1 Introduction

1.1 Coasts as high-risk areas
Coastal flooding is one of the world’s most threatening hazards and causes damages in the order of tens of billions of dollars per year (Kron, 2013). These large losses occur because a high proportion of the global population and economic assets are concentrated in low-lying coastal zones, and because many of the world’s largest cities are prone to coastal flooding (Hanson et al., 2011; Nicholls et al., 2008). Kummu et al. (2016) estimate that 27% of the global population (1.9 billion people) and 42% of global GDP are located in near-coastal zones. Moreover, Hinkel et al. (2014) estimate that 65 to 110 million people live within the 1 in 100-year floodplain, and that on average 0.8 to 1.1 million people per year are exposed to flooding.

Historical disasters exemplify the potentially devastating impact of coastal flooding. For example, Northwest Europe has a long history of severe flood disasters, which have caused thousands of deaths (Lamb and Frydendahl, 1991; Mitchell, 2003). A specific example is the 1953 flood that killed over 2,000 people in the Netherlands and the United Kingdom (McRobie et al., 2005; Spencer et al., 2013). Another area with a long history of severe flood disasters is the Bay of Bengal, especially Bangladesh (Alam and Dominey-Howes, 2015; Flierl and Robinson, 1972). This region was struck by the deadliest flood event on record, namely the Bhola tropical cyclone in 1970, which claimed the lives of at least 300,000 people (Frank and Husain, 1971) with some estimates as high as 500,000 people. Fortunately, major improvements in flood protection and flood forecasting in recent decades have led to a decrease in global mortality rates from storm surges (Bouwer and Jonkman, 2017). Governments have learned from past disasters and have enforced policies to prevent flood events from having such significant impacts (Lumbroso et al., 2017). In response to the flood of 1953, the government of the Netherlands spent billions of dollars building a flood protection system designed to cope with water levels with return periods up to 10,000 years (Bouwer and Vellinga, 2007). The large impacts of the floods also triggered major developments in the operational forecasting of coastal flooding (Verlaan et al., 2005), and nowadays tides and storm surges are predicted with great accuracy (Zijl et al., 2013). There were similar developments in Bangladesh in response to Cyclone Bhola.
(Lumbroso et al., 2017). However, despite these efforts, Cyclone Gorky caused 140,000 casualties when it struck in 1991 (Chowdhury et al., 1993). Since then, further improvements have been made in forecasting and in the availability of the public cyclone shelters used for evacuation, and the number of volunteers has increased (Paul, 2009; Paul and Dutt, 2010). As a result, Cyclone Sidr claimed far fewer lives in 2017 (3,400 fatalities) than Cyclone Gorky had done in 1991, despite having a similar magnitude.

These examples illustrate that the impact of a coastal flood does not simply depend on the physical characteristics of the flood itself. Rather, it is strongly influenced by socio-economic characteristics, including the number of people living in the inundated area, the flood protection system in place, the type of buildings, and the existence of an early warning system and evacuation plans. Flood risk is generally defined as a function of hazard, exposure, and vulnerability (IPCC, 2012; Kron, 2005). Hazard refers to the flood event itself, including its characteristics and probability of occurrence. Exposure refers to the values at risk, and can be expressed as the population or capital located in flood-prone areas. Vulnerability refers to the susceptibility of the exposed units to suffer damage and loss.

1.2 Controls on coastal flooding

Coastal flooding is caused by extreme sea levels, which are typically driven by a combination of tides, storm surges, and variations in mean sea level (Figure 1-1). A storm surge is a rise in sea level above the predicted astronomical tide, and is caused when low-pressure systems with strong winds push water towards the shore (Pugh and Woodworth, 2015; Pugh, 1988). The response of the sea surface to a change in atmospheric pressure is called the inverse barometric effect, which can also contribute to extreme sea levels, although usually of lesser importance than the wind setup. Using a simplified form of the shallow-water equations, the response of the sea surface height to wind can be represented by the following equation (Resio and Westerink, 2008; Woodruff et al., 2013):

\[ s = \frac{U^2 W}{h} \]

Equation 1.1

Where \( s \) is the surge height at the coast, \( U \) is wind speed, \( W \) is the shelf width, and \( h \) is the mean depth. This indicates that the height of a storm surge is strongly influenced by the continental shelf leading up to the coastal floodplain. The same storm will produce a much higher surge in areas with broad and shallow continental shelves, such as the North Sea or the western North Atlantic, than in areas with steep offshore slopes, such as islands in the western North Pacific and the Caribbean. Areas such as the North Sea and the Bay of Bengal act as a sort of funnel that can trap a storm surge and lead to higher sea levels.
Storm surges are caused by two main types of low-pressure systems: 1) extra-tropical cyclones (i.e. mid-latitude storms); and 2) tropical cyclones (including hurricanes and typhoons). These have different characteristics with respect to storm size and intensity, which are reflected in their associated storm surges. Tropical cyclones have lower interior pressures and higher wind speeds than extra-tropical cyclones and typically produce significantly higher storm surges (Resio and Westerink, 2008). However, tropical cyclones generally have a short duration (hours to days) and act on a relatively small spatial scale (<500 km). Extra-tropical cyclones often last longer (two to five days) and act on a larger spatial scale (>1,000 km) (Pugh and Woodworth, 2015). Within the regions they affect, tropical cyclones are generally the most damaging storms. However, at mid-latitudes, such as the northeast Atlantic coast of the United States, extra-tropical cyclones are generally more frequent, have longer durations, and impact considerably larger areas (Colle et al., 2010; Dolan and Davis, 1994). As such, they contribute significantly to the overall flood hazard the United States (Booth et al., 2016; Orton et al., 2016).

Figure 1-1 Components of extreme sea levels.

Whether a storm surge results in flooding often depends on the storm’s timing in relation to the tide. For example, extreme sea levels in the United Kingdom are generally caused by a moderate storm surge coinciding with high tides, rather than an extreme storm surge coinciding with moderate tides (Haigh et al., 2016). Moreover, the peak surge of the 1953 flood disaster in both the Netherlands and the United Kingdom coincided with spring tides (McRobie et al., 2005). The contribution of tides is often less substantial in the case of tropical cyclones, but is not negligible. For example, the flooding of New York City during Superstorm Sandy in 2012 was aggravated by the fact that its storm surge coincided with high spring tides (Forbes et al., 2014).

Variations in mean sea level due to oceanographic effects can also contribute to extremes. This can be due to seasonal changes, but it may also due to ocean-atmosphere oscillations that cause interannual variability. On short timescales, the changes in mean sea level are usually small in comparison to the daily changes in tides and surge (Pugh, 1988). However, in regions with small tidal ranges, variability in mean sea level can have
a significant influence on the generation of extremes (Haigh et al., 2013b; Marcos et al., 2009; Tsimpis and Woodworth, 1994). For example, higher mean sea levels during La Niña led to tidal flooding in Florida in 2015 (Sweet et al., 2016).

1.3 Temporal variability in coastal risk
Coastal flood risk is variable in time, both due to short-term variability and long-term change. This temporal variability can result from changes in hazard, exposure, and vulnerability. In this section, it is discussed how this short- to long-term variability can influence the risk of coastal flooding. Changes in flood hazard range from the seasonal and interannual cycles caused by natural climate variability to the long-term trends caused by the anthropogenic warming of the global climate. Changes in flood exposure and vulnerability are the result of both socio-economic development and changes in flood forecasting.

1.3.1 Short-term variability in flood hazard
Sea levels are composed of mean sea levels, storm surges, and tides, and vary according to different timescales (seasonal, interannual, decadal, and secular) due to local meteorological, oceanographic, and hydrological forcings. The range and drivers of the seasonal cycle vary from location to location (Feng et al., 2015; García-Lafuente et al., 2004; Luu et al., 2015; Tsimpis and Woodworth, 1994), but meteorology is generally the dominant driver (Pugh, 1988). Storm surges at mid-latitudes occur primarily during the storm season. For example, in the North Sea storms occur primarily in the winter months (Dangendorf et al., 2014b). Storm surges induced by tropical cyclones also have a strong seasonal component, as they require warm ocean temperatures to form and occur during a specific season. Seasonal fluctuations in salinity and temperature can drive variability in mean sea levels due to their steric effects (Tsimpis and Woodworth, 1994). In estuaries and deltaic regions, the seasonal cycle of sea levels will be significantly affected by river runoff. For example, in the Bay of Bengal the range of the seasonal cycle exceeds one metre due to seasonal monsoon effects and changes in steric levels as a result of fresh-water flow (Singh, 1999). There are also tidal variations that act on a seasonal scale, such as perigean spring tides, but their effects are generally small.

Interannual and decadal fluctuations are generally driven by coupled atmospheric-ocean circulation modes, such as the North Atlantic Oscillation (NAO) and the El Niño–Southern Oscillation (ENSO). The El Niño–Southern Oscillation (ENSO) is driven by fluctuation between unusually warm (El Niño) and cold (La Niña) conditions in the tropical Pacific, which typically recur every two to seven years and can affect global weather patterns (McPhaden et al., 2006). ENSO drives interannual changes in sea levels by both steric effects and by changes in the intensity, frequency, and tracks of storms (Marcos et al., 2015; e.g. Menéndez and Woodworth, 2010; Merrifield et al., 2013). Interannual and decadal fluctuations can also be driven by the tidal component, with
long periods driven by the motions of the moon’s orbit around the earth. These include the cycle of the lunar perigee of 8.9 years and the lunar nodal cycle of 18.6 years (Haigh et al., 2011; Sobey, 2005). However, the modulation of tides at these long frequencies is generally limited (Melet et al., 2018; Woodworth, 2012).

1.3.2 Long-term increases in flood hazard due to rising sea levels
As Section 1.3.1 explains, mean sea levels vary on seasonal and interannual timescales. However, mean sea levels also vary on millennial to centennial timescales due to changes in the global climate. Over the last century, anthropogenic emissions of greenhouse gases have resulted in global warming, the melting of glaciers, and the thermal expansion of sea water, causing a rise in the global mean sea level (IPCC, 1990). An immediate effect of sea-level rise (SLR) is the permanent submergence of land and increased flooding (Nicholls and Cazenave, 2010). Since 1990, the global mean sea level has risen by 16 to 19 cm (Church and White, 2011; Hay et al., 2015). Over the last century, the majority of the SLR has been driven by ocean warming and the loss of glaciers (IPCC, 2007). However, future SLR may also be significantly affected by the melting of the Greenland and Antarctic ice sheets (Dutton et al., 2015; Golledge et al., 2015; Levermann et al., 2013). The Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC, 2013a) projects a likely range of global sea-level rise of 0.5-1.0 m by 2100 for high emission scenarios, in comparison to 1986-2005 (Figure 1-2). However, sea-level projections have large uncertainties, and sea-level rise could be much large when there are significant contributions from the major Greenland and Antarctic ice sheets (Nicholls et al., 2014). Recent research indicates that the response of the ice sheets to global warming is non-linear due to ice-shelf hydrofracturing and ice-cliff collapse and thus more dynamic that previously thought (DeConto and Pollard, 2016). Recent SLR projections that include a larger response from Antarctica demonstrate that the likely range for 2100 may exceed one metre (Bakker et al., 2017; Kopp et al., 2017; Nauels et al., 2017). Furthermore, the non-linear response of the ice-sheets to climate warming means that sea level will continue to rise beyond 2100, even if we manage to completely reduce greenhouse gas emissions. Consequently, there is a multi-millennial commitment to sea level rise of several metre. This means that even under projections where the Paris Agreement is achieved and global temperature are stabilized at 1.5°C adaptation remains essential (Nicholls et al., 2018).

In some places, sea levels are rising ten times faster than the global average (Church and White, 2004). Regional variations in the rate of SLR derive from changes in ocean circulation (non-uniform warming of the ocean and changes in salinity), changes in gravitational forces due to the melting of the ice sheets, changes in the terrestrial storage of water, and glacio-isostatic adjustments (Nicholls and Cazenave, 2010; Slangen et al., 2012). Thus, the regional pattern of SLR is very much dependent on the contributing
components. With regard to SLR projections for 2100, Slangen et al. (2014) estimate that about 10% of the ocean area may experience deviations of more than 25% of the global mean. The equatorial oceans in particular will experience regional SLR well above the global mean. Therefore, flood risk assessments need to downscale global sea-level rise information to the local situation (Brown et al., 2013; Hinkel et al., 2015).

In addition to SLR, land subsidence may be an important driver of increasing flood damages in some regions. Human activities can exacerbate the naturally high subsidence rates in the world's deltas (Syvitski et al., 2009). Such activities include oil, gas, and groundwater extraction, the compression of soil due the load of constructions, and the trapping of sediments in upstream reservoirs. The rate of land subsidence can be many times faster than the rate of sea-level rise. For example, large parts of Jakarta in Indonesia are sinking by 1 to 15 centimetres each year, although the rate is as high as 20 to 28 centimetres per year for specific locations (Abidin et al., 2011).

In addition to SLR, a warming climate may also result in changes in storm intensity and frequency (IPCC, 2013a). Many global studies have assumed that future changes in storminess will be negligible, and that only SLR will drive changes in the frequencies of extremes (e.g. Hinkel et al., 2014; Jongman et al., 2012b). This is consistent with the
conclusions based on observed historical trends (Menéndez and Woodworth, 2010; Woodworth et al., 2011; Woodworth and Blackman, 2004; Zhang et al., 2000), although it is recognized that some locations may experience long-term trends and multi-decadal variations in the frequencies of extreme sea levels (Marcos et al., 2015, 2009; Marcos and Woodworth, 2017; Wahl and Chambers, 2015). However, these assumptions may not be valid for future changes. There are numerous studies that assess future changes in storm surges based on various climate change scenarios at the local and regional level (e.g. Brown et al., 2011; Lowe et al., 2001; Marcos et al., 2011). In the case of Europe, Vousdoukas et al. (2016a) demonstrated that, although the effects vary regionally, the changes in extreme sea levels due to changes in storm surge are generally small in comparison to the changes in mean sea level. However, in the case of higher return periods and higher emissions scenarios, the changes in storm surge can considerably aggravate the effects of SLR.

A warmer climate may also induce changes in the frequency and intensity of tropical cyclones. Warmer oceans may lead to an intensification of tropical cyclones, and result in an increased frequency of the most severe tropical cyclones during the following century (e.g. Emanuel, 2013; Knutson et al., 2010; Mendelsohn et al., 2012). At the same time, there may be a decrease in the total number of tropical cyclones. Tropical cyclone tracks may move poleward due to the warmer oceans (Kossin et al., 2014; Sobel et al., 2016). In the Atlantic basin, the tropical cyclone genesis area is expected to move poleward and to also extend eastwards (Zhao & Held, 2012), thereby increasing the number of tropical cyclones that reach Western Europe (Baatsen et al., 2015; Haarsma et al., 2013). In the western North Pacific, the most intense tropical cyclones may undergo a northward shift (Murakami et al., 2012). Such shifts in tropical cyclone tracks may result in increased risks in regions that do not currently experience tropical cyclones (Lin and Emanuel, 2015). Although trends are difficult to detect (Landsea et al., 2010, 2006), this is also suggested by observations from previous decades (Elsner et al., 2008; Webster et al., 2005).

1.3.4 Changes in flood exposure and vulnerability
The last three decades have seen a substantial increase in the global flood losses observed (Bouwer et al., 2007; Kron, 2013). Until now, this has primarily been driven by socio-economic development in flood prone areas (e.g Barredo, 2009; Bouwer, 2011; Changnon et al., 2000). Strong population growth, socio-economic development, and migration towards the coasts mean that an increasing number of people and economic assets are located in flood-prone areas (Jongman et al., 2012b; Kummu et al., 2016; Peduzzi et al., 2012). This is particularly true for rapidly-expanding coastal cities, especially in Asia and Africa (Guneralp et al., 2015; Seto, 2011). The population and capital located in flood prone areas have generally increased more rapidly than the global
average (Jongman et al. 2012). Projections for 2100 indicate that the population living within a 10 metre elevation of mean sea level may double or almost quadruple, particularly in Asia (Jones and O’Neill, 2016; Neumann et al., 2015).

While exposure is increasing, vulnerability appears to be decreasing over time due to disaster risk reduction and adaptation efforts. The implementation of flood risk management measures, such as improvements in weather forecasting and changes in building regulations and techniques (Nicholls, 2011), can limit societal and economic losses (Jongman et al., 2015). Flood risk management has been successful in reducing the global flood mortality rate over recent decades (Bouwer and Jonkman, 2017). Research indicates that the vulnerability of low-income countries is generally decreasing and that it is tending to converge with the vulnerability levels of high-income countries (Jongman et al., 2015; Tanoue et al., 2016). The reduction of flood vulnerability through economic development has considerable potential to reduce the increasing flood risks under future climate projections (Kinoshita et al., 2018).

1.4 Assessing coastal risk at the global scale

Recent years have seen increased attention for large-scale flood risk assessments. Global flood hazard maps are increasingly used to assess climate change impacts, disaster risk reduction, the detection of risk hotspots in data-scarce regions, and for (re)insurance applications (Ward et al., 2015). An example of a global risk assessment is the biennial Global Assessment Report on Disaster Risk Reduction (GAR), published by the United Nations Office for Disaster Risk Reduction (UNISDR). By monitoring risk patterns and trends in disaster risk, GAR seeks to contribute to achieving the risk-reduction targets of the Sendai Framework Hyogo Framework for Action. Another example is a study by the World Bank and the OECD that projects future losses in major global port cities (Hallegatte et al., 2013; Hanson et al., 2011). These global assessments have been instrumental in identifying hotspots of risks and in advocating for climate change adaptation and disaster risk management in an international context.

A risk approach requires a chain of different models that link the components of hazard, exposure, and vulnerability. The first step is to assess the global flood hazard, and requires the accurate mapping of extreme sea levels along the world’s coasts. Historically, global studies focussing on extreme sea levels were based on tide gauge observations (Marcos et al., 2015; Menéndez and Woodworth, 2010; Merrifield et al., 2013; Woodworth and Blackman, 2004). These studies contributed to an improved understanding of the global patterns and trends in extreme sea levels. However, the spatial coverage of tide gauges is sparse and is biased towards the Northern Hemisphere (Woodworth et al., 2016). Furthermore, the records of many of these observations are not long enough to estimate return periods using extreme value statistics. Moreover, the interpolation of extreme sea levels between observation stations is not likely to capture
the spatial variability of extreme sea levels, which are strongly influenced by the local coastline’s bathymetry and geometry. While the use of altimetry data may overcome these issues (Merrifield et al., 2013), their application in near-coastal areas remains challenging (Cipollini et al., 2017), and the limited length of altimetry records prevents their application to low-probability extreme events. As a result, the use of observations for flood risk assessment at the global scale is limited.

Therefore, a modelling approach is a prerequisite for an accurate assessment of the global risk to coastal flooding. Hydrodynamic modelling is a state-of-the-art method at the regional and local scale (Aerts et al., 2014; e.g. Bates et al., 2005). Hydrodynamic models provide continuous and full coverage of sea levels, and enable the assessment of various future climate scenarios (Lowe and Gregory, 2005; Vousdoukas et al., 2016a). More simplistic approaches have been applied to estimate flood hazard at the global scale. In the early 1990s, the first global estimates of extreme sea levels were published as part of the Global Vulnerability Assessment (GVA; Hoozemans et al., 1993, 1992; Nicholls and Hoozemans, 2005). These estimates were based on a static approximation of storm surge conditions and mean high tide levels per country. Further improvement and refinement occurred in 2004 with the DINAS-COAST (Dynamic and Interactive Assessment of National, Regional and Global Vulnerability of Coastal Zones to Climate Change and Sea-Level Rise) project (Hinkel and Klein, 2009; McFadden et al., 2007; Vafeidis et al., 2008). For over a decade, the DINAS-COAST extreme sea levels (DCESL) was the only global dataset of extreme sea levels. Various continental- to global-scale studies have applied the DCESL in order to assess coastal flood risk. These include studies using the DIVA (Dynamic Interactive Vulnerability Assessment) model (Brown et al., 2013; Hinkel et al., 2014, 2011; Nicholls et al., 2010), together with other impact models (Hallegatte et al., 2013; Jongman et al., 2012b; Muis et al., 2015; Sugiyama et al., 2008; Ward et al., 2010b). These studies have been widely used and have provided important insights into the dynamics of coastal flood risk, such as which coastal areas may experience the highest increases in risk due to SLR. The prime focus of these studies has been to assess long-term changes in coastal risk due to socio-economic development and SLR (Hinkel et al., 2014; Jongman et al., 2012b). Little attention has been given to the validation of the DCESL dataset or to improving the methodology used to estimate the extreme sea levels. In addition, previous studies at the global scale have not accounted for the conflicting vertical datum of extreme sea levels and global land elevation. While extreme sea levels generally use mean sea level as datum, global elevation datasets such as the Shuttle Radar Topography Mission (SRTM) use the EGM96 geoid as datum. The dynamic sea surface of the ocean means that there can be an offset of up to 1.5 metres between mean sea level and the geoid. Therefore, not harmonizing the vertical datum may induce severe errors in inundation modelling.
Given the limitations discussed, the global modelling of coastal risk faces a number of major research challenges. However, there has also been considerable improvement in the quality and availability of the global datasets required for global risk modelling, which are not yet utilized in current methodologies and global datasets. The world’s land elevation is mapped at a 3 arc-seconds (~30 m) resolution by the Shuttle Radar Topography Mission (SRTM) (Rabus et al., 2003). Satellite-derived gravity data have helped to map the ocean floor over large areas that had not previously been surveyed by ships (Becker et al., 2009; IOC et al., 2003). Furthermore, climate models provide atmospheric fields across the globe at an increasingly high resolution. There are now various climate reanalysis products that provide a consistent historical record of the weather from the beginning of the satellite era in 1979 to the present (Dee et al., 2011; Kalnay et al., 1996; Onogi et al., 2007). The climate community also produces global projections of future climates for a range of climate models and emission scenarios (e.g. IPCC, 1990; Meehl et al., 2000). Moreover, advances in numerical algorithms and the use of high-performance computing enable the upscaling of hydrodynamic modelling. The implementation of flexible mesh (or unstructured grids) in hydrodynamic algorithms allows for a local refinement of the model grid (Kernkamp et al., 2011). This enables the development of models with sufficient resolution at the shallow coast that are still computationally efficient for running on a large scale. To summarize, the utilization of recent advances in data availability and methods means that there is a large potential for addressing key limitations and providing better estimates of extreme sea levels. This applies to both current and future climates, and to both the scientific community and decision- and policy-makers.

1.5 Research objectives and outline

To address the issues raised in the previous sections, the main objectives of this thesis are:

1. To develop a hydrodynamic modelling approach for improving the assessment of extreme sea levels globally;
2. To advance the global assessment of coastal flood risk;
3. To improve our understanding of the drivers and patterns of flood hazard and risk.

These objectives are addressed through the following research questions:

1. How can currently available data and methods be used to assess both river and coastal flood risk globally, and what are the key limitations at this scale?
2. How do extreme sea levels simulated using a global hydrodynamic model compare with observations and a static model approach?
3. How can we improve the assessment of global coastal flood hazard using a hydrodynamic modelling approach, and what are the resulting spatial patterns of coastal flood exposure?

4. How can we improve the representation of interannual climate variability in simulated sea level time-series, and what is the influence of interannual climate variability on coastal flood exposure?

5. How can tropical cyclones be better included in the global hydrodynamic modelling framework, and what are the patterns and drivers of extreme sea levels along the North-Atlantic coastlines?

These research questions are addressed in the various chapters of this thesis. The individual chapters address the following:

- Using Indonesia as a case study, in Chapter 2 data and methods are explored that are currently available to assess global risk for both river and coastal flooding. It also identifies key limitations of the data and methods at this scale. We consider rivers to be able to compare the current state of both fields.

- In Chapter 3, a hydrodynamic modelling approach is applied in order to develop a global reanalysis of astronomical tides and storms surges, as well as return periods of extreme sea levels. This chapter validates the dataset and discusses its use for flood risk applications. It includes a first application of the dataset that assesses global exposure to 1 in 100-year flood levels.

- To assess the advancement of the use of a hydrodynamic approach, in Chapter 4 we compare the return periods of extreme sea levels developed in Chapter 3 with a previously available global dataset of extreme sea levels. In addition, the methodology for assessing coastal flood exposure is improved by correcting for the conflicting vertical datum, a correction that was ignored in previous global studies.

- In Chapter 5 we further develop the global reanalysis developed in Chapter 3 by including changes in steric sea levels. The improved time-series of sea levels are also used to assess the influence of ENSO on coastal flood hazard.

- In Chapter 6, the inclusion of tropical cyclones in the global reanalysis is discussed. This is achieved by the explicit modelling of tropical cyclones. The improved modelling framework is applied to the western North Atlantic Basins, and historical time-series are used to analyse the drivers of extreme sea levels. The chapter provides a discussion of how such an analysis could be scaled up globally, as well as how we can extend the methodology to be able to estimate return periods.