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# A Tale of Three Winters: Repeated Extreme Event Damage Along the Central California Coast

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**ABSTRACT**

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California's coastal counties, which account for about 70% of the state's population and its marine economy contributes \$51.3 billion annually to California's gross domestic product, have experienced multiple destructive extreme events over the past three winters. Repeated coastal storms significantly damaged public infrastructure, homes, businesses, and resources on which coastal communities depend. It is estimated that the California coastal storms between December 2022 and March 2023 alone caused \$4.7 billion in economic losses. The frequency and severity of recent coastal flooding and associated impacts emphasize that projected future extreme events are already happening and adversely affecting coastal cities and counties. This study explores the phenomena and consequences of the extreme storms that hit the Central California Coast in the 2022–23, 2023–24, and 2024–25 winters. The intensification and the frequency of recent coastal storms and the magnitude of social and economic impacts highlight that it is time to rethink the typical historic responses of repairing, rebuilding, and reopening. Time is running out and action is needed to develop new or reassess the existing adaptive management strategies and accelerate their implementation to prevent or at least reduce the potential damage from future natural disasters to coastal assets, coastal infrastructure, and the well-being and livelihood of coastal communities.

**ADDITIONAL INDEX WORDS:** Coastal storms, sea-level rise, natural hazards, coastal development, economic damage.

**INTRODUCTION**

Climate change continues to alter the pattern, magnitude, frequency, and severity of natural events such as sea-level rise, atmospheric rivers, wind, waves, storm surges, and associated hazards (Douville *et al.*, 2021; IPCC, 2023; Reguero *et al.*, 2019). Sea levels are rising globally at an accelerating rate (Figure 1). However, the rate of local sea-level rise varies depending upon the regional geologic setting and whether the coastline is stable, rising, or sinking (Ballu *et al.*, 2011; Church *et al.*, 2013; Griggs, 2017). In California, sea levels are projected to rise 0.8 ft by 2050 and 3.1 ft by 2100 in the intermediate scenario (OPC and OST, 2024). The recent evaluations also indicate that waves are getting larger and more energetic because of a changing climate (Bromirski, 2023; Reguero *et al.*, 2019). Accelerated sea-level rise collides with extreme rainfall, storm surges, winds, waves, and high tides, resulting in coastal floods that threaten lives, human-made systems, and the natural environment (Barnard *et al.*, 2019; OPC and OST, 2024). California's coast is already experiencing increased risks of natural hazards such as extreme storms, floods, and coastal erosion,

causing damage to coastal communities. California's coastal counties are home to about 70% of the state's population, and its marine economy contributes \$51.3 billion to California's gross domestic product (NOAA, 2021). According to the National Oceanic and Atmospheric Administration (NOAA)'s National Centers for Environmental Information, recent California floods (between December 2022 and March 2023) caused \$4.7 billion in economic losses (NOAA NCEI, 2025a). In Santa Cruz County alone, storm surges in late December 2023 left about \$2.8 million in damage and primarily affected infrastructure, recreational areas, and small businesses (Kathan, 2024). The scale, severity, and frequency of recent coastal extreme events and associated impacts raise questions about whether adaptation plans are effective in reducing the impacts and if implementation timelines are fast enough to keep pace with climate change-exacerbated risks and reduce the impacts (UN, 2024). Observations indicate that projected future climate-change-induced extreme events are here, and action is needed to adjust the adaptation strategies and implement them in a timely manner (Beck, 2023; Griggs, 2024b). This study explored the phenomena and consequences of the extreme storms that hit the Central California Coast in 2022, 2023, and 2024 and provide a broader picture of the history and current status of risk management strategies and their strengths and weaknesses in the face of natural hazards.

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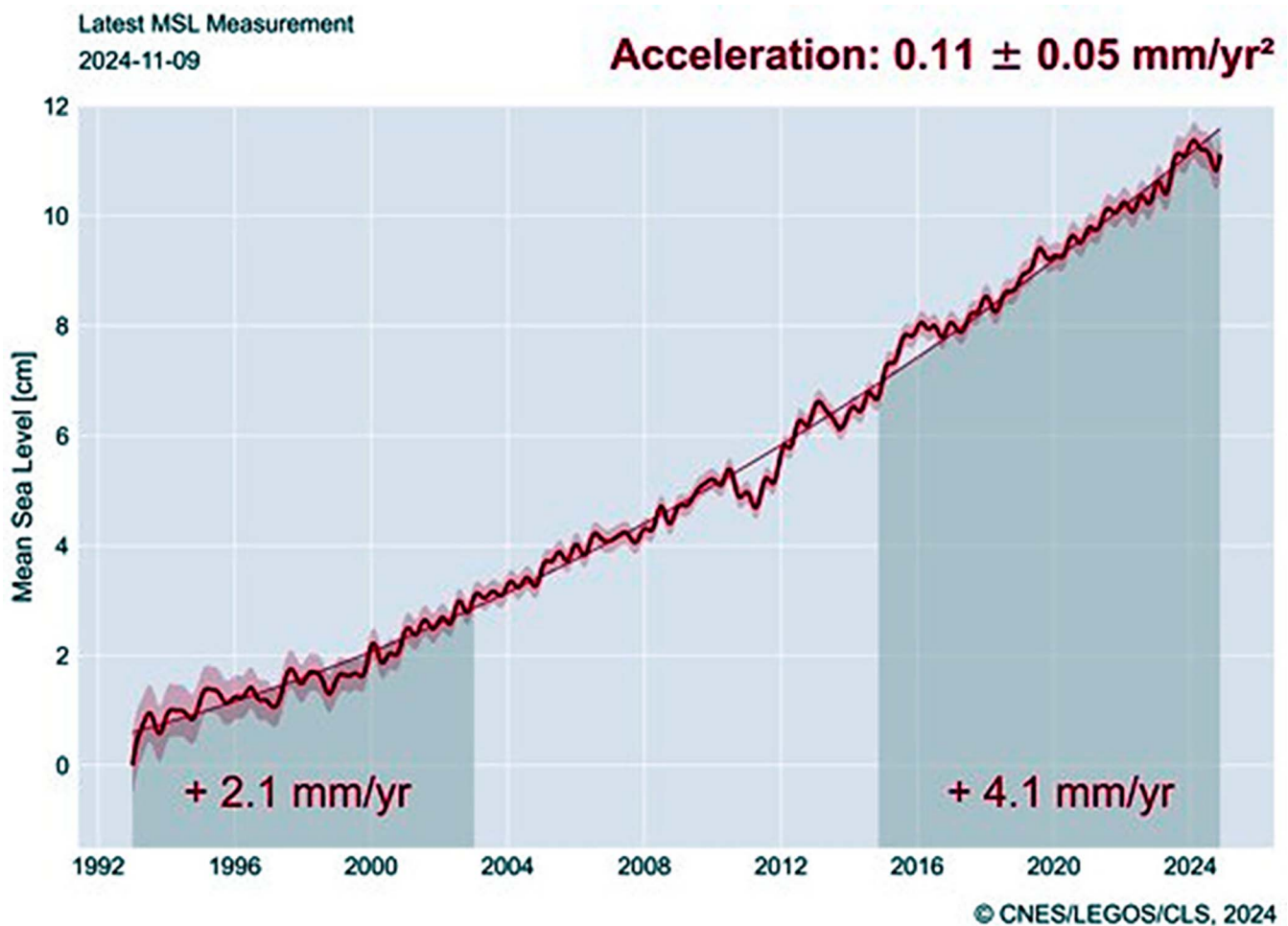


Figure 1. Accelerating rate of mean global sea-level rise (AVISO, 2025).

### Central California Coast and Development: A Background

California now has about 39 million people, with 70% living in coastal counties, which only make up 22% of the state's area. Eighty percent of the state's population lives within an hour of the coast. The northern Monterey Bay area on the Central California Coast has been a desirable area to live for centuries. The native inhabitants lived in seasonal villages and were wise enough to avoid hazardous locations. Multiple tribal communities occupied the area for thousands of years before the Spanish arrived in the late 1700s. The transformation to the current residential and recreational development along the Monterey Bay coast had its origin in the arrival of the Spanish and the establishment of the mission system, followed by Mexican and then U.S. colonial occupation of California. The lands of California's indigenous peoples were dispossessed via missionization during the Spanish period, and then through various forms of violence and marginalization that continued through the Mexican and especially the American period. Coastal development initially was focused on the extraction of the area's abundant natural

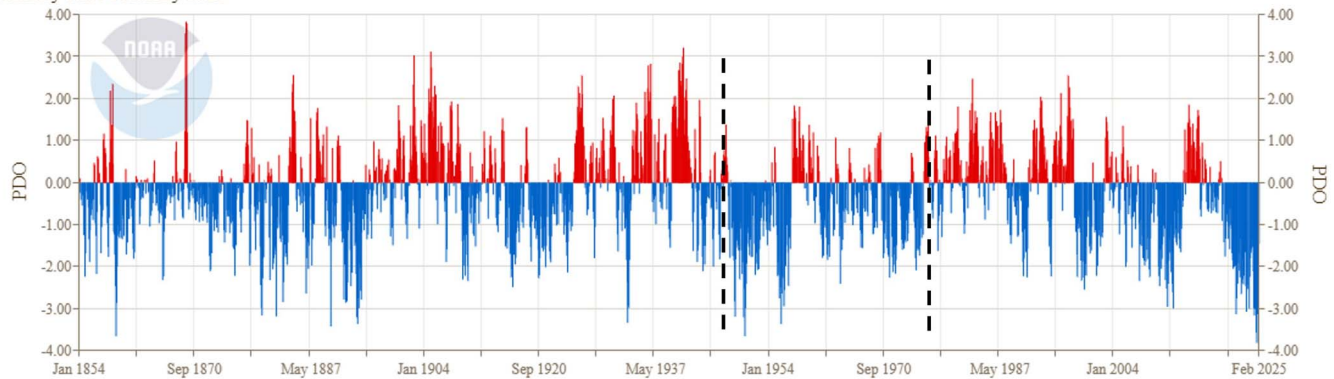
resources (lime for cement, redwood trees for lumber, and rich soil for agriculture) and began in the mid-1800s. The limited development during these early years generally avoided the areas closest to the bluff edges and the beach itself. Over time, however, as early tourism brought more people from the greater San Francisco Bay, Santa Clara, and Central Valley areas to the Monterey Bay region for recreation, the desirability of the region for both vacation and permanent homes was recognized. As with many coastal communities in California, the back beach and bluff top sites closest to the shoreline and with the best views were gradually subdivided and developed along with the supporting infrastructure.

### Physical Setting (Climate) and Coastal Development

The period of California's most extensive coastal land division and development followed World War (WW) II and corresponded to a cool Pacific Decadal Oscillation (PDO) interval that extended from about 1945 to 1978 (Figure 2), which was characterized by a lower frequency of large El Niño events, fewer periods of severe wave attack, and generally more benign coastal weather (Griggs, Patsch, and Savoy, 2005; Storlazzi and

### Pacific Decadal Oscillation (PDO)

January 1854–February 2025



Source: <https://www.ncei.noaa.gov/pub/data/cmb/ersst/v5/index/ersst.v5.pdo.dat>

Figure 2. Pacific Decadal Oscillation history from January 1854–January 2025. Blue represents cooler (and calmer) conditions along the West Coast and red is indicative of warmer and generally stormier conditions with more frequent and stronger El Niño–Southern Oscillation events. Note the shift around 1945 to calmer or cooler conditions (blue) and then a shift to warmer, stormier conditions (red) around 1978 (NOAA NCEI, 2025).

Griggs, 2000). Many bluff, dune, beach, and other shoreline areas were developed during this largely calmer

climatic interval. Along the northern Monterey Bay shoreline (Figure 3), large stretches of the back beach

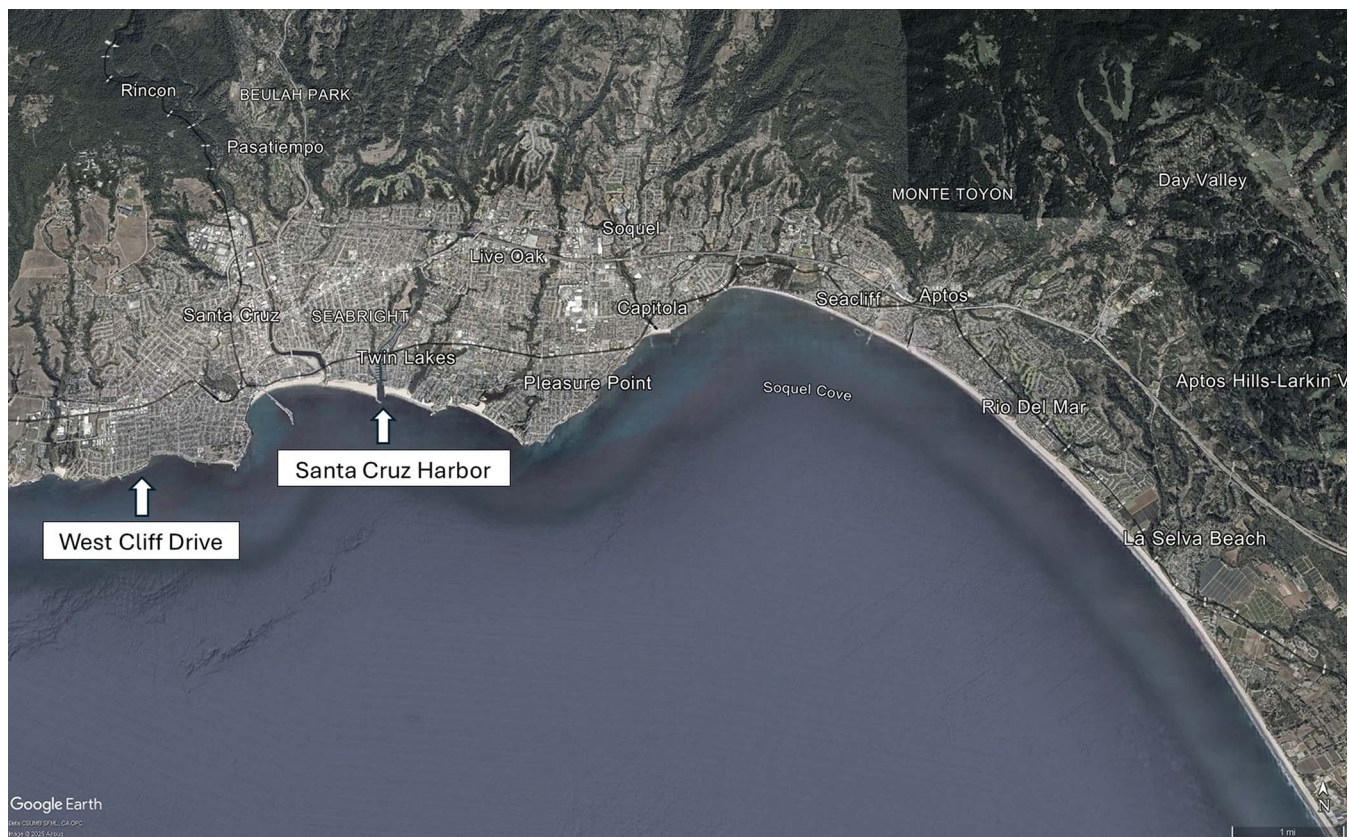


Figure 3. Location map for the northern Monterey Bay coast, showing locations of West Cliff Drive, Capitola Village, Seacliff State Beach, and Rio del Mar (Google Earth, 2025).

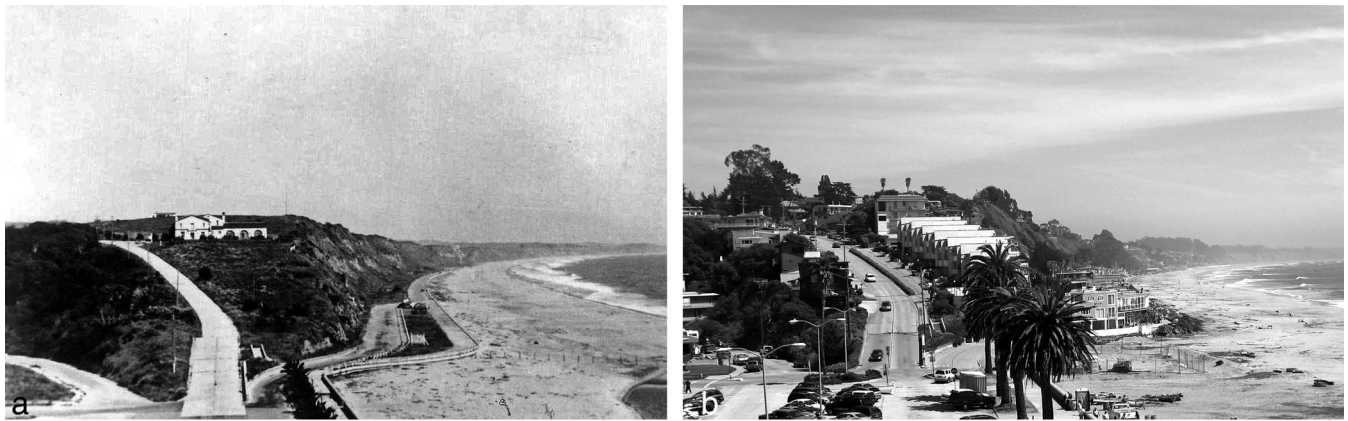


Figure 4. (a) Back beach shoreline in Rio del Mar ~1930 with a road built on the back beach (to be named Beach Drive) before and in anticipation of home development (photo courtesy of Special Collections, University Library, University of California, Santa Cruz). (b) Same view as (a). Complete development of the bluff top and shoreline has encroached ~100 feet onto the back beach (2006).

(Figure 4a,b) were built on with no recognition of the hazards inherent in encroaching onto this vulnerable geomorphic environment (Griggs and Battalio, 2025).

### Coastal Geology, Natural Processes, and Development

In recent decades, a dilemma of increasing magnitude has developed between oceanfront development and the inherent geologic instability of the shoreline. The two coastal hazards of greatest concern to any oceanfront development, whether private homes, businesses, or public infrastructure, are coastal cliff or bluff erosion and flooding of low-lying shoreline areas by storm waves and extreme high tides. The shoreline is one of the most active and dynamic geologic environments on the planet, where waves, tides, wind, currents, rain, storms, and human activity are constantly changing and reshaping the coastline. Similarly, the beaches in California come and go seasonally (Griggs, 2010; Warrick *et al.*, 2025), cliffs crumble and collapse, houses and highways appear and sometimes disappear, and

seawalls are built and eventually fail. The consequences of changing climate and rising sea levels, including short-term extreme events, accelerate natural coastal processes such as shoreline erosion and put coastal developments at a greater risk. About 85–90% of the state's 1,100-mile California shoreline is currently eroding (MBNMS, 2024), and a U.S. Geological Survey study showed that by 2100, about 31% to 67% of Southern California beaches might completely erode under sea-level-rise scenarios (Vitousek *et al.*, 2017). The natural ongoing processes of seasonal beach erosion, shoreline flooding, and bluff or cliff retreat were either not recognized or appreciated, or were largely ignored by most developers, builders, or homebuyers in the past. Within the past 4 decades, however, the problem has come into clearer focus along virtually the entire state's coastline. Over the long term, it is challenging, expensive, and futile to try to stop the Pacific Ocean from its natural tendencies. However, we have spent considerable public and private money attempting to do so, but often on only a very temporary basis (Griggs, 2024a).

### History of Natural Disasters and Subsequent Impacts along the Central California Coast

With the shift to a warmer PDO interval in about 1978 (see Figure 2), the combination of more frequent and stronger El Niño events (Figure 5), which elevated sea levels as much as a foot or two (Table 1), combined with large storm waves from the SW arriving at times of high tides to severely affect shoreline development along northern Monterey Bay (Griggs, 2018). In particular, the shoreline village of Capitola

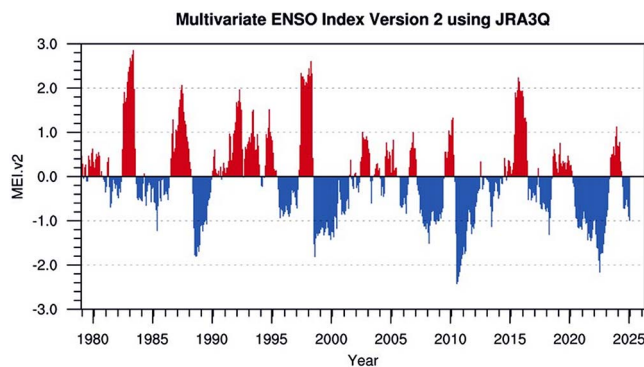


Figure 5. El Niño Southern Oscillation (ENSO) Index from 1979 to 2025. The largest red peaks correspond to major ENSO events (1982–83, 1987, 1997–98, and 2015–16) (NOAA Physical Sciences Laboratory, <https://psl.noaa.gov/enso/mei/>).

Table 1. *El Niño high-tide records on 27 January 1983. MLLW = mean lower low water.*

| Station       | Predicted Tide (FT. MLLW) | Recorded Tide (FT. MLLW) | Difference (Feet) |
|---------------|---------------------------|--------------------------|-------------------|
| San Diego     | 7.40                      | 8.35                     | 0.95              |
| Los Angeles   | 6.9                       | 7.96                     | 1.06              |
| San Francisco | 7.1                       | 8.87                     | 1.77              |



Figure 6. (a) Overtopping of low seawall at times of elevated sea levels and large waves has repeatedly flooded the esplanade area of Capitola, with significant damage to commercial development. (b) Sand and debris deposited when waves overtopped the low seawall along Capitola's esplanade. View similar to (a). Arrow points to the same seawall in (a).

(see Figure 3 and Figure 6a,b), the back beach development along Beach Drive in Rio del Mar (see Figure 4), and Seaclyff State Beach (Figure 7) are all locations that have been repeatedly flooded and damaged (Anderson *et al.*, 2024; Griggs, 2018; Griggs and Battalio, 2025). During the winter of 1983, the combined effects of elevated El Niño sea levels, along with high tides and large storm waves, inflicted over \$310 million (2023 dollars) in damage to oceanfront property (Figure 8). Damage in these storms wasn't restricted to undermined decks and broken windows; 33 oceanfront homes were destroyed. Recreational facilities like piers, parking lots, access stairs, and bathrooms from San Diego to San Francisco had over \$82 million in losses (2023 dollars). Damage to large engineering structures like breakwaters and jetties designed to protect harbors from storm waves reached

~\$62 million (Griggs, Patsch, and Savoy, 2005). The 1983 winter was the most damaging storm season along the California coast in several decades and provided a wake-up call to coastal homeowners, community planners, and permitting agencies. It also led to a large increase in applications by homeowners for new coastal protection structures from local city and county planning departments and, ultimately, the California Coastal Commission, which almost always has the final authority.

Over the past century, extreme and damaging events like the winter of 1982–83 were usually seen as just that, extreme events that occurred only infrequently. Consequently, reconstruction proceeded from the perspective that such an event would not likely happen again soon. This response seems to reflect a short “disaster memory,” which appears to be a common character of many Californians. We experience floods,

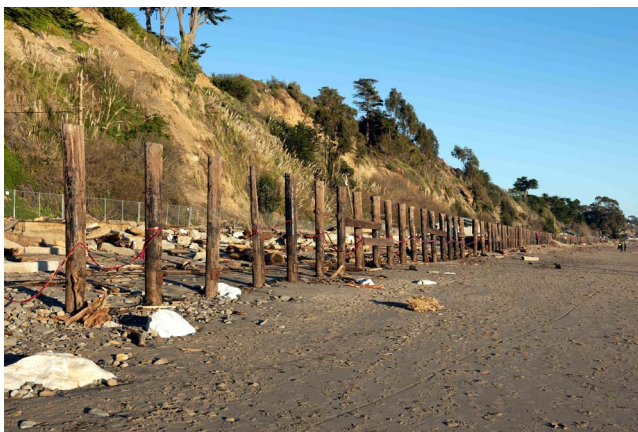


Figure 7. Remains of a timber bulkhead that supported a recreational vehicle camping and day use area at Seaclyff State Beach that has been built, destroyed, and rebuilt seven times over the past 98 y (photo credit: Kim Steinhardt).

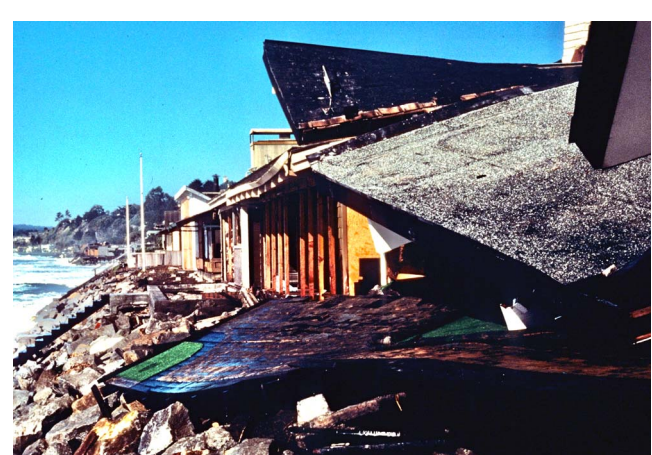


Figure 8. Damage to back beach development from wave overtopping at Aptos Seascapes along the northern Monterey Bay shoreline during the severe El Niño of 1983.

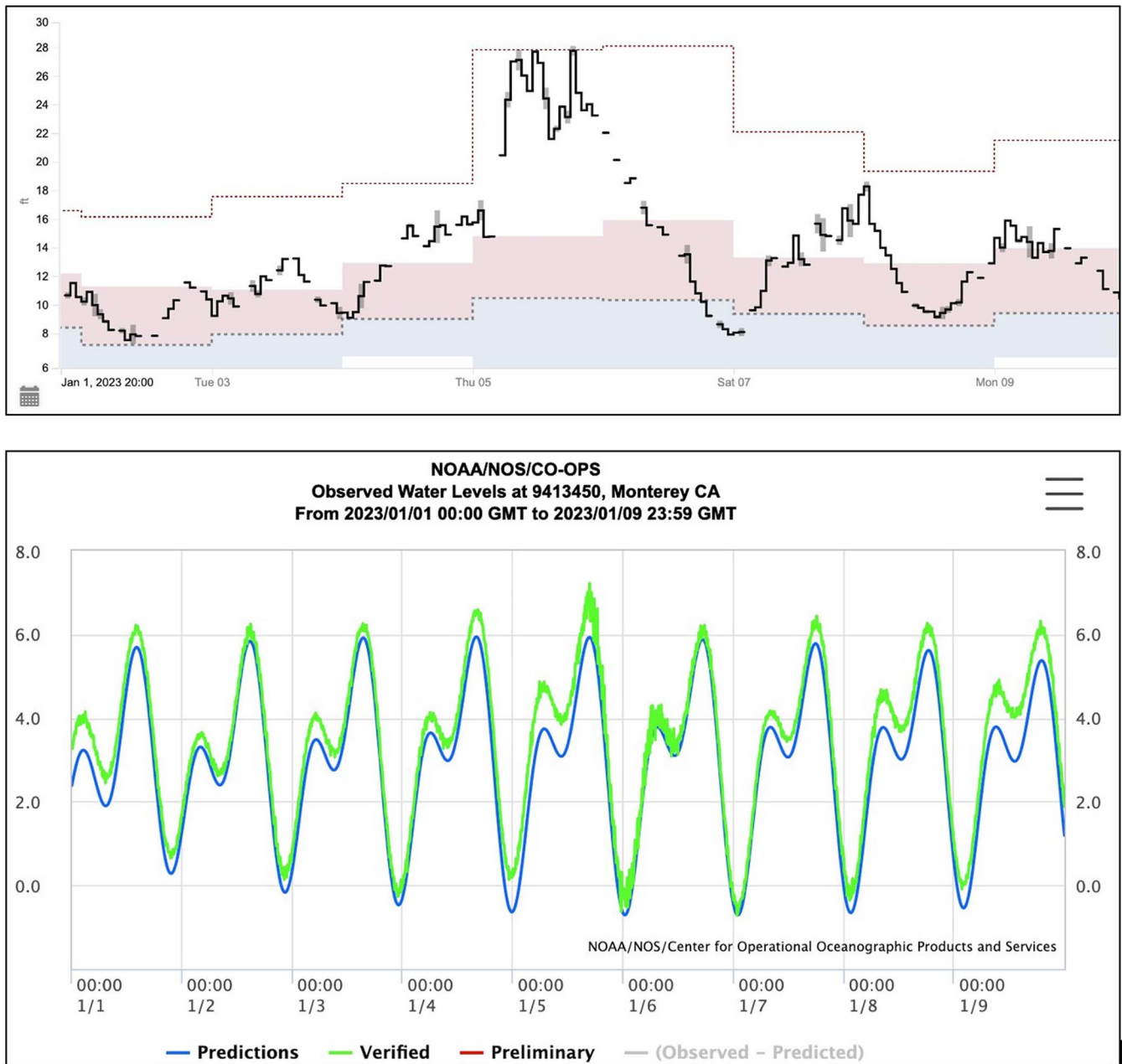


Figure 9. Simultaneous arrival of very large waves (top) and high tides (bottom) on the morning of 5 January 2023. Wave data from Coastal Data Information Program buoy no. 46042 (NOAA National Data Buoy Center; <https://www.ndbc.noaa.gov>).

earthquakes, or major storms; we suffer but then typically rush to rebuild, often in the same locations, and forget about the damages, losses or injuries, and fatalities of the past. However, climate is clearly changing, and the conditions of the past are no longer reliable indicators of future events. Over the past 3 years, the repeated extreme events along the Central California Coast and the associated damages present an excellent example of these changing conditions, which are described in the following section.

### WINTERS OF 2022–23, 2023–24, AND 2024–25 January 2023 Coastal Extreme Storm

The first of what were to become three severe and damaging back-to-back coastal winters arrived on the morning of 5 January 2023, with the simultaneous occurrence of extremely large waves at the precise time of the highest monthly tides. These are the conditions that have historically produced the greatest erosion and storm damage along the Central California Coast (Griggs 2018; Griggs, Davar, and Reguero, 2019). The 5



Figure 10. Large waves at high tide affecting the bluffs along West Cliff Drive on the morning of 5 January 2023.

January event severely affected the northern Monterey Bay shoreline from West Cliff Drive in Santa Cruz to Rio del Mar along the inner Bay (see Figure 3) and larger-than-normal waves persisted for several more days. The closest wave recorder was anchored about 20 miles offshore of Santa Cruz, where the water depth is ~1694 m (Coastal Data Information

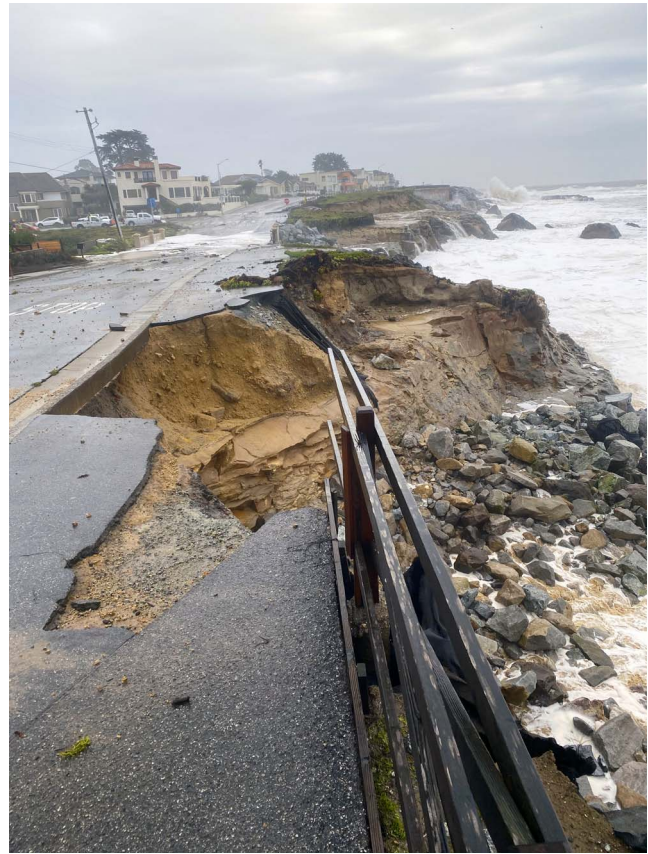


Figure 12. Erosion of unconsolidated terrace deposits, loss of pedestrian sidewalk, and undermining of West Cliff Drive in city of Santa Cruz on 5 January 2023.



Figure 11. Typical section of coastal bluff along West Cliff Drive with pervasively jointed mudstone bedrock capped by terrace deposits. Slab failure typically occurs along the steeply dipping joint sets (arrows) that produce a ramp allowing large waves to overtop the bedrock and erode the overlying highly erodible terrace deposits.

Program [CDIP] wave buoy no. 46042). Significant wave heights on the morning of 5 January 2023 reached approximately 28 ft. These waves were from the WSW (255°) and approached this section of shoreline more directly with less energy loss from refraction than the typical NW winter storms. The nearest tide gauge in operation at that time was mounted on the Monterey Breakwater and is located 25 miles south of Santa Cruz (NOAA gauge 9413450). High tide that morning was predicted at 5.93 ft, but actual maximum verified high water was 7.22 ft (Figure 9), 1.3 ft above predicted water level.

#### Impacts on West Cliff Drive

The West Cliff Drive area (see Figure 3) is most exposed to the waves from 255° and was severely affected by the largest waves (Figure 10). This section of coast is backed by an uplifted marine terrace ranging from 20 to 30 ft in height and consists of pervasively jointed siltstone/mudstone bedrock capped by 10–12 ft of poorly consolidated and very erodible terrace deposits (Figure 11). Wave damage to the West Cliff Drive area was as severe as any prior winter on record as large waves at high tide overtopped the bedrock, eroded the unconsolidated terrace deposits, and led to collapse of several sections of the pedestrian walkway and began to undercut the roadway (Figure 12).

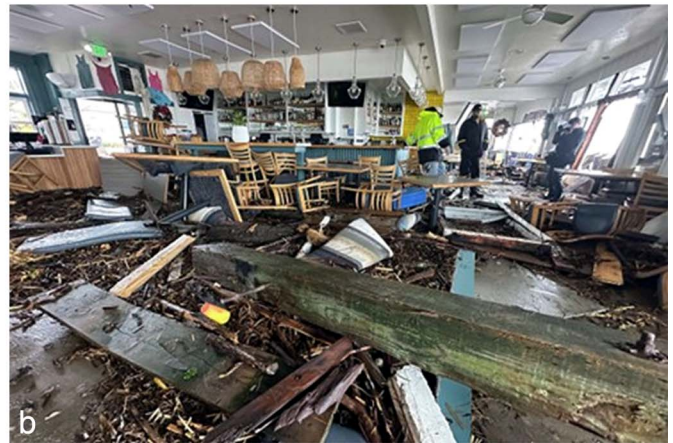
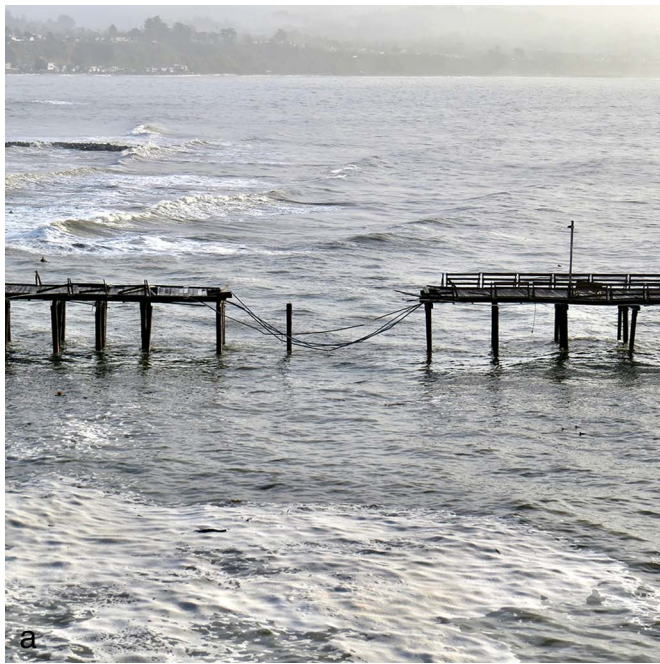


Figure 13. (a) Collapse of a portion of the pier at Capitola on 5 January 2023. (b) Flooding of an oceanfront restaurant and damage from timber and other debris from the collapsed pier (photo credit: Kevin Painchaud, Lookout Santa Cruz).

### Impacts on the Village of Capitola

Six miles down the coast to the east in the shoreline village of Capitola (see Figure 3), a portion of a pier collapsed (Figure 13a), and restaurants along the oceanfront esplanade were flooded and damaged as large timbers from the partially collapsed pier were carried through the outer walls and left inside one restaurant (Figure 13b). Waves washed across the beach, battering and flooding (Figure 14) beach-level apartments and commercial establishments causing major damage from wave attack and flooding. This was not the first time that the shoreline village of Capitola had experienced

storm damage, however. This community has a long history of storm damage (see Figure 6a,b) extending back to 1865, and there have been at least 22 winters over the past 160 years when significant wave impact and flooding have been reported (Griggs, 2018). Coastal disasters have been a way of life in Capitola for over 150 years. Through a combination of public funds, grants, and private donations the pier was rebuilt after the January 2023 damage.



Figure 14. Flooding of Venetian Court on the back beach in Capitola in early January 2023 (photo credit: Kevin Painchaud, Lookout Santa Cruz).



Figure 15. Seacliff State Beach recreational vehicle parking area on the back beach protected by a timber bulkhead (2019 California Coastal Records Project, Kenneth and Gabrielle Adelman).

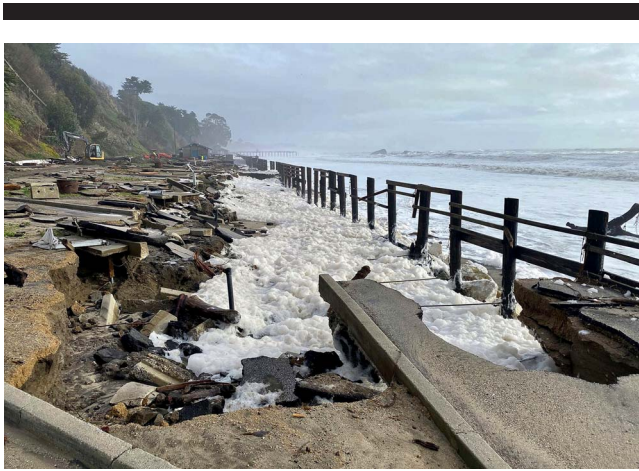


Figure 16. Large waves at high tides destroyed the timber bulkhead and asphalt; decomposed granite parking area and washed-out fill at Seacliff State Beach (photo credit: Kim Steinhardt).

### Impacts on Seacliff State Beach

Two to three miles down the coast from Capitola Village lies Seacliff State Beach and the shoreline development of Rio del Mar (see Figure 3), which also had major damage from the very large waves and high tides of early January 2023. Seacliff State Beach has a history extending back nearly a century, initially as a beach resort and then as a State Beach with a recreational vehicle (RV) “campground,” day use, and parking on the back beach. These use facilities extend 75–125 ft seaward from the base of the coastal bluff (Figure 15) and have been raised above the original beach level with fill supported and partially protected by a timber bulkhead. During its nearly 100 years of recreational use, the timber bulkhead and camping/parking area have been built,

destroyed by winter storms, and rebuilt seven times (Anderson *et al.*, 2024). In the first week of January 2023, the wooden lagging was battered loose by logs and debris as large waves at high tides overtopped and broke through the timber bulkhead. The asphalt surface was broken up and was followed by erosion of the underlying fill (Figure 16). This was precisely how all earlier versions of the wall had failed and was the eighth time that the timber bulkhead and parking/camping area have been damaged or destroyed.

One of the unique attractions of Seacliff State Beach over the years was the SS *Palo Alto*, a concrete ship built for the military in the closing days of WW I and brought to the site in 1930. The ship slowly deteriorated over the years along with the pier, which initially provided access to the ship and later became a fishing platform (Figure 17a). Continuing battering by winter waves had led to gradual deterioration of the ship, and the extreme waves and high tides of early January 2023 broke up what was left and destroyed much of the remaining pier (Figure 17b).

### Impacts on Shoreline Development of Rio del Mar

A few hundred feet down the coast from Seacliff State Beach, the community of Rio del Mar was built partly on a former marsh, with an entire development of homes also built on the back beach (see Figure 4). Like Seacliff State Beach, a road and homes encroached 80–100 ft onto the beach (Griggs and Battalio, 2025). Large waves and very high tides have periodically washed over the normally wide beach; overtopped a low rock revetment and a steel, concrete, and timber seawall; flooded Beach Drive; and left large logs, debris, and sand on the roadway, in carports, and occasionally in homes. This occurred again in early January 2023 (Figure 18a,b).

### Late December 2023–Early January 2024 Coastal Storms

It soon became clear that the large wave and high tide conditions of early January 2023 were not infrequent or isolated

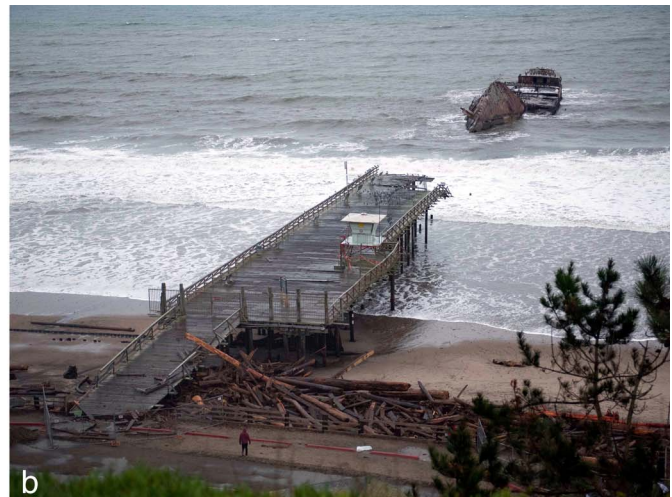


Figure 17. (a) SS *Palo Alto* at Seacliff State Beach and the fishing pier (~2015) (photo credit: Santa Cruz City/County Library System). (b) Remains of SS *Palo Alto* and the connecting pier in early 8 January 2023 (photo credit: Kim Steinhardt).



Figure 18. (a) Logs and debris were carried over the low rock revetment and deposited on patios of homes along Beach Drive in Rio del Mar. (b) Beach sand and logs were carried over the low seawall, threatening back beach homes (photo credit: Kim Steinhardt).

events. Very similar oceanographic events occurred in late December 2023 and continued into early January 2024. A series of large wave events were recorded at CDIP buoys all along the West Coast from extratropical storm activity in the Pacific Ocean, consistent with the ongoing El Niño. The waves that arrived on December 28 came close to historic records at several California buoys and were compounded again by high

tides that caused significant coastal flooding and erosion (Timmerman, 2024). Unfortunately, storms earlier in December had broken loose the wave buoy off Monterey Bay so no data were recorded. On 28 December 2023, the closest other CDIP buoys documented maximum wave heights of 5.7 m (18.7 ft) at Pajaro Beach South (Figure 19), 15.8 m (51.7 ft) at Cape Mendocino, 270 miles north, and 15.4 m (50.4 ft) at Point Sur, 45

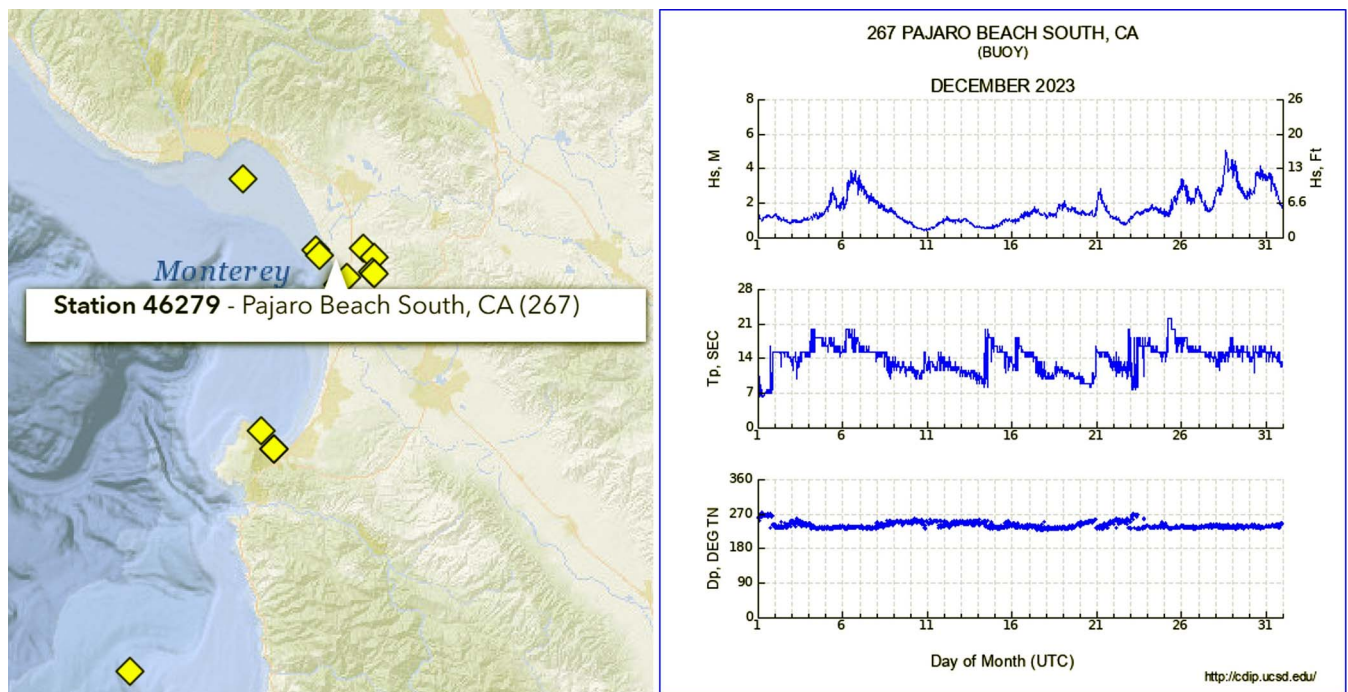


Figure 19. Wave conditions in late December 2023 at Coastal Data Information Program buoy 267 (Pajaro Beach South) (NOAA National Data Buoy Center, 2025; [https://www.ndbc.noaa.gov/station\\_page.php?station=46279](https://www.ndbc.noaa.gov/station_page.php?station=46279)).



Figure 20. Excavation and site preparation for seawall construction along West Cliff Drive in Santa Cruz after January wave damage (November 2023).

miles south. High tides on 28 December peaked at 6.7 ft. In response to the bluff erosion and damage to the pedestrian path and edge of West Cliff Drive in the city of Santa Cruz, the roadway had been closed off to vehicle traffic and work had begun on seawall construction at the two areas of greatest damage (Figure 20), which was to continue for the next 18 months. Waves continued to wash up into the construction areas, but additional damage was minimal.

Sand, logs, and other debris from the January 2023 storms were gradually removed from oceanfront restaurants, living rooms, carports, streets, and parking lots in Capitola and Rio del Mar (Figure 21a,b) so homeowners, renters, and visitors could return and shoreline parking areas could reopen. Some structural repairs, however, would take considerably longer

because of a combination of absentee landlords, timing required to get insurance payouts and permits, and a general shortage of getting contractors or workers to take on additional work.

The Venetian Court in Capitola was again battered by large waves at high tide, which partially demolished the front walls of several units and filled them with sand and debris (Figure 22). Sand and debris also filled the village's oceanfront esplanade, which had to again be cleaned up. Along Rio del Mar's shoreline esplanade, waves again overtopped the low seawall, flooded the streets, and left behind logs, sand, and debris (Figure 23). Immediately down the coast, waves again washed across the normally wide beach, topped the seawall, and flooded Beach Drive (Figure 24).

### December 2024 Coastal Storm

The debris left behind by the late December 2023/early January 2024 waves and high tides had just been cleaned up, and damage repairs were underway from Santa Cruz to Rio del Mar, when the third severe winter in a row affected this stretch of coast. Conditions peaked on 23 December 2024, when waves at a newly installed wave gauge in northern Monterey Bay (Soquel Cove South, CDIP buoy 281) recorded significant wave heights of 19 ft with periods of 22 seconds from the SW (Figure 25). Tidal elevations recorded at a new gauge mounted on the Santa Cruz Municipal Pier reached a peak of 5.5 ft. The most significant damage during this event was to the pier, which was originally constructed in 1914. Piers require regular maintenance, however, primarily involving replacement of the supporting pilings and the wooden decking. When the large waves and high tides of 23 December 2024 arrived, repairs were underway to replace older pilings in anticipation of building a large public structure at the end of the pier. Cross-members that tied the pilings together and some of the decking had been removed beneath the outer 150 ft of the pier as new pilings were to be driven into the seafloor to strengthen the outer end. This significantly reduced the structure's shear strength, and within hours, while two engineers were inspecting the area

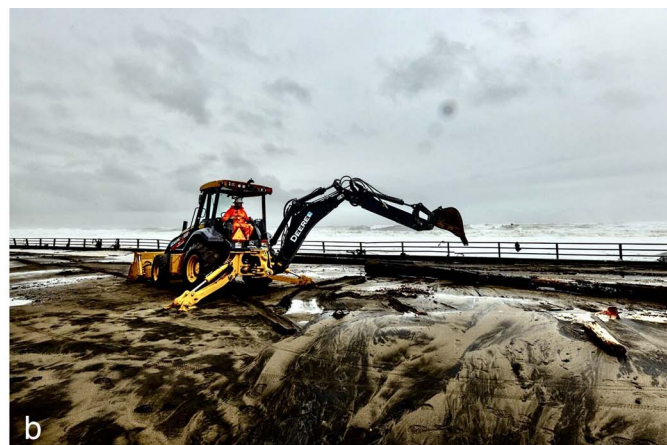


Figure 21. (a) Removing sand from a back beach home on Beach Drive, Rio del Mar. (b) Removing sand and debris from Beach Drive (photo credit: Kevin Painchaud, Lookout Santa Cruz).



Figure 22. Late December 2023 storms further damaged the beach-level Venetian Court (photo credit: Kevin Painchaud, Lookout Santa Cruz).

under construction, the outer 150 ft, with its public restroom, collapsed into the large swells. This process occurred slowly enough that two engineers went down with the decking, still standing up, along with two pieces of heavy equipment (Figure 26a). They were soon rescued without injury while the nearly intact section of the pier decking and the restroom drifted toward the beach where it floundered at the mouth of the San Lorenzo River before being demolished and removed (Figure 26b). The destruction of the outer end of the pier and the estimated \$20 million replacement cost led the city of Santa Cruz to rethink their plans to rebuild the destroyed section and build a major public structure at the outer end of the pier. Loose pilings and large timbers from the collapsed section of the pier were carried down the coast as far as 12 miles, creating a severe hazard for anyone in the water, including surfers as well as vessels.



Figure 23. Large wave at high tides in late December 2023 washed over the seawall and onto the esplanade, leaving logs, sand, and debris in the parking area (photo credit: Kevin Painchaud, Lookout Santa Cruz).



Figure 24. Waves at high tide on 28 December 2023 overtopped the seawall and again flooded Beach Drive (photo credit: Kevin Painchaud, Lookout Santa Cruz).

The other facility that had significant damage during the late January swells was the Santa Cruz Small Craft Harbor. The harbor is now 60 years old and had been damaged by three tsunamis since its completion in 1964 (Griggs, 2018). Because in large part of the configuration of the entrance jetties (Figure 27a), it had never been seriously affected by waves. The large waves on 23 December 2024, however, washed into the harbor and battered boats and docks. The harbor sustained about \$25 million in damage, as at least 12 boats reportedly sank and many others were damaged (Figure 27b). The closest wave gauge indicated that waves at the time of greatest harbor impact were from  $\sim 220^\circ$  (see Figures 25 and 27a). It appears that because of a combination of wave refraction and diffraction, waves still had enough energy to produce major damage within the normally protected harbor.

## DISCUSSION AND CONCLUSIONS

Both private development and public infrastructure along the northern Monterey Bay shoreline of California's Central Coast have been damaged and destroyed multiple times over the past 150 years, with most damage having occurred during periods when very large waves arrived at times of highest monthly tides. Coastal impacts and losses have typically been greatest during El Niño years when swells arrived from the southwesterly quadrant and approached the shoreline more directly than during periods when the more dominant waves approached from the NW with substantial energy loss through refraction (Griggs, 2018; Storlazzi and Griggs, 2000).

In contrast to the Gulf and South Atlantic coasts of the United States where multiple hurricanes occur every year, large damaging events along the Central Coast of California have been relatively infrequent, occurring closer to a decadal time frame. However, climate is changing and at least two previous studies have shown that wave heights and energy are gradually increasing (Bromirski, 2023; Reguero *et al.*, 2019), which is consistent with the effects of a warming planet.

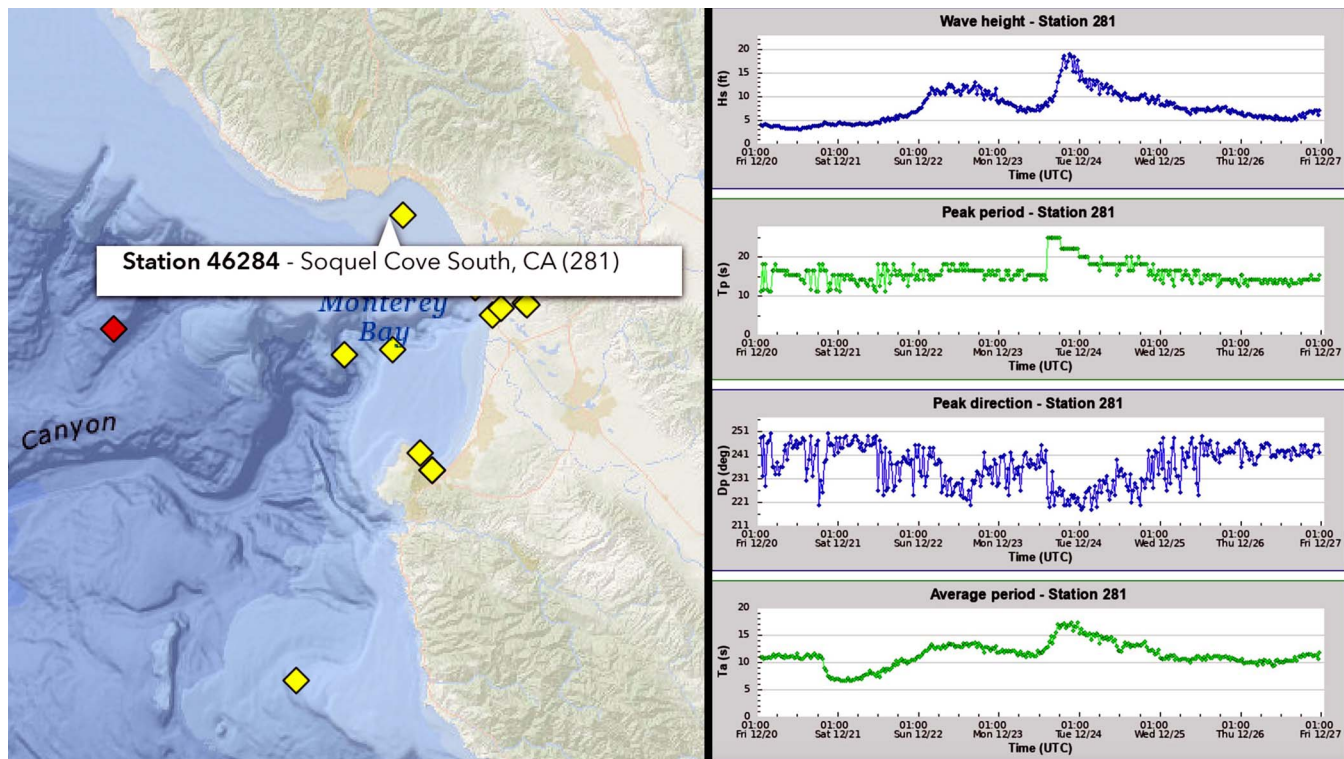


Figure 25. Wave conditions in late December 2024 at Coastal Data Information Program buoy 281 (Soquel Cove South) (NOAA National Data Buoy Center, 2025).

The three most recent winters (2022–23, 2023–24, and 2024–25) have produced significant damage to both public infrastructure and private development (homes and businesses) along the northern Monterey Bay shoreline. Both bluff retreat

and shoreline flooding have taken place, closing roadways, parking areas, public piers, restaurants, and apartments. These repeated damages have altered thinking among public agencies at the local and state level, as well as the affected public,



Figure 26. (a) Outer end of the Santa Cruz pier after collapsing into the ocean on 23 December 2024 (photo credit: Brad Porter, City of Santa Cruz). (b) Restroom from end of municipal wharf was carried intact where it floundered on the beach at the mouth of the San Lorenzo River (courtesy of: Kevin Painchaud, Lookout Santa Cruz).

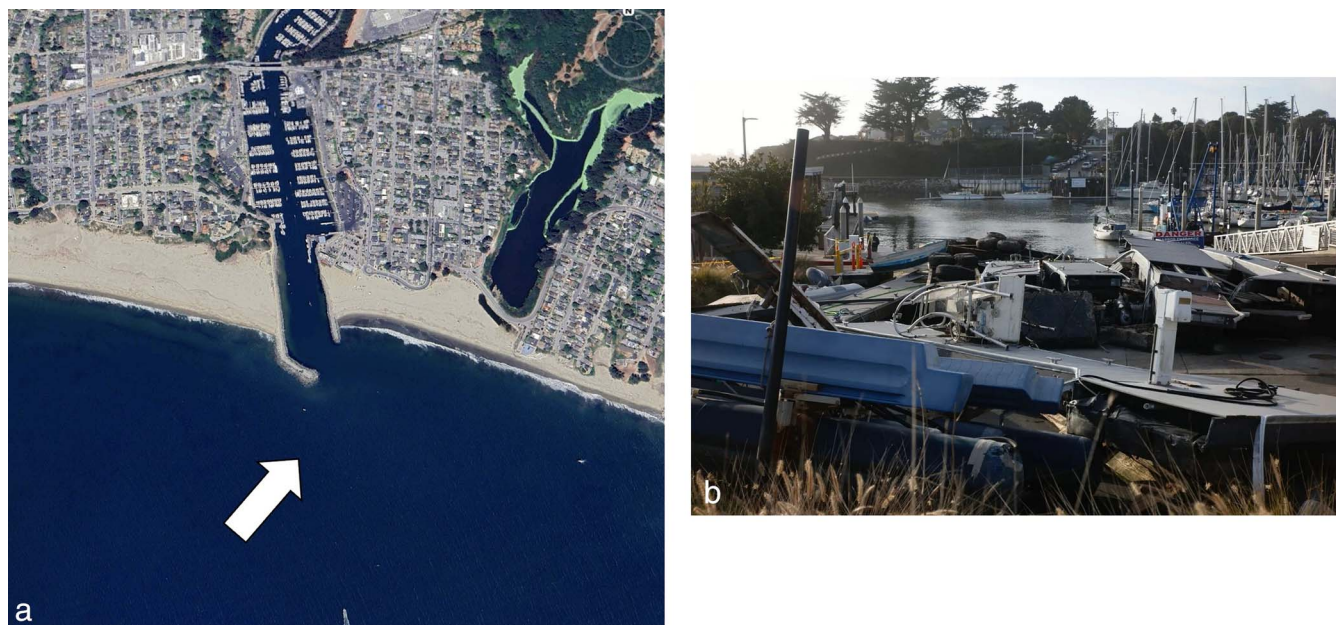


Figure 27. (a) Santa Cruz Small Craft Harbor with direction of wave approach on 23 December 2024 (Google Earth). (b) Damage to boats and docks at the Santa Cruz Small Craft Harbor from 23 December 2024 waves (courtesy of: Keven Painchaud, Lookout Santa Cruz).

about the typical historic responses of repairing, rebuilding, and reopening.

With the damages from these three winters still clear in our minds, this is the time to carefully and thoughtfully consider how this shoreline can adapt to what appears to be changing coastal climate conditions and impacts. Adaptation is an overarching approach to long-term trends, and planning options under adaptation include resistance, resilience, and relocation.

Resistance along this shoreline can involve the use of protective devices such as seawalls or rock revetments, and rebuilding structures such as piers stronger to resist future wave attack. This approach may be appropriate if the protection is deemed to be cost effective for a reasonably long period and the asset is highly valued. This has been the historical approach used for the damaged and threatened portions of West Cliff Drive in Santa Cruz, where about \$35 million has been spent to armor the damaged sections of the intensively used roadway. Over 50% of the city's coastline has now been armored and most of the 2023 winter damage was in locations already protected by rock revetments, which either collapsed or were overtopped. In the village of Capitola where a portion of their pier was destroyed during the January 2023 storms, a decision was made, on the basis of the importance of this iconic structure to the community, to rebuild the pier.

The owners of the Venetian Court apartment/condominium complex and the commercial establishments along the city's esplanade have decided to clean up the debris and make necessary repairs, with no additional protection or resistance built or planned. This response appears to fall within the resilience approach. Either with personal, insurance, or

disaster relief funding, repairs are made with no significant change to their resistance to future storm wave attacks, as has been the approach for the past century and longer. The same approach has been taken in Rio del Mar, both along the esplanade and with the homes along Beach Drive, which have been repeatedly flooded during periods of large waves and high tides. Although no new plans or improvements have been announced, both locations continue to remove sand, logs, and other wave-borne debris with the goal of bouncing back and no doubt anticipating similar future events but no change in strategy.

The future or fate of two of the most damaged structures, the Santa Cruz Municipal Pier and Seacliff State Beach, is still being evaluated. Early indications are that after seven episodes of rebuilding the timber bulkhead and RV camping and public parking areas on the beach, followed by destruction, the California Department of Parks and Recreation is rethinking this approach and giving serious consideration to providing these same use opportunities on the bluff top above the shoreline. Discussions to date regarding the original plans to build a large public structure on the now-destroyed outer end of the Santa Cruz Municipal Pier have thrown this project into question. In both cases, these projects may likely fall into the relocation approach.

Over the long term, there is absolutely nothing we can do to hold back or halt the Pacific Ocean as the planet continues to warm, expanding seawater and melting land ice. One key question to answer for each community is what is the long-term goal? How far into the future do we plan for and what can we expect, both with sea-level rise and, more important, short-term extreme events?

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