GEOLOGY

Tracking California's sinking coast from space: Implications for relative sea-level rise

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Coastal vertical land motion affects projections of sea-level rise, and subsidence exacerbates flooding hazards. Along the ~1350-km California coastline, records of high-resolution vertical land motion rates are scarce due to sparse instrumentation, and hazards to coastal communities are underestimated. Here, we considered a ~100-km-wide swath of land along California's coast and performed a multitemporal interferometric synthetic aperture radar (InSAR) analysis of large datasets, obtaining estimates of vertical land motion rates for California's entire coast at ~100-m dimensions—a ~1000-fold resolution improvement to the previous record. We estimate between 4.3 million and 8.7 million people in California's coastal communities, including 460,000 to 805,000 in San Francisco, 8000 to 2,300,00 in Los Angeles, and 2,000,000 to 2,300,000 in San Diego, are exposed to subsidence. The unprecedented detail and submillimeter accuracy resolved in our vertical land motion dataset can transform the analysis of natural and anthropogenic changes in relative sea-level and associated hazards.

INTRODUCTION

A substantial proportion of the world's population lives in low-lying coastal areas (*1*). Of these, nearly 1 billion live in flood-prone areas lying below 10-m elevation (*2*). Coastal populations are expected to increase by the year 2050 due to coastward migration (*3*). Moreover, these coastal lands are subject to subsidence due to natural and anthropogenic processes (*4*). Land subsidence can increase flooding risk (*5*), wetland loss (*6*), and damage to infrastructure (*5*, *7*) by increasing a region's relative sea-level rise (RSLR) (*8*). In a coastal setting, such as California's San Francisco Bay Area (*9*), low-elevation, highly populated coastal cities experiencing subsidence have an increased hazard of flooding, inundation, and related economic damages—especially if the area is financially disadvantaged, lacks proper infrastructure, or does not have adequate monitoring efforts in place (*10*). Furthermore, subsiding coastal wetlands, the U.S. Gulf Coast for example, are at increased risk of drowning and disappearing due to ocean flooding (*11*).

Natural drivers of subsidence and uplift, such as tectonics (*12*–*14*) [except coseismic events (*14*)], isostasy (*15*), and sediment compaction (*16*, *17*), often cause slow monotonic vertical land motion (VLM). Conversely, the VLM associated with anthropogenic processes such as surface water management or extraction of groundwater and hydrocarbons (*6*, *8*, *18*, *19*) can be fast with temporally variable behavior. In some cases, depletion and recharge of aquifers can cause VLM at rates up to tens of centimeters per year VLM [e.g., (*20*, *21*)]. Depending on the local geology, these processes can combine to generate overall uplift or subsidence in a landscape.

In California, the oblique convergence between the Pacific and North American plates is primarily accommodated by strike-slip motion along major faults such as the San Andreas fault system (*22*). However, the minor dip-slip component of these near-vertical faults can cause spatially and temporally variable VLM during earthquake cycles (*22*). Farther north, the migration of the Mendocino Triple Junction drives crustal thickening and uplift north of the junction and crustal thinning and subsidence to the south (*23*). California experiences slow subsidence due to glacial isostatic adjustment with rates up to ~2 mm/year at latitudes >37°N and up to ~1.5 mm/year at lower latitudes (*24*). Sediment compaction leads to subsidence in sedimentary basins, such as in the San Francisco Bay (*9*, *16*), and droughts and groundwater withdrawal lead to subsidence in aquifer basins, such as in the Santa Clara Valley (*25*–*27*). These combined effects significantly alter regional RSLR rates along California's coast (*9*).

Despite the importance of monitoring land subsidence, the large-scale, high-resolution observations that would help characterize VLM and its related hazards are often not available. Instead, understanding of VLM in California is limited to sparsely distributed (~20 km average spacing) Global Navigation Satellite System (GNSS) stations. This coarse GNSS resolution reduces the accuracy of RSLR estimates; the lack of colocated GNSS stations with tide gauges leads to errors in estimates of global mean sea-level rise (*28*).

Spaceborne geodesy through combining observations obtained via interferometric synthetic aperture radar (InSAR) with those measured by GNSS stations offers a means to improve the accuracy, density, and spatial extent of VLM measurements (*13*, *26*, *29*–*31*). Here, we present the first VLM rate map for the coast of California at ~100-m resolution and unprecedented precision (~1 mm/year) as a combination of the full archive of Advanced Land Observing Satellite (ALOS) L-band and Sentinel-1A/B C-band satellites with observations of horizontal velocities at GNSS stations. The ALOS archive covers 2007–2011, Sentinel-1A/B covers 2014–2018, and the GNSS data cover 1996–2018, with individual stations covering time frames ranging from 1 to 22 years and a mean observation time of 8 years. This map, composed of ~35 million pixels, shows a wide range of uplift and subsidence rates with both large- and small-scale patterns. We discuss these results in the context of the underlying drivers of VLM in California, exploring both the natural and anthropogenic effects. We also discuss the consequences of coastal land subsidence in California.

The results presented here, in combination with other hydrogeological measurements, can contribute to understanding rates of discharge and recharge and the elastic and inelastic responses of aquifers to groundwater exploitation (*6*, *8*, *19*). It also can elucidate the effects of fossil fuel extraction and wastewater injection in regions of gas and oil production (*6*, *8*). Furthermore, this VLM rate map

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