williams, J.A., Proctor, R.N.F., 2016. Tide and skew surge independence: New insights for flood risk. Geophysical Research Letters 43, 6410–6417.
WMO (World Meteorological Organization (WMO), 2010. Tropical Cyclone Operational Plan for the Bay of
Wolf, J., 2009. Coastal Flooding — Impacts of coupled wave-surge-tide models. Natural Hazards 49 (2), 241-260.
Wolf, J., 2016. Measurement and analysis of waves in estuarine and coastal waters. In: Uncles, R.J., Mitchell, S.B. (eds), Estuarine and coastal hydrography and sediment transport. Estuarine and Coastal Science Association. Cambridge University Press, Cambridge, UK.
Wolf, J., Brown, J. M., Howarth, M.J., 2011. The wave climate of Liverpool Bay — observations and modelling. Ocean Dynamics 61, 639-655.
Wolf, J., Lowe, J., Howard, T., 2015. Climate Downscaling: Local Mean Sea-Level, Surge and Wave Modelling. In: Nicholls, R. J., Dawson, R.J., Day, S. A. (eds), Broad Scale Coastal Simulation: New Techniques to Understand and Manage Shorelines in the Third Millennium. Springer, Dordrecht, Netherlands.
Wolf, J., Woolf, D. K., 2006. Waves and climate change in the north-east Atlantic. Geophysical Research Letters 33 (6), L06604.
Wong, P.P., Losada, I.J., Gattuso, J.P., Hinkel, J., Khattabi, A., McInnes, K.L., Saito, Y., Sallenger, A., 2014. Coastal systems and low-lying areas. In: Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastandrea, M.D., Bilir, T.E., Chatterjee, M., Elbi, K.L, Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N, MacCracken, S., Mastandrea, P.R., White, L.L. (eds), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge,United Kingdom and New York, USA, pp. 361-409.
Woodworth, P.L., 2010. A survey of recent changes in the main components of the ocean tide. Continental Shelf Research 30, 1680-1691.
Woodworth, P.L., Blackman, D.L., 2004. Evidence for systematic changes in extreme high waters since the mid-1970s. Journal of Climate 17(6):1190–1197.
Woodworth, P.L., Gehrels, W.R., Nerem, R.S., 2011. Nineteenth and twentieth century changes in sea level. Oceanography 24 (2), 80–93.
Woodworth, P.L., Teferle, N., Bingley, R., Shennan, I., Williams, S.D.P., 2009. Trends in UK mean sea level revisited. Geophysical Journal International 176, 19–30.
Woolf, D., Wolf, J., 2013. Impacts of climate change on storms and waves. MCCIP Science Review undefined, 20–26.
Woolf, D.K., Challenor, P.G., Cotton, P.D., 2002. The variability and predictability of North Atlantic wave climate. Journal of Geophysical Research 107 (10), 3145.
Woolf, D.K., Cotton, P.D., Challenor, P.G., 2003. Measurements of the offshore wave climate around the British Isles by satellite altimeter. Philosophical Transactions: Mathematical, Physical & Engineering Sciences 361 (1802), 27–31.
Woollings, T., 2010. Dynamical influences on European climate: an uncertain future. Philosophical Transactions of the Royal Society A 368, 3733–3756.
Woth, K., Weisse, R., Von Storch, H., 2006. Climate change and North Sea storm surge extremes: an ensemble study of storm surge extremes expected in a changed climate projected by four different regional climate models. Ocean Dynamics 56, 3-15.
Zacharioudaki, A., Pan, S., Simmonds, D., Magar, V.Reeve, D.E., undefined, 2011. Future wave climate over the west-European shelf seas. Ocean Dynamics 61 (6), 807–827.