This manuscript is a non-peer reviewed preprint submitted to EarthArXiv. It has been submitted to *Cambridge Prisms: Coastal Futures*.

What is coastal subsidence?

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Abstract. While major technological advances have made measurements of coastal subsidence more sophisticated, these advances have not always been matched by a thorough examination of what is actually being measured. Here we draw attention to the widespread miscommunication about key concepts in the coastal subsidence literature, much of which revolving around the interplay between sediment accretion, vertical land motion, and surface-elevation change. We attempt to rectify this by drawing on well-established concepts from the tectonic geomorphology community. A consensus on these issues by means of a common language can help bridge the gap between disparate disciplines (ranging from geophysics to ecology) that are critical in the quest for meaningful projections of future relative sea-level rise.

Main text

Land subsidence is a major compounding problem for low-elevation coastal zones that are feeling the effects of accelerating global sea-level rise, including some that host the world's largest population centres. This "slow-motion disaster" is receiving rapidly increasing attention within the research community (Buffardi and Ruberti 2023) and is particularly prevalent along depositional coastlines that are subject to long-term passive margin subsidence. Superimposed on this relatively steady (10^5 to 10^6 yr or more) and slow geologic process are non-steady components of vertical land motion (VLM) including glacial isostatic adjustment that affects every shoreline worldwide over shorter timescales of 10^3 to 10^5 yr, plus sediment compaction and fluid extraction that operate mainly over 10^0 to 10^2 yr timescales and exhibit large spatial variability but often dominate subsidence on local scales. This short paper asks the simple question "What is coastal subsidence?" – a question with a seemingly straightforward answer. However, we argue that the complexities of coastal subsidence are not always recognized and appreciated within the highly multidisciplinary subsidence research community, presenting an obstacle to subsidence projections and coastal policymaking.

As pointed out by Shirzaei et al. (2021), within the context of VLM distinction must be made between static and dynamic coastal landscapes. We use these terms in a morphodynamic sense: in the former deposition and erosion have been essentially halted, whereas in the latter (e.g., coastal wetlands) these processes operate relatively uninhibited. The landscapes that we consider to be morphodynamically "static" include urban as well as agricultural settings with minimal relief. These are common in low-elevation coastal zones and characterized by geomorphic processes that are sufficiently slow that they can be neglected over human-relevant timescales. The implications of this distinction for subsidence measurements are profound: in static landscapes, VLM can be directly observed by measurements of deformation of the land surface with remote sensing techniques. Therefore, subsidence studies in such settings are relatively straightforward. The situation is entirely different in dynamic landscapes, where such methods measure surface-elevation change (SEC) rather than VLM (Fig. 1). These are fundamentally different things.

VLM and SEC in subsiding coastal landscapes can be viewed as the mirror image of what occurs in uplifting, erosional landscapes, as outlined in the pioneering paper of England and Molnar (1990) where rock uplift was differentiated from surface uplift. Rock uplift is the upward VLM of a specific reference horizon relative to a fixed datum, whereas surface uplift is equivalent to SEC as used herein and equals rock uplift minus erosion (exhumation). Similarly, subsidence is the downward VLM (a negative number) of a specific reference horizon relative to a fixed datum, and SEC equals the difference between VLM of the reference horizon and vertical accretion (or erosion) of sediment. SEC will be a positive number if vertical accretion exceeds subsidence, SEC will equal zero if vertical accretion balances subsidence, and SEC will be a negative number if subsidence exceeds vertical accretion.

Measuring SEC and VLM can be accomplished by a wide range of methods, some of which strictly determine changes at the land surface, whereas others explicitly monitor subsurface processes. Combining both is essential to disentangle driving mechanisms. Space-based methods like Interferometric Synthetic Aperture Radar (InSAR) have become some of the most powerful tools to obtain spatially continuous data on SEC and/or VLM (e.g., Jones et al. 2016). Global Navigation Satellite System (GNSS) data can provide point observations on VLM in coastal settings (e.g., Hammond et al. 2021) and are often used to ground truth InSAR measurements. While InSAR is potentially invaluable, it cannot differentiate the drivers, or causal mechanisms, if multiple processes contribute to SEC. Most importantly, InSAR fundamentally measures SEC, which will be equivalent to VLM in static landscapes only (Fig. 1). Even in such settings, care must be taken that reflectors measure change at the land surface, given that large buildings often rest on foundations that may be tens of meters deep.

Despite this caveat, ground truthing of InSAR data with GNSS measurements is comparably straightforward in static landscapes (e.g., Fabris et al. 2022). In contrast, as shown by Keogh and Törnqvist (2019), this is more challenging in wetland environments where shallow subsidence is typically not captured by GNSS instruments (Fig. 1). As a result, understanding subsidence in coastal landscapes requires independent measurements of vertical accretion and/or erosion to complement time series on SEC from InSAR. (Separate from these considerations, it should be noted that the collection of InSAR data in wetlands is extremely challenging – a topic beyond the scope of the present paper.) It is therefore imperative that vertical accretion and SEC not be conflated with each other, as has been the case in recent, widely cited papers (e.g., Crosby et al. 2016; FitzGerald and Hughes 2019). Along the same lines, InSAR measurements that encompass both static and dynamic landscapes (e.g., Ohenhen et al. 2023) measure SEC, which can only be equated with VLM in morphodynamically inactive settings.

A related, widespread misconception is associated with the interplay between deposition and subsidence. For example, studies of river delta vulnerability have implied that a reduction of sediment supply increases subsidence (e.g., Becker et al. 2020; Glover et al. 2023). However, the opposite is true: vertical accretion and subsidence from compaction in the upper portion of the sediment column are closely coupled (Saintilan et al. 2022) due to the effective stress exerted by newly accumulated sediment (Zoccarato and Da Lio 2021). Nevertheless, even though deposition typically enhances subsidence, it still often results in net surface-elevation gain (Fig. 1; Chamberlain et al. 2021; Saintilan et al. 2022). Put differently, wetlands that lose elevation compared to relative sea-level rise may still gain elevation with respect to a fixed geodetic datum, as long as SEC outpaces subsidence (Fig. 1).

Coastal subsidence research has enjoyed rapid progress, not least due to a wide range of technological advances and an increasingly high spatial and temporal resolution in the detection of VLM at or near the Earth's surface (e.g., Da Lio et al. 2018; Steckler et al. 2022; Zoccarato et al. 2022; Zumberge et al. 2022). However, as shown by the examples discussed above, new and/or increasingly sophisticated measurements have not always gone hand in hand with progress on our understanding of the relevant surface and subsurface processes: the vital question of "what exactly is being measured?" must never become an afterthought.

An important motivation for this contribution is the increasing recognition of coastal subsidence as an existential threat that adds to the risks posed by global sea-level rise for millions of people worldwide. In fact, along many deltaic coastlines the magnitude of coastal subsidence can equal or exceed current and projected rates of geocentric sea-level rise (Jelgersma 1996; and many subsequent studies). Increased concern about subsidence will be addressed by the recently established International Panel on Land Subsidence (IPLS; Minderhoud and Shirzaei 2022; https://sites.google.com/view/iplsubisdence/home). One of the key objectives of the IPLS will be to produce subsidence projections that can be combined with IPCC-style sea-level projections (Fox-Kemper et al. 2021; Oppenheimer et al. 2019) to generate more powerful forecasts of relative sea-level change. A recent community paper on sea-level terminology (Gregory et al. 2019) has reduced confusion on critically important concepts from this neighbouring field. In that spirit, we hope that this brief paper can be an initial contribution toward a more clearly defined conceptual framework for understanding and projecting subsidence in the coastal zone.

Competing interest: The authors declare none.

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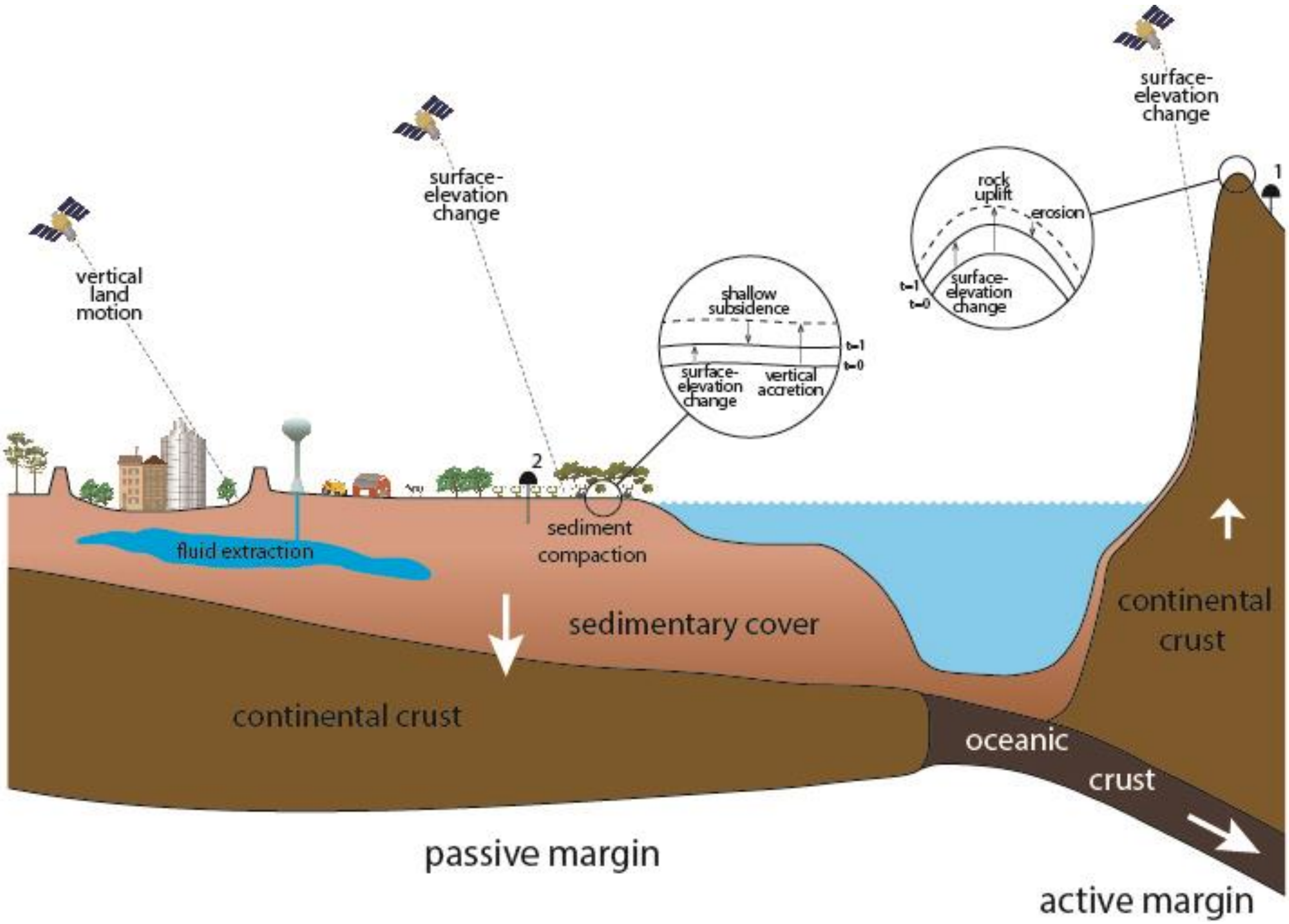

Figure 1: Schematic cross section of two continental margins subject to subsidence (passive margin) and uplift (active margin), respectively. Note that InSAR measurements provide rates of surface-elevation change which only in static landscapes (e.g., urban areas) can be directly interpreted as vertical land motion. Also note the difference between the two GNSS stations: #1 is set in exposed bedrock and measures rock uplift, whereas #2 measures subsidence but misses the shallow subsidence component because the instrument rests on a foundation several meters below the wetland surface. Insets (circles) provide details of the key processes operating in erosive uplifting settings, versus subsiding coastal wetlands where deposition can drive shallow subsidence. In the latter, there is subsidence despite net surface-elevation gain.