HYDROMETEOROLOGICAL EXTREME EVENTS

COASTAL STORMS

Processes and Impacts

Edited by Paolo Ciavola and Giovanni Coco

WILEY Blackwell

Coastal Storms

Hydrometeorological Extreme Events

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Edited by

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Series Foreword

The increasing frequency and severity of hydrometeorological extreme events are reported in many studies and surveys, including the 5th IPCC Assessment Report. This report and other sources highlight the increasing probability that these events are partly driven by climate change, while other causes are linked to the increased exposure and vulnerability of societies in exposed areas (which are not only due to climate change but also to mismanagement of risks and 'lost memories' about them). Efforts are ongoing to enhance today's forecasting, prediction and early warning capabilities in order to improve the assessment of vulnerability and risks and develop adequate prevention, mitigation and preparedness measures.

The Book Series on 'Hydrometeorological Extreme Events' has the ambition to gather available knowledge in this area, taking stock of research and policy developments at an international level. While individual publications exist on specific hazards, the proposed series is the first of its kind to propose an enlarged coverage of various extreme events that are generally studied by different (not necessarily interconnected) research teams.

The series encompasses several volumes dealing with various aspects of hydrometeorological extreme events, primarily discussing science – policy interfacing issues, and developing specific discussions about floods, coastal storms (including storm surges), droughts, resilience and adaptation. While the books are looking at the crisis management cycle as a whole, the focus of the discussions is generally oriented towards the knowledge base of the different events, prevention and preparedness, early warning, and improved prediction systems.

The involvement of internationally renowned scientists (from different horizons and disciplines) behind the knowledge base of hydrometeorological events makes this series unique in this respect. The overall series will provide a multidisciplinary description of various scientific and policy features concerning hydrometeorological extreme events, as written by authors from different countries, making it a truly international book series.

The book, *Prevention of Hydrometeorological Extreme Events – Interfacing Sciences and Policies* is the first book of this series; it has been written by policy-makers and scientific experts in the field. It offers the reader an overview of EU international policies, discussions on science – policy interfacing, and a snapshot of the knowledge base of various types of events which are developed in separate volumes of the series.

Philippe Quevauviller
Series Editor

Introduction

Paolo Ciavola and Giovanni Coco

Coastal storms can be one of the most destructive natural hazards. In coastal cities, they can disrupt activities and affect large parts of the population; they can also cause major economic damage and often pose a threat to human lives. The problem of understanding the physical processes operating during a storm and predicting their impact is relevant for scientists and has clear societal implications. Here, we focus on some specific aspects of coastal storms, from inundation to the morphological changes along the coastline. An understanding of this is becoming increasingly relevant because of the ongoing climatic changes and the ever increasing population pressure along coastlines. We have tried to provide a textbook that we hope will be useful to advanced undergraduate and graduate students in variety of fields, ranging from ocean sciences to geomorphology, coastal engineering and geophysics. We decided to split the book in two parts. In the first part, we asked authors to provide a general overview of the present understanding of storms. In the second part we looked more closely at how storms impact different natural systems. In the first part, the definition of a 'storm' is addressed (Chapter 1) and detailed reviews of processes controlling hydrodynamics (Chapter 2), sediment transport (Chapter 3) and overwash processes (Chapter 4) under storm conditions are provided. The reader is then ready to tackle an understanding of how storms impact a variety of geomorphic landscapes, from barrier islands (Chapter 5) to cliffed coastlines (Chapter 6), tidal flats (Chapter 7) and coral reefs (Chapter 8). We also decided that a specific chapter should be dedicated to the role of storm clustering (Chapter 9) and to the most up-to-date advances on the numerical modelling of storm dynamics and effects (Chapter 10). The final chapters focus on the societal aspects of storms and show how to develop frameworks to assess hazards (Chapter 11) and risk management (Chapter 12).

We asked some of the most well-known scientists in the field to help us provide this overview on coastal storms by writing individual chapters. On several occasions the chapters report knowledge gained by the authors during years of research on their topic of expertise, developed with financial support from research agencies in Europe, USA, Australia and New Zealand. We are hugely indebted to the authors, it has been a privilege to share their passion for research and their effort to promote science. Finally, while reading the chapters, it will appear evident that there are still many poorly understood issues that require attention. Research on this topic is still constrained by a limited understanding of the analogies between theoretical process and natural system behaviour during extreme forcing. Field measurements still remain scarce, as acquisition of pre- and post-storm datasets requires quick and costly deployment of state-of-the-art equipment. We hope this book will stimulate scientists to advance knowledge on coastal storms and contribute to a better planning of measures to increase resilience of coastal communities.

Acknowledgments

This book is the result of many years of research and fruitful collaborations with scientists worldwide. None of this could have happened without funding from a number of agencies in a variety of countries. Here, we wish to specifically acknowledge the role of the EU in promoting research on coastal storm processes and impacts during the Seventh Research Framework (e.g. MICORE and RISC-KIT projects). The ongoing support from the EU-RISC-KIT Project-grant 603458 (Paolo Ciavola) and the MBIE-GNS Hazard Platform (Giovanni Coco) is gratefully acknowledged.

Paolo Ciavola would also like to express gratitude to his wife, Clara, and his son, Leonardo, for putting up with late nights trying to bridge the time zone with New Zealand. Together we have seen plenty of beaches around the world and not many mountains. Giovanni Coco would like to thank Mattia for reminding him that beaches are for fun, not for work. Thanks to Jennifer Montano for spotting the final typos.

Finally a little story about the editors of this book. We both grew up in Catania in Italy, on the foothills of the largest volcano in Europe. We both went to scientific high schools there, only a few kilometres from each other. But we never met at the time when we were living on the island. Once again, we studied different topics in different places in Italy and abroad, and destiny did not bring us together. Then life took us around the world and finally science enabled us to meet and discover another fellow who liked the idea of a book on storm processes. Some would call this serendipity, but without doubt it shows us the power of research in bringing people together, whatever their country, belief and personal opinions are.

1

Coastal Storm Definition

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1.1 Introduction

Storms represent nature in one of its most energetic and violent states. The word "storm" is synonymous with images of destruction – strong winds lashing at trees and buildings, intense precipitation flooding towns or dumping meters of snow, large seas eroding beaches and coastal properties, and rapid surges in ocean levels inundating entire islands and vast lowland areas. At the same time, storms are essential to human life and an integral part of the global weather and natural ecosystems. Storms help break droughts by delivering much needed water to drought-stricken areas, thereby recharging reservoirs, river systems and underground aquifers. Many ecosystems are also reliant on the episodic arrival of large storms for their rejuvenation after extended periods of calm, stable conditions (e.g. the flushing of hypersaline lagoons due to hurricanes, Tunnell, 2002).

Globally, storms rank as one of the deadliest of all natural hazards (International Federation of Red Cross and Red Crescent Societies, 2014). In the decade spanning the years 2004–2013, storms were responsible for over 180,000 deaths worldwide – second in terms of lives lost only to those of earthquakes and tsunamis (Table 1.1). Flooding, including marine flooding as a result of waves and storm surge, were meanwhile responsible for over 60,000 deaths worldwide and rank fourth on this list. In the United States, storms have contributed to the vast majority of monetary losses resulting from natural hazards over the last half century. Hurricanes and tropical storms alone have overwhelmingly been the most costly of all natural hazards, having resulted in a total of US$ 267 billion in monetary losses between the years 1960 and 2014 (Figure 1.1). Severe weather, flooding, tornadoes and miscellaneous coastal hazards (loosely defined as hazards including rip currents, coastal flooding, coastal erosion, strong winds, etc.) have also caused combined losses of US$ 364 billion (Hazards and Vulnerability Research Institute, 2015).

There are few regions more vulnerable to storms than the narrow ribbon of the Earth's surface that constitutes the coastal zone. Situated at the interface between land and large water bodies such as oceans, seas and lakes, the coastal zone is a region in constant flux as consolidated and unconsolidated sediments are constantly shaped and re-shaped by Earth's forces. As these forces – winds, waves and currents – interact with

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Table 1.1 Total number of people killed globally by natural disasters between 2004 and 2013 according to disaster type.

Rank	Disaster Type	Total number of people killed
1	Earthquakes/tsunamis	650,321
2	Storms	183,457
3	Extreme temperatures	72,088
4	Floods*	63,207
5	Mass movement: wet	8,739
6	Forest/scrub fires	705
7	Droughts/food insecurity	384
8	Volcanic eruptions	363
9	Mass movement: dry	273
	Total	979,537

*includes wave and surge events
(*Source:* International Federation of Red Cross and Red Crescent Societies, 2014, p. 226)

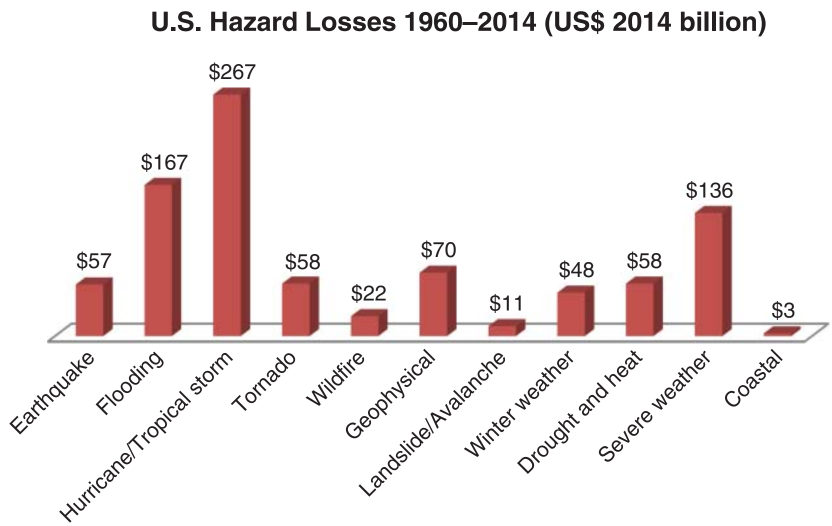

Figure 1.1 Total hazard losses in the United States (1960–2014) by hazard type (*Source:* Hazards and Vulnerability Research Institute, 2015).

coastal sediments, energy is dissipated to such a degree that under normal everyday conditions, their short-term effects on the adjacent coastal hinterland are minimal. During destructive storm conditions, however, the elevated energy and/or water levels may well be beyond the capacity of the coastal zone to dissipate, potentially exposing the backshore and coastal hinterland to unusually large forces and hazardous conditions.

Given the low-lying nature as well as the sheer density of people living close to the coast (with an estimated 23% of the world's population and population densities greater than three times the global average, Small & Nicholls, 2003), the exposure to elevated water levels, waves and currents that may occur during storm conditions can have devastating effects. Some historical examples of extreme storms striking the coast include the 1900 hurricane in Galveston, Texas that claimed the lives of an estimated 8000–12,000 people and is recognized even today as the deadliest natural disaster in the United States' history (Blake & Gibney, 2011). In 1953, a large storm surge in the North Sea inundated tens of thousands of hectares of coastal hinterland in the Netherlands, Belgium and the United Kingdom and claimed over 2500 lives. In Bangladesh, the Bhola cyclone of 1970 is considered one of the worst natural disasters of all time, generating a 10 m storm surge that killed up to 500,000 people and left a huge toll on the country's population and economy. Such devastation was repeated in the same region 21 years later, when another tropical cyclone caused a surge that extended 160 km inland and resulted in 138,000 deaths (Haque, 1997).

In more recent years, coastal storms have received considerable attention as access to news and information via the Internet has grown exponentially and the world has become more aware of the dangers associated with climate change. A particularly significant event that has remained in the conscience of many people was that of Hurricane Katrina that struck the Louisiana coastline in 2005. Hurricane Katrina demonstrated that even in an age of significant advancements in scientific understanding, technology and computer forecasts, nations can still be caught off-guard by the arrival of coastal storms. Hurricane Katrina also highlighted that when coastal storms do occur, it is often the most vulnerable people of a society that are affected the most (Laska & Morrow, 2006). Some other recent examples of coastal storms include Cyclone Sidr in Bangladesh (2007), the Xynthia cyclone in France (2010), Hurricane Sandy in the Caribbean, New Jersey and New York (2012), Typhoon Haiyan in the Philippines (2013), the 2013/2014 winter storms in the United Kingdom and Tropical Cyclone Pam in Vanuatu (2015). Figure 1.2 indicates a rare occurrence of three concurrent tropical cyclones close to the coastline that was observed in southern hemisphere waters in March 2015.

Considering their destructiveness and relevance to today's world, surprisingly few books have dealt specifically with the subject of coastal storms and no overarching definition presently exists to assist in their identification. Indeed a degree of confusion surrounding the use of the term coastal storm is evident. An inspection of Table 1.1, for example, indicates that coastal storms fall into the category of both storms *and* floods, but are not recognized as a category on their own. This is in spite of the fact that the processes governing the formation and development of coastal storms are very different from those of, for instance, river floods. Figure 1.1, meanwhile, highlights the variety of ways in which coastal storms are classified in the commonly-used SHELDUS database for US disaster statistics, with hurricane/tropical storms and coastal hazards treated separately.

As this chapter discusses, the lack of clarity when it comes to defining coastal storms stems from the complexities surrounding the ways in which storm energy is generated, transported and interacts with the coastline. A robust definition of a coastal storm is, however, necessary if we want to answer important societal questions, such as:

- How vulnerable are coastal communities and ecosystems to coastal storms?
- Are coastal storms becoming more frequent or increasing in magnitude?
- What influence is climate change having on coastal storms?

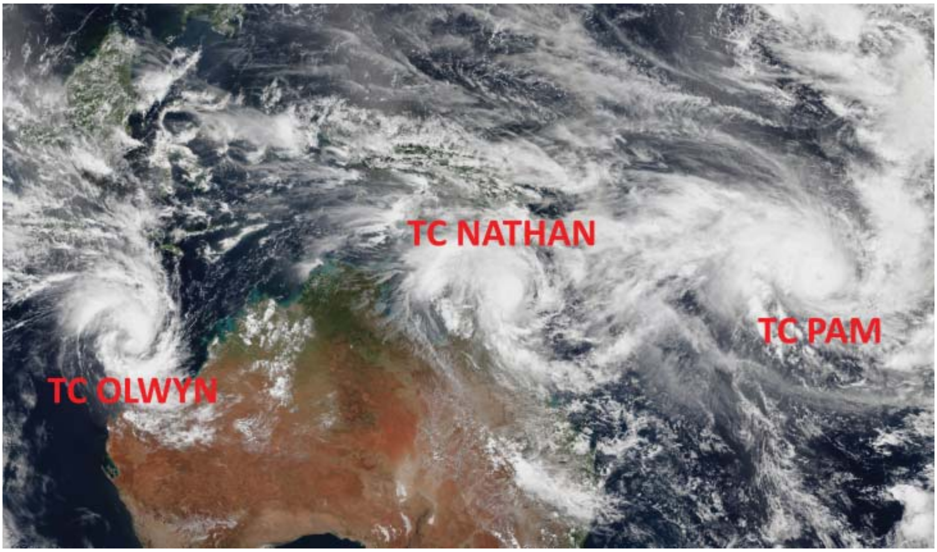

Figure 1.2 A composite image taken from the NASA of three tropical cyclones occurring simultaneously in the southern hemisphere in March, 2015. Tropical Cyclone Pam to the right of the image struck the island of Vanuatu and is considered one of the worst natural disasters in the island's history (*Source:* NASA Earth Observatory: http://earthobservatory.nasa.gov/).

- How near to the coast can we safely build infrastructure away from the influence of coastal storms?
- How can we design coastal structures to withstand coastal storm forces?

This chapter begins by first summarizing the challenges of defining coastal storms. These challenges are then taken into consideration to form a general qualitative coastal storm definition that can be applied to all coastlines. Section 1.2 follows by describing the most common synoptic conditions associated with coastal storms. Section 1.3 then presents the various approaches taken to identify coastal storm events from observational records and summarizes ways of quantifying coastal storm severity.

1.1.1 The challenge of defining coastal storms

The term storm is defined as: "a disturbance of the atmosphere marked by winds and usually by rain, snow, hail, sleet, or thunder and lightning" (Merriam-Webster, 2015). When it comes to defining coastal storms, however, a simple application of this definition to the coastal zone is not sufficient. Although storms and coastal storms go hand in hand – indeed a coastal storm cannot take place without some sort of atmospheric disturbance occurring somewhere – there are several important features about coastal storms that make them unique from other storm types (thunderstorms, and snowstorms, for instance) and hence particularly challenging to define and categorize. These features include:

- The location of the atmospheric disturbance relative to the impact area
- The diversity of environments in which coastal storms occur
- The ways in which these diverse environments respond to the same environmental forcing
- The timing and duration of the storm

By their very nature, coastal storms must comprise a maritime component, such as waves, currents and/or water levels. One of the first inroads into defining storms in a maritime setting dates back to the works of the British Royal Navy officer, Sir Francis Beaufort, in the early 1800s. Since the methods of reporting weather and sea conditions in ship logs were very subjective at the time, Beaufort proposed a system of standardizing these observations by using consistent language according to a thirteen-point scale. This system has since evolved to what is now known as the Beaufort Scale, and describes the relationship between wind speed and the associated sea state on the open ocean. Storms according to the modern version of the Beaufort Scale have a ranking (or Beaufort number) of 10 or more, which translates to wind speeds of at least 24.5 m/s (approximately 88 km/h). In terms of sea state, the Beaufort Scale specifically identifies storm conditions using the following terminology: "Very high waves with overhanging crests; sea-surface takes on white appearance as foam in great patches is blown in very dense streaks; rolling of sea is heavy and visibility is reduced" (Wright *et al.*, 1999).

While the Beaufort Scale serves as a practical guide for use in weather forecasts and seafaring, its application to storms on the coastline is somewhat limited. This is because sea states in this scale are based on the idealized concept of the "fully-developed sea", which is the equilibrium sea state that develops when winds blow on the open ocean according to a number of conditions: (1) a constant wind speed; (2) a constant wind direction; (3) over a sufficiently-long fetch; and (4) for a sufficiently-long period of time. In reality these conditions are almost never met and, close to the coastline, wind and wave fields become increasingly influenced by the coastal boundary. Ultimately this means that coastal waves are usually much smaller and steeper than those found on the open ocean. The modification of storm waves as they move from deep to shallow water is described in detail in Chapter 2.

Another limitation of the Beaufort Scale is that it focuses on the local sea conditions and does not include the influence of *swell* – waves that have moved outside their area of wave generation and travel freely across the ocean surface. To take into account the additional influences of swell waves, Sir Percy Douglas devised a scale in the 1920s of describing the *overall* state of the sea. This scale, which is known nowadays as the Douglas Scale, is based on a two-digit code system. The first digit describes the local sea state from 0 to 9 (with 0 being the least energetic and 9 the most energetic sea state) and the second digit describing the swell conditions, also from 0 to 9. The nature of swell waves means that it is possible to stand on the coastline and observe large waves arriving from a distant storm even when there are clear blue skies in the area (as illustrated in Figure 1.3). In terms of coastal storms, this means that the local atmospheric conditions do not necessarily influence the storm itself.

As sea and swell waves approach the shore, the *type* of coastal environment plays a major role in determining how the coastline responds. For coastlines usually susceptible to low-energy wave conditions (such as those found in bays and estuarine environments), even relatively small waves can induce significant changes to the coastal

Figure 1.3 Large swell waves arriving on a coastline during a sunny day with clear skies (photo: A.D. Short).

environment. In Delaware Bay on the northeast seaboard of the USA, for example, the average height of waves reaching the shore is in the order of just 0.1 m. In such a low energy environment, wave heights of a mere 0.5 m can for all intents and purposes be considered "storm waves" that leave a long-lasting signature on the beach profile (Jackson *et al*., 2002). At the other end of the spectrum, high-energy coastlines such as those found in southwest Tasmania (south of mainland Australia) are exposed to year-round significant wave heights in excess of 2.5 m (Hemer *et al*., 2008). On these types of coastlines, the same 0.5 m wave from the previous example is easily absorbed by the coastal environment and has negligible impact at the shoreline. Hence the magnitude of the waves relative to the *modal* or *equilibrium* wave conditions helps determine the magnitude of coastal response.

While up until now we have focused on wave conditions, another critical component to coastal storms is the water level at the coastal boundary. The *total water level* (TWL) represents the sum of both astronomical tides and non-tidal residuals, also known as tidal anomalies. Non-tidal residuals can occur on the coastline due to a variety of factors, such as storm surge (discussed in detail in Chapter 2), wave set-up, basin seiching, complex tide-surge interactions and freshwater input. The TWL can be expressed as a function of time according to the equation:

$$\mathbf{TWL}(t) = \mathbf{Z_0}(t) + \mathbf{T}(t) + \mathbf{R}(t) \tag{1.1}$$

where Z_0 (t) is the mean sea-level (which varies over longer time-scales), **T** (t) is the tidal component and **R** (t) represents non-tidal residuals (Pugh, 1987). The TWL is a critical factor for erosion of barrier islands (discussed in Chapter 4) as well as for overwash and inundation on low-lying coasts (discussed in Chapter 9).

Finally, the timing and duration of a storm event is also an important factor contributing to the identification of a coastal storm. Depending on the stage of the tidal cycle in which a storm occurs (i.e. high vs low tides, spring vs neap tides), tidal anomalies can result in either exceptionally high total water levels, or levels typical of everyday tidal fluctuations. Likewise, large waves that occur at high tides are more likely to cause impacts than those at low tide. Storm duration is also important as it determines the timescales over which sediment can be transported from its pre-storm location, as well as increasing the probability that a storm occurs at higher tide levels.

1.1.2 A general coastal storm definition

By taking the above factors into consideration, we can now define a coastal storm in a broad sense as a: "meteorologically-induced disturbance to the local maritime conditions (i.e. waves and/or water levels) that has the potential to significantly alter the underlying morphology and expose the backshore to waves, currents and/or inundation". They are usually associated with the passage of cyclonic systems such as tropical or extra-tropical cyclones (discussed in section 1.2), which can strike the coastline directly or track at a sufficient distance from the coastline to influence the local maritime conditions. Coastal storms may also (but not necessarily) coincide with strong winds and/or precipitation that, in conjunction with the anomalous maritime conditions, can contribute to a storm's severity.

The disturbance to the local maritime conditions that occurs during a coastal storm must be of sufficient magnitude that the underlying morphology (sandbars, coral reefs, etc.) can be *significantly* altered from its modal or everyday form. This means that in the absence of human interventions (e.g. the construction of breakwaters, temporary protection barriers, etc.), or abnormal antecedent conditions, the morphology is transformed in such a way that a period of *recovery* ensues. This recovery period, whereby the storm-altered morphology returns to a modal form associated with non-storm conditions, usually transpires over a time-scale larger than the storm itself. In the case of storm clusters (see Chapter 8), the recovery period may be unusually prolonged as storms continue to interrupt or reverse the recovery process. For extreme coastal storms, it is possible that the coastal zone may never recover and a new equilibrium state associated with these higher-energy conditions is reached.

Alternatively or in conjunction with the above impacts to the *underlying* morphology, the *coastal backshore* – which under normal conditions is protected from waves, currents and inundation – can in the event of a coastal storm (and without human intervention), be suddenly exposed to these processes. This exposure may occur over a brief period of time during the actual coastal storm event, or in the case of particularly severe events, remain for many weeks and months after the event itself has subsided. Depending on factors such as local topography and the severity of the event, this exposure may be sufficient to erode or overtop backshore dunes and inundate the adjacent coastal hinterland.