# 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

*Coastal Storms: Processes and Impacts*, First Edition. Edited by Paolo Ciavola and Giovanni Coco.

**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)

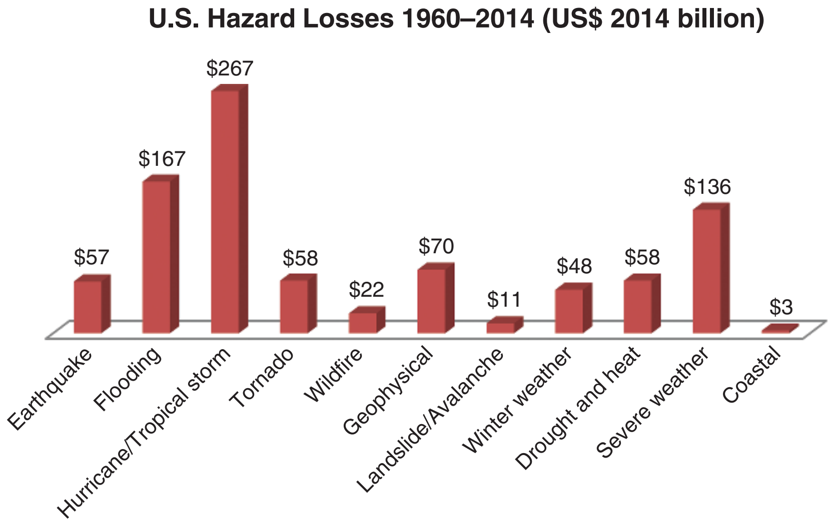

**Figure 1.1** Total hazard losses in the United States (1960–2014) by hazard type (*Source:* Hazards and Vulnerability Research Institute, 2015).

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?

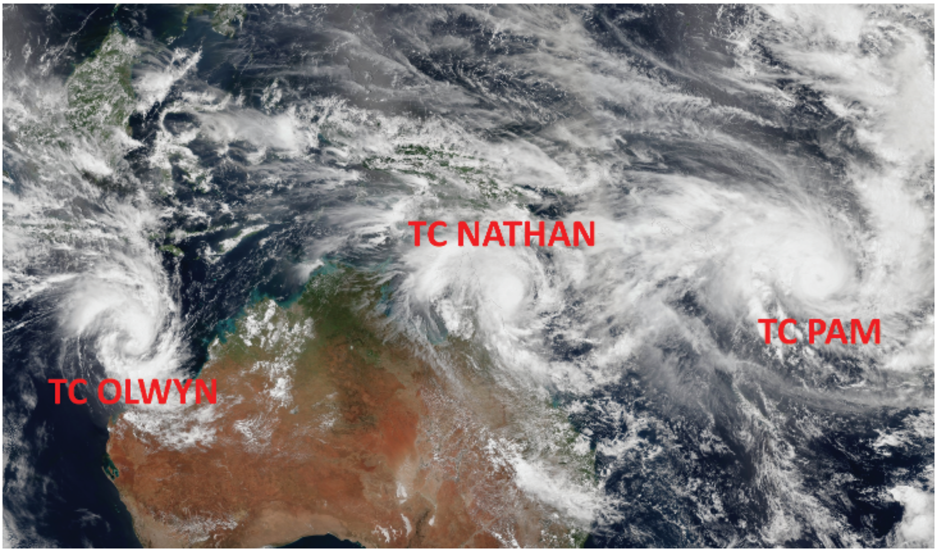

**Figure 1.2** A composite image taken from the NASA of three tropical cyclones occurring simultaneously in the southern hemisphere in March, 2015. Tropical Cyclone Pam to the right of the image struck the island of Vanuatu and is considered one of the worst natural disasters in the island's history (*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 $\mathbf{Z}_0(t)$ is the mean sea-level (which varies over longer time-scales), $\mathbf{T}(t)$ is the tidal component and $\mathbf{R}(t)$ 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.

### 1.1.3 Approaches to assessing coastal storminess

A key question to understanding the degree of exposure to coastal storms for a particular coastal region is to examine temporal patterns and trends of storm arrivals – in other words, the *storminess* of a coastal region. Assessments of coastal storminess may include studies such as:

- The frequency of coastal storms arriving over a given year
- The timing of storm arrivals (e.g. regular/irregular intervals, storm clusters, seasonal patterns)
- Teleconnections with large-scale climate patterns (e.g. the El Niño/Southern Oscillation, the North Atlantic Oscillation)
- Directional shifts in coastal storms
- Trends in coastal storm extremes
- The effects of climate change

The various ways taken to assess the storminess of a coastal region can be summarized into two main approaches: (1) a *synoptic climatological approach* and (2) a *statistical approach*.

The synoptic climatological approach to assessing coastal storminess involves the pairing of regional synoptic information such as storm tracks and sea level pressure data with coastal-based observations (instrumental records, hindcast data, historical newspaper reports, etc.) for the particular coastal region of interest. As outlined by Yarnal (1993), depending on which set of paired information is analyzed first, this approach can either be described as a *circulation-to-environment* approach or an *environment-to-circulation* approach.

In the circulation-to-environment approach, a synoptic classification of the region is first undertaken independently of the coastal response. This information is in turn compared to the coastal-based observations, in order to gain an understanding of the relationships between regional-scale storminess and localized coastal response. In the environment-to-circulation method, the coastal-based observations are analyzed first and only the synoptic configurations associated with the extreme local maritime disturbances are determined. Some examples of synoptic climatological approaches to assessing coastal storminess include that of Mather *et al*. (1964) for the eastern seaboard of the United States, Short and Trenaman (1992) for the southeast coastline of Australia, Betts *et al*. (2010) for the Atlantic coast of Northern France and Lionello *et al*. (2012) for the Adriatic coastline of Northern Italy.

The statistical approach to assessing coastal storminess, on the other hand, focuses purely on the coastal-based observational data and uses statistical methods to separate individual storm events from quiescent or non-storm periods. Statistical methods used to separate these periods are described in detail for wave and water-level time-series datasets in section 1.3. While the statistical approach does not provide an overall understanding of the meteorological processes associated with coastal storms (as the synoptic climatological approach does), it is objective and capable of quantifying coastal storm variability across entire regions and basins. Some examples of the statistical approach include coastal storminess assessments for the coastline of Sydney, Australia (Harley *et al*., 2010), the Gulf of Cadiz in Spain/Portugal (Plomaritis *et al*., 2015) and for the entire Southern European region (Cid *et al*., 2015).

## 1.2 Synoptic systems and coastal storms

A fundamental aspect with regards to coastal storms that distinguishes them from other extreme events (e.g. tsunamis) is that they are ultimately generated by atmospheric disturbances over a water body. Although these disturbances may occur in a variety of forms, two main synoptic systems are responsible for the vast majority of coastal storms worldwide – *tropical cyclones* and *extra-tropical cyclones*. Depending on a number of factors, related to both the cyclonic system as well as the coastal setting in which it occurs, these systems may also generate storm surge.

### 1.2.1 Tropical cyclones

There are few things more awe-inspiring and destructive than that of a tropical cyclone (TC) impacting on a coastal area. Tropical cyclones are intense low-pressure systems that consist of strong winds spiraling around a warm central core. They go by a variety of names according to their wind strength and the region of the world in which they occur. A TC with sustained one-minute wind speeds at the surface between 17 and 32 m/s is known as a *tropical storm*, whereas those with sustained wind speeds in excess of 32 m/s are known as *hurricanes* in the north Atlantic and northeastern Pacific, *typhoons* in the northwestern Pacific and *tropical cyclones* elsewhere. The general term tropical cyclone is typically used collectively to represent all of these cyclonic system types.

Tropical cyclones derive their energy primarily from the evaporation of water off the sea surface and hence are formed in areas where the water temperature is sufficiently high (typically greater than 26.5°C). Other conditions that favor TC growth are a sufficiently strong Coriolis force (i.e. at latitudes of 5° of greater) and weak vertical wind shears between the lower and upper troposphere (Wallace & Hobbs, 2006). Structurally, a TC cell consists of a central core approximately 30–50 km in diameter, known as the *eye*, within which the surface air is calm and has minimal cloud cover. Adjacent to the eye is the *eye wall* – a circular rim of intense thunderstorms where the strongest surface winds of the entire storm cell are situated. Moving further away from the center, the outer structure consists of a series of *rain bands* (smaller cells of converging and diverging air) and the surface winds gradually diminish in strength until they reach ambient conditions. A typical diameter for the entire TC cell is in the order of 650 km.

Figure 1.4 illustrates the spatial distribution of TC tracks worldwide according to their severity, based on the Saffir-Simpson scale (a measure of TC severity discussed in section 1.3.3). On average there are 80–90 TCs per year globally (Marks, 2003), most of which are concentrated in several regions of pronounced TC activity. The most active region in terms of annual rates of TC formation is the northwestern Pacific, which includes the coastlines of Japan, Taiwan and the Philippines and has an average of 27 TCs per year. Other active regions include the northeastern Pacific (17 TCs/year), the southwestern Indian region (12 TCs/year) and the northwestern Pacific and the Australian/southeast Indian regions (each with 10 TCs/year).

The path which TCs take is steered by a combination of external factors as well as internal dynamics of the TC itself (Ahrens, 2000). This path is difficult to predict, but, in the absence of environmental steering, tends to move in a polewards and westwards direction (Marks, 2003). A TC is said to make *landfall* when the eye of the TC crosses a

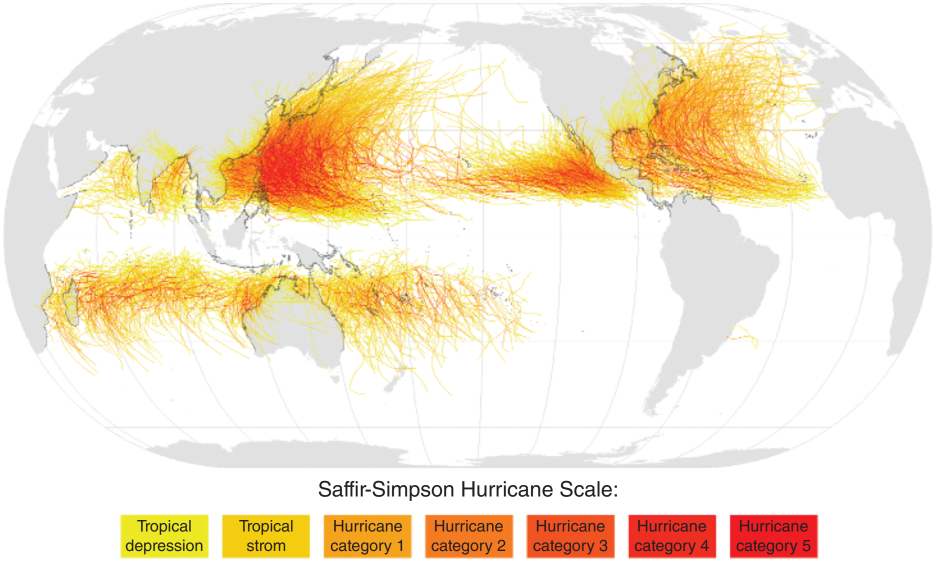

**Figure 1.4** Spatial distribution of tropical cyclone storm tracks (1946–2006) and their intensities according to the Saffir-Simpson Hurricane Scale (*Source:* Radical cartography: www.radicalcartography.net).

coastal boundary. In this case the system loses its main source of energy and, in combination with the increased friction over land, the system rapidly dies out. Tropical cyclones may also die out when they move polewards into cooler mid-latitude waters. If a coastal location is subjected directly to the maximum radial winds of the cyclone (but the TC hasn't necessarily made landfall), the location it is said to have taken a *direct hit*.

## 1.2.2 Extra-tropical cyclones

Extra-tropical cyclones (ETCs, or *mid-latitude cyclones*) reflect a broad class of cold-core cyclones, including *lows*, *depressions* and *frontal systems* that draw their energy from temperature gradients in the atmosphere (such as those that occur between warm and cold air masses). They form predominantly in the mid-latitudes between 30° and 60° and, unless interrupted by other synoptic systems, tend to follow a zonal west-east path across the globe. The strongest ETCs usually occur during the winter months when atmospheric temperature differences are most pronounced (May *et al.*, 2013). In comparison to TCs, ETCs are usually much larger (with length scales in the order of 2000 km) and slower-moving systems. Extra-tropical cyclones are also much more widespread and frequent than TCs, with 234 ETCs forming on average over the northern hemisphere winter (Gulev *et al.*, 2001) and some 2500–2900 ETCs forming annually in the southern hemisphere (Simmonds & Keay, 1999).

While ETCs typically have lower surface wind speeds than TCs, their slow-moving nature and size means that they are capable of affecting vast swathes of coastline and linger offshore for extended periods of time. Extra-tropical cyclones are subsequently capable of coastal impacts comparable or even greater in severity than those of TCs (Zhang *et al*., 2000). Some common examples of coastal storms generated by ETCs are *nor'easters* that occur on the eastern seaboard of the USA (e.g. Dolan & Davis, 1992), winter windstorms in Europe (e.g. Kolen *et al*., 2013) and east-coast lows in southeastern Australia (e.g. Browning & Goodwin, 2013). Figure 1.5 presents an example of the erosive potential of extra-tropical cyclones for a storm that struck the SE Australian coastline in June 2007. This event, which is known as the *Pasha Bulker* storm due to the 40,000 ton bulk carrier that ran aground in the resulting storm conditions, was an east-coast low that caused onshore wind gusts of up to 37 m/s and waves reaching a significant wave height of 6.9 m. The coastal impacts from this storm were significant: daily shoreline measurements from a video monitoring station installed permanently at Narrabeen-Collaroy Beach (lower-left panel, Figure 1.5) indicate that the average width of the beach retreated 29 m during the storm event, as sand was rapidly removed from the subaerial beach and deposited offshore. The ensuing recovery period for this event took approximately ten months (Phillips *et al*., 2015).

## 1.2.3 Storm surge

Storm surge refers to the sudden increase in water levels associated with certain coastal storms that can have catastrophic consequences for low-lying coastlines. This rapid

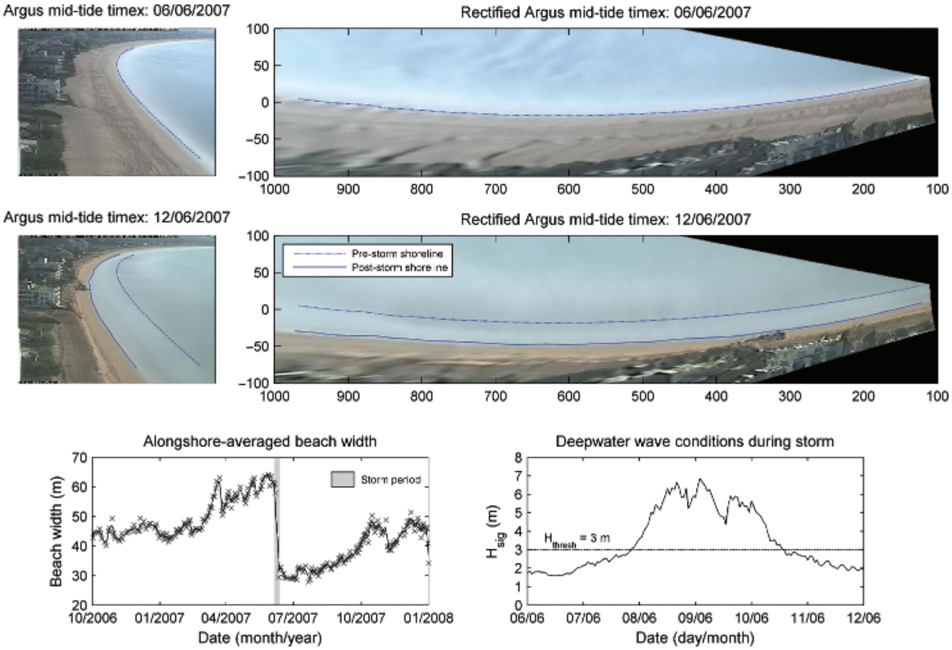

**Figure 1.5** Pre- and post-storm shoreline measurements following the *Pasha Bulker* storm, an extra-tropical cyclone that struck the coastline of southeastern Australia in June 2007. A video monitoring station installed permanently at Narrabeen-Collaroy Beach (see Harley *et al.*, 2011) measured 29 m of rapid retreat in beach width as a result of the storm.

onset of high water levels is considered the most destructive component of TCs and, to a lesser extent, ETCs. The degree of storm surge resulting from a coastal storm, however, is a complex process and depends on interactions between meteorological factors and the coastal setting in which they occur. Meteorological factors include the radial wind speeds of the cyclone, the cyclone's central pressure and the forward speed of the cyclone system. Influences of the coastal setting, meanwhile, include the angle of cyclone approach relative to the coastline, the width and slope of the coastal shelf, as well as local features (National Weather Service, 2013). Storm surge is discussed in extensive detail in Chapter 2.

## 1.3 Statistical approaches to identifying coastal storms

Statistical approaches to identifying coastal storms involve the analysis of wave or water-level time-series from an appropriate maritime location close to the site of interest. For wave-dominated coastlines, this analysis is typically conducted on time-series of the significant wave height. For coastal sites where meteorologically-driven increases in the water level beyond the range of usual tidal variability (i.e. greater than mean high water spring) are more significant, coastal storms can, meanwhile, be defined from measured water-level time-series. The various approaches to identifying storm events from these two data types are outlined below.

### 1.3.1 Coastal storm events from wave time-series

As long-term wave measurement and hindcast datasets become increasingly available, a common means of identifying coastal storm events for a particular coastal location is through statistical analysis of the significant wave height ($H_{sig}$) time-series. The identification of coastal storms from $H_{sig}$ time-series is usually undertaken through the application of the so-called peaks-over-threshold (POT) method. The POT method has its origins in extreme value analysis, where it is used as a robust way of extracting data subsets for estimating the return values of environmental variables, for example the 50-year design wave for coastal structure design. As the name suggests, the POT method obtains a set of peak values from data clusters above a certain threshold level. In extreme value analysis, these data clusters and associated peak values are generally used to fit a Poisson – Generalized Pareto distribution. For coastal storm identification approaches, meanwhile, these data clusters represent the actual storm events.

As shown in Figure 1.6, storm events can be identified by the POT method through the specification of three parameters:

1. The storm threshold ($H_{thresh}$)
2. The minimum storm duration (D)
3. The meteorological independence criterion (I)

The *storm threshold* is defined as the critical value that separates storm waves from non-storm waves for a particular coastal site. The *storm duration*, meanwhile, is defined by the length of time between an up-crossing and subsequent down-crossing of the

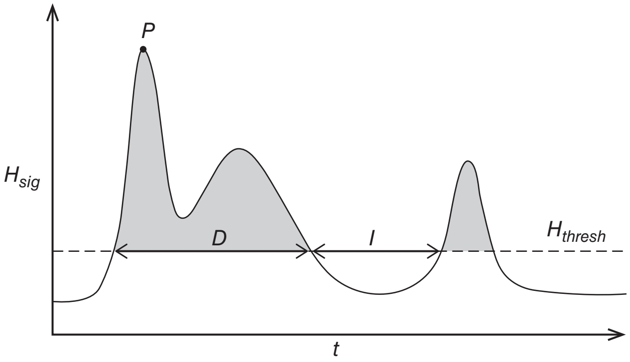

**Figure 1.6** The Peaks-Over-Threshold (POT) method for defining individual storm events from a significant wave-height time-series. *P* denotes the peak significant wave height of the storm, *D* the storm duration, *I* the meteorological independence criterion and $H_{thresh}$ the threshold signignificant wave height. Individual storm events classified by this method are shaded gray.

storm threshold. Since wave heights can fluctuate for a brief period of time above (and below) this threshold, a minimum storm duration D is set to include only storm events of a significant duration. The final parameter is the *meteorological independence criterion*, which is a value that restricts the period of time between individual storm events and hence ensures that they are generated by independent synoptic systems such as a particular tropical or extra-tropical cyclone. The meteorological independence criterion also ensures that brief crossings below the storm threshold during a single storm event are included within the same event.

Table 1.2 presents an overview of different values adopted of the three parameters discussed above for different coastal settings worldwide. From this table it is clear that the chosen values of these three parameters fluctuate greatly from site to site and that no standardized method currently exists to aid in their selection. Despite the absence of a standard method, some general guidelines can be ascertained. In terms of the storm threshold (the most critical of the three parameters), for reasons discussed in section 1.1.1, $H_{thresh}$ is strongly related to the modal wave conditions of the site (represented in Table 1.2 by the average significant wave height). While statisticians argue that the threshold should be set according to a goodness of fit to the Generalised Pareto distribution (e.g. Mazas & Hamm, 2011), a more pragmatic approach related specifically to coastal storm analyses is to simply set the threshold according to the 95th percentile of the significant wave height dataset. This approach intrinsically takes into account the modal wave conditions and has been applied to wave-dominated coastlines in both the United Kingdom (e.g. Masselink *et al*., 2014) and France (e.g. Castelle *at al*., 2015). In terms of values for the minimum duration and meteorological independence criterion, an understanding of the local setting and regional meteorology is necessary. Tropical cyclones, for instance, are generally faster-moving systems and hence may afford a smaller time period (e.g. 12 hours) to differentiate individual coastal storm events. Slower-moving extra-tropical cyclones, on the other hand, may warrant a larger time gap (e.g. 24–72 hours) to distinguish between events. For complex cases such as a TC transitioning into an ETC, a careful (i.e. manual) selection of the meteorological independence criterion may be required.

**Table 1.2** Overview of different storm classifications based on significant wave heights and the peaks-over-threshold method

| Site | Average significant wave height | Wave height threshold ($H_{thresh}$) | Minimum storm duration (D) | Meteorological independence criterion (I) | Reference |
|---|---|---|---|---|---|
| Lake Huron, Canada | 0.4 m (summer)<br>1.0 m (winter) | 2.0 m | None specified | None specified | Houser & Greenwood (2005) |
| East Coast, USA | | 2.5 m | None specified | None specified | Dolan & Davis (1992) |
| New South Wales, Australia | 1.6 m | 3.0 m (primary)<br>2.0 m (secondary) | 6 hours (primary)<br>72 hours (secondary) | 24 hours | Shand *et al.* (2010) |
| Perth, Australia | 1.6 m (summer)<br>2.7 m (winter) | 4.0 m (primary)<br>2.0 m (secondary) | None specified | None specified | Lemm *et al.* (1999) |
| Durban, South Africa | 1.7 m | 3.5 m | None specified | 2 weeks | Corbella & Stretch (2012) |
| Algarve, Portugal | 0.9 m | 3.0 m | None specified | 30 hours | Almeida *et al.* (2012) |
| Perranporth, UK | 1.4 m | 2.8 m (primary)<br>1.7 m (secondary) | None specified | None specified | Masselink *et al.* (2014) |
| Catalonia, Spain | 0.8 m | 2.0 m (primary)<br>1.5 m (secondary) | 6 hours | 72 hours | Mendoza *et al.* (2011) |
| Gironde, France | 1.4 m | 3.9 m (primary)<br>2.2 m (secondary) | None specified | None specified | Castelle *et al.* (2015) |
| Emilia-Romagna, Italy | 0.4 m | 1.5 m | 6 hours | None specified | Armaroli *et al.* (2012) |
| Cadiz, Spain | 1.0 m | 1.5 m | None specified | None specified | Plomaritis *et al.* (2015) |

Table 1.2 also indicates a two-threshold approach to coastal storm identification undertaken at several sites. In most of these cases, the upper wave height threshold represents the primary threshold used for storm identification as depicted by the POT method in Figure 1.6. A secondary lower threshold is then used to calculate the start time (i.e. up-crossing of the lower threshold) and end time (i.e. down-crossing of the lower threshold) of the storm and hence the storm duration. Masselink *et al.* (2014) define this lower threshold for identifying the start duration as the 75th percentile of the significant wave height data. A secondary lower threshold may also be used to further refine the meteorological independence criterion (e.g. Mendoza *et al.*, 2011),

or to include coastal storm events of particularly long duration but not necessarily of high peak wave heights (e.g. Shand *et al.*, 2010).

### 1.3.2 Coastal storm events from water-level time-series

The approach taken to identifying coastal storm events from water-level time-series is similar to that taken for wave time-series discussed above. A key question for this type of storm identification, however, is whether or not to base classifications on the total water levels (TWL, Equation 1.1), or to eliminate tidal variability and use the non-tidal residuals (R, Equation 1.1). The answer to this question lies in the purpose of the coastal storm assessment being undertaken. For studies focused on coastal storm impacts, or for communicating coastal storm hazards to the wider community (e.g. for issuing alerts within the context of a coastal storm early warning system), it is the TWL that ultimately dictates the exposure of the backshore and hinterland to inundation. Hence it follows that coastal storms be identified based on the TWL in these scenarios. This is the case for low-lying coastlines such as Venice in Northern Italy, where the commonly-occurring *acqua alta* (Italian for "high water" – a form of coastal storm caused by strong SE winds blowing along the length of the Adriatic Sea) is defined by TWL exceedances above a local threshold $TWL_{thresh}$. These thresholds are directly linked to local features that represent measures of coastal storm exposure – in the case of Venice, the TWL in which a significant part of the city is inundated (Massalin *et al.*, 2007). By the same measure, Aagaard *et al.* (2007) identified storm events for the Danish coastline based on a $TWL_{thresh}$ of 2.4 m above a local datum, which coincides with the approximate elevation of the dune toe of this region.

For studies where an understanding of coastal storminess variability over time is the main goal, a more appropriate identifier of coastal storms is given by the exceedance of R above a certain threshold $R_{thresh}$. By defining coastal storm events based on R (as opposed to the TWL), the influence of the tidal signal on long-term storminess trends (after taking into consideration complex tide-surge interactions) is removed and the focus is solely on meteorological effects. Table 1.3 indicates a number of approaches taken to define $R_{thresh}$ for coastal storm identification at various sites worldwide. For the eastern seaboard of the USA, Zhang *et al.* (2000) define $R_{thresh}$ as equal to two standard deviations of R. Similar to the coastal storm identification based on wave height data, a meteorological independence criterion of 12 hours was applied to discern individual events. This period was selected to remove the influences of free oscillations in the water level following the storm surge, which had residence times of approximately this period. Bromirski and Flick (2008) meanwhile define $R_{thresh}$ as the $98^{th}$ percentile of the low-pass filtered R time-series, which was applied to remove high-frequency variability in the non-tidal residuals. A minimum storm duration of six hours was also adopted in this analysis to ensure only events of an adequate persistence were identified.

To highlight the differences in the storm occurrence depending on the type of water-level threshold adopted, Figure 1.7 presents a hypothetical scenario whereby a coastal storm has been identified from the same water-level time-series using both the TWL and R thresholds. As indicated by the shaded regions in the upper and lower panels, both the timing and duration of the storm differ significantly between the two threshold types. In the case of defining the event based on $R_{thresh}$ (upper panel), the storm remains above the selected 1 m threshold for a period of 11 hours. The fact that

**Table 1.3** Site-specific classifications of coastal storms based on water-level information.

| Site | Spring tidal range | Threshold | Meteorological independence criterion (I) | Reference |
|---|---|---|---|---|
| San Francisco, USA | 3 m | $R > 98^{th}$ percentile | None specified | Bromirski & Flick (2008) |
| North Carolina, USA | 1.2 m | R > 2 x standard deviation | None specified | Zhang *et al*. (2000) |
| East coast, UK | 3.6–6.2 m | $R > 0.25$ m | 12 hours | Horsburgh & Wilson (2007) |
| Venice, Italy | 1.1 m | $TWL > 1.1$ m (linked to % flooding of Venice) | None specified | Massalin *et al*. (2007) |
| Skallingen, Denmark | 1.8 m | $TWL > 2.4$ m (typical dune toe elevation) | None specified | Aagaard *et al*. (2007) |

this event commenced at a period of relatively low tide, however, meant that, when considering only the TWL, the event only became a storm according to this definition ($TWL_{thresh} = 2$ m) following the onset of high tide some 6 hours later. The duration of the storm in the lower panel is also considerably shorter.

### 1.3.3 Indicators of coastal storm severity

Following the initial identification of a coastal storm event from the methods described above, a subsequent step is to understand the potential *severity* of the storm itself. In terms of TCs, severity is commonly communicated in the form of the familiar Saffir-Simpson hurricane wind scale. This hurricane scale ranks cyclone severity into one of five categories based on the maximum one-minute sustained wind speeds. A Category 1 cyclone according to this scale therefore has a maximum one-minute sustained wind speed between 33 m/s and 42 m/s, whereas a Category 5 cyclone has a maximum wind speed in excess of 70 m/s. As noted by Fritz *et al*. (2007), based on observations of hurricane impacts at New Orleans, however, this scale only has limited application in terms of understanding potential storm surge and can in fact mislead the public into a false sense of security about hurricane impacts. Hurricane Katrina that struck New Orleans in 2005, for instance, was only classified as a Category 3 cyclone at landfall according to this scale, but produced peak surges in excess of 10 m and tremendous destruction. In contrast, Hurricane Camille that hit the same coastal location in 1969 was classified as a Category 5 cyclone at landfall, but resulted in more moderate storm surge and impacts. Another limitation of the Saffir-Simpson scale is that it is only relevant to TCs and cannot be applied to other synoptic systems.

As a first-pass assessment of coastal storm severity with regards to the local maritime conditions, a common indicator is the return period of the peak wave or water level (as

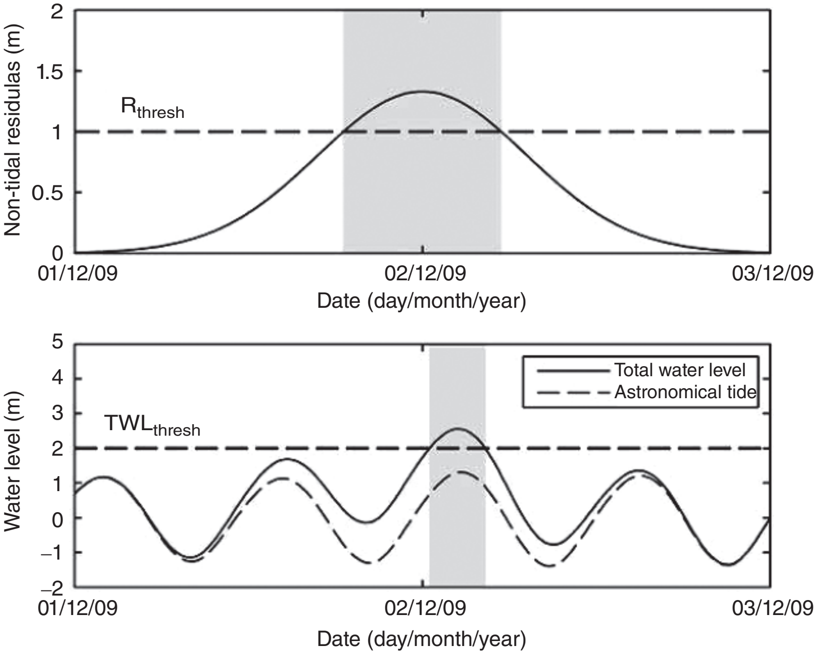

**Figure 1.7** Comparison between coastal storm definitions based on a non-tidal residual threshold $R_{thresh}$ (upper panel) and a threshold of the total water-level $TWL_{thresh}$ (lower threshold). Shaded regions highlight the different coastal storm periods identified according to these two definitions.

depicted by P in Figure 1.6). This assessment entails an extreme value analysis of the historical data and means that coastal storm severity can be communicated in terms of its average recurrence interval or annual exceedance probability. A limitation of using only peak values to classify storm severity, however, is that it does not take into account the duration of the event or its joint occurrence with elevated water levels. To address the limitation of storm severity and event duration, Dolan & Davis (1992) developed a storm intensity classification specifically for longer-duration ETC storms on the East coast of the USA. The duration of the storm event was taken into account in this severity classification by integrating the wave energy over the whole event, as given by the equation:

$$E = \int_{t1}^{t2} H_{sig}{}^{2} dt \qquad \mathrm{H_{sig}} \geq \mathrm{H_{thresh}} \tag{1.2}$$

where E is the storm energy content and $t_1$ and $t_2$ correspond to the start and end times of the storm event determined by the up and down-crossings of the storm threshold $\mathrm{H_{thresh}}$. Storm severity levels were subsequently developed based on ranges of these E values, using a five-category system analogous to the Saffir-Simpson hurricane wind scale. Note that this system was developed for the East coast of the USA only and is therefore site-specific. Mendoza *et al.* (2011) applied this same classification methodology to the coastline of Catalonia in Spain and resulted in different ranges of E for each storm class (Table 1.4). These differences can be attributed to the different storm

**Table 1.4** Coastal storm severity classifications for the coastlines of the East Coast, USA and Catalonia, Spain based on the total storm energy methodology of Dolan and Davis (1992).

| Storm class | Description | Storm Energy Range ($m^2h$) | |
|---|---|---|---|
| | | East Coast, USA (Dolan and Davis, 1992) | Catalonia, Spain (Mendoza *et al.*, 2011) |
| I | Weak | <72 | 24–250 |
| II | Moderate | 72–164 | 251–500 |
| III | Significant | 164–929 | 501–700 |
| IV | Severe | 929–2323 | 701–1200 |
| V | Extreme | >2323 | >1200 |

thresholds selected for the two sites (see Table 1.3), as well as local storm wave characteristics. Zhang *et* al. (2000), meanwhile, adopted a similar intensity index for storm surge events on the East Coast of the USA by instead integrating the non-tidal residual time-series over the duration of the surge event.

Further refinements to coastal storm severity indicators have been undertaken by combining the effects of both wave and water levels during a coastal storm event. Kreibel *et al*. (1997) developed a Risk Index RI for ETCs on the East Coast of the USA based on the wave height, storm duration and storm surge level. This index is given by:

$$\mathrm{RI} = \mathrm{SP}(\mathrm{D}/12)^{0.3} \tag{1.3}$$

where S is the surge elevation in feet, P is the peak wave height in feet and D is the event duration in hours. As shown in Equation 1.3, this index scales the event duration by 12 hours to obtain the number of tidal cycles during the storm event. In order to achieve an index range between 0 and 5 (i.e. similar to that of the Saffir-Simpson and Dolan and Davis scales discussed above), the index is then normalized by that of the most severe storm on record (RI = 400 for a severe ETC in March, 1962) and multiplied by a factor of five.

## 1.4 Conclusion

Coastal storms are a particularly challenging phenomenon to define and have historically been misrepresented in both the literature and various natural hazard evaluation studies. This chapter has outlined the numerous issues associated with defining coastal storms, which include the location of the atmospheric disturbance relative to the impact area, the diversity of coastal environments and ways in which they respond to maritime forcing, as well as storm timing. Based on these considerations, a general coastal storm definition has been established for all coastal environments 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*.

Statistical approaches to identifying coastal storms involve the establishment of a site-specific storm threshold that discriminates storms from non-storm periods. For coastal storms based on wave height information, this storm threshold is strongly related to the modal wave conditions of the site. For those based on water-level data, meanwhile, a consideration of whether the total water level or non-tidal residuals is more appropriate to define storms is required. Once the coastal storm event has been identified, the potential storm severity can then be gauged through consideration of the peak storm wave height, the duration of the event and water-level variability.

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