Introduction

As a geological oceanographer who has given many presentations to the public about how coastlines work, I have always been surprised by the fact that many people are struck when they learn that the sea level has moved vertically on many different time scales over many different amplitudes ever since the earth has had oceans, about 3.8 billion years. However, we live in a world in which elevations on topographic maps and key geographic elevations (fig. 1.1) are given in units above sea level, indicating that the sea level is somehow permanently fixed in time and space. The same is true for bathymetric maps—depths are presented as feet, fathoms, or meters below sea level. The highest point on earth, Mount Everest, is 8,848 meters above sea level (and may be rising about four millimeters per year due to presently active tectonic processes, as measured by very accurate global positioning devices installed in the Himalaya Mountains) while the deepest point on earth, the Challenger Deep within the Marianas Trench, is 10,911 ± 40 meters below sea level. Pilots set their altimeters in relationship to sea level and use the numbers from these devices as a measurement of aircraft altitude.

We have many monuments and survey markers all over the United States indicating elevation above sea level. There is even a stone step leading up to the state capitol building of Colorado in Denver engraved with the inscription “One Mile Above Sea Level” providing the “mile high” nickname for that city (fig. 1.2). So, naturally, we have grown to think that sea level is some absolute, immutable fact that we can count on as a constant in nature. Nothing could be further from the truth.

As we all know, the daily tides, which are easily observed and measured along coastlines, actually constitute a short-term, cyclical sea level change. These are the astronomical tides created by the gravitational pull of the earth, moon, and sun and their physical location in relationship to each other. Shorter term (interannual, decadal sea level changes result from high -and low-pressure weather systems, changes in temperature, variations in rainfall levels, aquifer retention, changes
in winds and circulation, and changes in levels of evaporation and run- 
off. Longer-term sea level variations are due to waxing and waning of 
continental ice sheets during glacial and interglacial periods whereby 
water is removed and returned to the ocean (which take place over 
thousands of years) and changes take place in the volume of ocean 
basins due to tectonic plate activity (which take place over tens to hun-
dreds of millions of years).

We have become well attuned to surges generated by storms, partic-
ularly hurricanes, typhoons, and cyclones (fig. 1.3). Some of the largest 
storm surges commonly exceed 10 meters. Finally, other disasters, such 
as tsunamis generated by earthquakes and even underwater landslides, 
can produce catastrophic surges. The Tohoku earthquake off the shore 
of Japan in 2012 produced a tsunami that was 40 meters deep on land.

![Figure 1.3. Storm surge hydrograph for Hurricane Camille, a Category 5 storm that struck the northern Gulf of Mexico coast in 1969. The total vertical magnitude of the surge was approximately 8.3 meters (7.62 meters above mean low water). It was one of the costliest natural disasters in the United States up to that point and killed nearly 300 people. But within only a few hours, the level of the ocean returned to what it had been before the storm. MLW indicates mean low water. Source: U.S. Army Corps of Engineers.](image-url)
The highest elevation on land affected by a tsunami (generated by an earthquake-induced landslide) was 524 meters in Alaska in 1958!

As deadly as these locally or regionally generated events might be, we generally do not consider them to be changes in sea level in the broader sense. A surge is a localized, short term, but potentially hugely damaging change in sea level accompanied by strong currents and high waves. Surges, whether they are driven by storms or earthquakes, quickly return to the mean sea level that existed prior to the event. As best as we can determine, they are not cyclical.

So one purpose of this chapter is to introduce the reader to the fact that cyclical, global sea level changes have occurred throughout
geologic time over many cycles (periodicities) and amplitudes (vertical elevation differences). A second purpose is to provide background information about what we think will come in the next 100 years and beyond. (These sea level projections form the subject of chapter 2.)

Cyclical changes occur, from daily tides to changes that take place over hundreds of millions of years; the full vertical range over that time frame possibly approaches 600 meters (fig. 1.4). At the moment scientists do not agree on the total vertical range of sea levels defined by the global ocean’s maximum high-water mark and its maximum low-water mark over geologic time scales. More accurate studies indicate a total vertical range closer to 400 meters (250 meters above and 150 meters below the present sea level).

**What Does Mean Sea Level Mean?**

Another surprise is that sea level is never level. It slopes from one place to another and varies from ocean basin to ocean basin at any one time. And of course, it fluctuates vertically with time. So how can we come up with a standard, a benchmark we can use? Actually there have been a number of different benchmarks. These are human constructs. We require artificial sea level data as benchmarks in order to measure sea level change over time.

**Direct Indicators of Sea Level**

A big challenge in understanding paleofluctuations in sea level is determining exactly where (in terms of elevation or depth) and when (in terms of age dating) sea level changes occurred. To do this, geologists use direct indicators of sea levels. These are geologic features that we know formed very close to sea level, such as elevated notches (fig. 1.5), shallow-water coral reefs, marshes, and preserved paleoshorelines (fig. 1.6). The elevated notches found along limestone islands, such as the Bahamas, were formed by organisms living in the intertidal zone. The marine animals scraped algae off the rocks for food and removed some of the limestone, in the process creating the notch over time (fig. 1.5). However, determining the age of the notch can be challenging, if not impossible.
Figure 1.5. A biologically eroded notch etched into limestone on Great Sale Cay in the Bahamas on Little Bahama Bank. Such notches are excellent direct indicators of sea level since they were formed by intertidal organisms scraping algae off the rock for food or other organisms boring into the rock for protection. Eventually, the notch becomes so large the overhanging rock collapses. Using surveyors’ tools, the elevation above the present-day sea level can be measured. However, age dating a notch is nearly impossible, so sometimes indirect methods are used, such as age dating ancient corals found below the notch. From this, geologists make the assumption that the corals grew in several meters of seawater when the notch was made and that the corals and the notch represent the same sea level event. In this specific case, the notch is approximately 6.0 meters above the present-day sea level and nearby ancient corals exposed about 6.0 meters below the notch provide an age date of approximately 125,000 years ago. This sea level highstand took place during the interglacial event before the modern interglacial we are in today. Photo courtesy of Dr. A. C. Neumann.