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Earth's Future

COMMENTARY
10.1029/2024EF005539

From InSAR-Derived Subsidence to Relative Sea-Level Rise—A Call for Rigor

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Key Points:

- Thiéblemont et al. (2024, https://doi.org/10.1029/2024ef004523) show coastal subsidence is widespread in Europe, with almost half its coastal floodplains subsiding over 1 mm/yr
- A robust Interferometric Synthetic Aperture Radar data processing framework is essential for accurately processing and interpreting vertical land motion (VLM)
- Standardized workflows and cross-disciplinary collaboration are crucial to correctly link VLM to sea-level rise

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Citation:
Minderhoud, P. S. J., Shirzaei, M., & Teatini, P. (2025). From InSAR-derived subsidence to relative sea-level rise—A call for rigor. *Earth's Future*, *13*, e2024EF005539. https://doi.org/10.1029/2024EF005539

Received 6 NOV 2024
Accepted 2 JAN 2025

Abstract Coastal subsidence, the gradual sinking of coastal land, considerably exacerbates the impacts of climate change-driven sea-level rise (SLR). While global sea levels rise, land subsidence often increases relative SLR locally. Thiéblemont et al. (2024, https://doi.org/10.1029/2024ef004523) reached a remarkable milestone by providing a continental-scale estimate of vertical land motion (VLM) across European coastal zones by utilizing European Ground Motion Service (EGMS) data, obtained from Interferometric Synthetic Aperture Radar (InSAR) data from Sentinel-1 satellites. Their findings reveal widespread coastal subsidence, with nearly half of the coastal floodplains, including major cities and ports, subsiding at rates exceeding 1 mm/yr, thereby exacerbating relative SLR. The study emphasizes the critical role of InSAR-data calibration, indicating that the EGMS geodetic reference frame significantly influences VLM estimates. This study highlights the need for a robust InSAR-data processing framework to accurately interpret VLM and its relationship to relative SLR. The processing pipeline should ensure internal consistency of SAR data and rigorously assess output accuracy, considering also post-processing effects. Correct interpretation of results is essential as InSAR satellites measure reflector movement, which may not always align with land surface movement, particularly in urban areas. Ignoring these discrepancies can lead to underestimation of subsidence rates. While InSAR data offers valuable research opportunities, it poses risks of oversimplification and misinterpretation, especially when linked to sea-level change. We call for standardized processing workflows and cross-disciplinary collaboration, essential for accurate VLM interpretations, particularly in coastal cities and river deltas, to ultimately enhance the reliability of relative SLR projections and inform effective coastal management strategies.

Plain Language Summary Coastal subsidence is the gradual sinking of land along shorelines, worsening the hazards of rising sea levels caused by global warming. Thiéblemont et al. (2024, https://doi.org/10.1029/2024ef004523) advance the state of knowledge by quantifying vertical land movement along European coastlines using satellite data sets. Their research shows that many coastal regions, including cities and critical economic centers like ports, are sinking at rates faster than 1 mm per year. The study highlights the importance of adequately processing the data collected by satellites, and the need for careful interpretation of the results. Interpreting the movements detected by the satellites can be challenging because the subsurface processes that cause land subsidence are variable in time and space and may affect each building or structure differently. Considering these complexities is crucial when interpreting the results to avoid over- or under-estimation of the hazards. We advocate for standardizing and benchmarking satellite data products across disciplines to maintain an open, collaborative field driven by diverse perspectives. Such efforts are essential for reliable interpretations of land motion and enable more accurate projections of coastal subsidence. Combined with sea-level rise projections, these insights will better inform governments and support the development of effective management strategies for coastal resilience.

1. Background

Coastal subsidence, the gradual sinking of coastal land (Törnqvist & Blum, 2024), is widely recognized as a coastal hazard that can severely exacerbate the impacts of climate change-driven sea-level rise (SLR). Global sea levels are rising, predominantly because ongoing climatic warming of the Earth melts ice caps and causes thermal expansion of seawater (Arias et al., 2021). However, a growing body of literature (e.g., Buffardi & Ruberti, 2023) indicates that the relative SLR (i.e., the change in sea level relative to a land surface) in coastal cities or river deltas is primarily caused by coastal land subsidence rather than global SLR (Nicholls et al., 2021). Hence, worldwide scientific efforts to accurately measure, understand, and project coastal subsidence are rapidly advancing (Candela & Koster, 2022; Herrera-García et al., 2021; P. S. J. Minderhoud, Middelkoop, et al., 2020; Pedretti et al., 2024; Shirzaei et al., 2021) and with it also the need to establish and grow new inter- and transdisciplinary research traditions to connect land-based observations and projections of vertical land motion (VLM) to sea-level change projections (P. Minderhoud et al., 2024). These integrated assessments and projections of relative SLR are crucial to properly inform governments and coastal decision-makers on the current and expected (near-)future changes. Relative SLR assessments will broaden the scope of their action perspectives for SLR from focusing solely on "adaptation" to a wider systems perspective and more integrated effective strategies (Schmitt & Minderhoud, 2023). This strategy includes a mix of adaptation, mitigation, and prevention, specifically the direct reduction or avoidance of local human-induced land subsidence (Yan et al., 2020). Addressing land subsidence is a very effective strategy against accelerated relative SLR (e.g., P. S. J. Minderhoud, Middelkoop, et al., 2020), yet it remains largely unknown and underexploited.

2. First Continental-Scale Assessment

Thiéblemont et al. (2024) achieved a remarkable milestone in this context by providing the first continental-scale coastal VLM assessment. They used data on contemporary VLM based on satellite measurements from the European Ground Motion Service (EGMS, an EU Copernicus program released in 2022) and performed a pan-European assessment for the coastal zones (i.e., identified lowlaying coastal floodplains). Significant advancements in Interferometric Synthetic Aperture Radar (InSAR)-data acquisition and processing have enabled services like the EGMS to provide periodically updated products on contemporary VLM on an unprecedented spatial scale. This has enabled recent assessments of nationwide coastal subsidence (e.g., Haghighi & Motagh, 2024; Ohenhen et al., 2024) and now, for the first time, at the scale of an entire continent.

In their assessment of the European continent, Thiéblemont et al. (2024) analyzed the EGMS InSAR data for coastal floodplain areas and computed the average coastal VLM for each segment. They found that coastal subsidence is widespread in Europe, with substantial regional variability. Certain areas like Northern Italy, the Netherlands, and parts of the Mediterranean show significant subsidence. In contrast, the Northern European countries, influenced by glacial isostatic adjustment (GIA), show coastal uplift rather than subsidence. Their assessment revealed that nearly half of Europe's coastal floodplains are subsiding at a rate faster than 1 mm/yr. By relating these values with socioeconomic data sets, they assess exposed assets (e.g., (air)ports, industry) and population (e.g., cities). Their study reveals that, on average, coastal, flood-prone cities in Europa currently sink at 1 mm/yr, while some critical economic assets, such as harbors, sink even faster, at 1.5 mm/yr on average. As European coastal cities and economic assets sink, they experience a relative SLR which is higher than the global average SLR induced by climatic warming alone. The study highlights the utility of continental-scale land motion services to detect (new) areas experiencing subsidence and underscores the necessity of incorporating coastal subsidence into assessments of SLR and future coastal flood exposure. Proper accounting for VLM in coastal adaptation planning, alongside SLR, is particularly important in flood-prone areas with high urban and industrial concentration.

Thiéblemont et al. (2024) highlight the significant role of VLM and coastal subsidence in relative SLR across Europe. However, their results also offer a positive outlook: European coastal cities, on average, experience subsidence at lower rates compared to cities in the U.S. (Ohenhen et al., 2024), China (Ao et al., 2024), and other regions (Chaussard et al., 2013; Wu et al., 2022). For instance, Europe's coast sinking rates are an order of magnitude smaller than those observed in East and Southeast Asia, a hotspot of human-induced rapid relative SLR (Nicholls et al., 2021). Coastal cities sinking rates of several cm/yr can be found in China (Ao et al., 2024) and other Asian countries (e.g., Jakarta (Wu et al., 2022; Yan et al., 2021), Ho Chi Minh City (Minh et al., 2022) and Yangon (van der Horst et al., 2018)). In some extreme cases, contemporary sinking rates even exceed a cm/yr, for instance, in Indonesia in the Northern Java cities of Semarang and Pekalongan (Andreas et al., 2019; Chaussard et al., 2013; Mous et al., 2024; Van Bijsterveldt et al., 2023).

The phenomenon of sinking coastal cities is not new, with earliest observations dating back to the early 20th, for example, Tokyo and Osaka-Kobe in Japan, Houston in the USA or Venice in Italy (Poland & Davis, 1969), followed by cities like Jakarta, Bangkok and Ho Chi Minh city in the 1980s and 1990s (see Pedretti et al. (2024) for an overview) and more recently joined by, for example, cities in China (Ao et al., 2024). In addition to dense

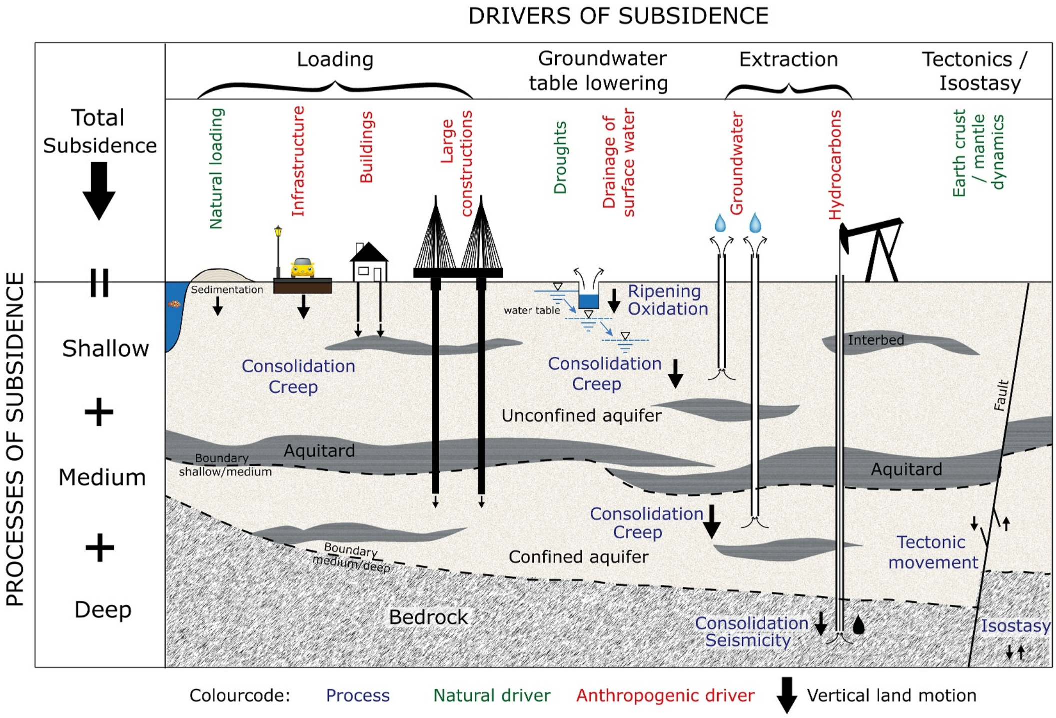

Figure 1. Natural and anthropogenic drivers and corresponding vertical land motion processes causing land subsidence within different depth domains in the subsurface. Depending on which objects at the land surface reflect the satellite signal, Interferometric Synthetic Aperture Radar provides an estimate of a part or the full subsidence signal (modified after P. S. J. Minderhoud et al. (2015) and P. S. J. Minderhoud (2019) CC BY 3.0).

urban areas, enhanced coastal subsidence is increasingly observed, affecting entire coastal plains and river deltas beyond city borders. For example, in Europe, this is witnessed in the Po River plain, Italy (Tosi et al., 2016) and large parts of the coastal zone of the Netherlands (Koster et al., 2018), where coastal subsidence rates exceed rates of SLR, similar to sinking deltas elsewhere like the Mississippi (Jankowski et al., 2017) and the Mekong (Dörr et al., 2024; Erban et al., 2014; P. S. J. Minderhoud et al., 2017) deltas. Also, in these larger coastal-deltaic regions, a similar trend is visible in the sinking magnitudes, where in Europe these are in the order of mm/yr up to a cm/yr, in East Asia deltas for example, these can be in the order of multiple cm/yr up to a dm/yr (e.g., 5–6 cm/yr in the Mekong Delta, Vietnam (Dörr et al., 2024; P. S. J. Minderhoud, Hlavacova, et al., 2020) and >11 cm/yr in the Pampanga delta, Philippines (Sulapas et al., 2024).

3. Drivers, Processes, and Spatiotemporal Variability of Coastal Subsidence

To explain the vast differences of sinking rates in coastal cities and deltaic areas around the world, one needs to assess the various processes underlying land subsidence. The observed VLM is the superimposition of the effects from a myriad of processes in the Earth's subsurface (Figure 1). Such processes occur at different spatiotemporal scales and depths, comprising multi-kilometer, deep-rooted tectonics, and isostasy to shallow compaction of recently deposited silts and clays occurring in the top decimeters in a deltaic floodplain. They can be of natural origin but can also be enhanced or newly created by human land use or resource exploitation. For example, shallow compaction rates can increase following urbanization loading or drainage, leading to decreasing surface water tables, while extraction of groundwater and hydrocarbons may instigate respectively aquifer-system and reservoir compaction. Each land subsidence process has unique spatial (the extent to which a process's effect is detectable) and temporal (magnitude of rates, non-linearity over time, duration, lag time between driver and process) characteristics. Some movements, for example, interseismic strain accumulation or isostatic movements, may produce low, near-constant vertical movements (sub-mm/yr) but for long durations of time (tens of thousands of years), while others, especially when governed by human-induced processes, may create fast and highly non-linear movements. For example, aquifer system compaction caused by groundwater over-extraction may go from negligible to rates of a dm/yr, eventually returning to almost zero over several decades (as happened, for

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example, in Tokyo and Bangkok). The complex VLM patterns are mainly observed in densely populated coastal settings with unconsolidated sediments, for example, cities in river deltas and alluvial plains. Here, the diversity of subsurface processes in depth, space, and time is the largest, making unentangling individual drivers and interpreting observed subsidence particularly challenging and requiring a site-specific understanding of local subsurface composition and natural and human drivers (e.g., Candela & Koster, 2022; Shirzaei et al., 2021; Tosi et al., 2009).

At a global scale, the majority of the coastal land subsidence occurring in coastal cities and entire river deltas is attributed to the over-extraction of groundwater (Bagheri-Gavkosh et al., 2021; Herrera-García et al., 2021; P. S. J. Minderhoud, Middelkoop, et al., 2020; Pedretti et al., 2024), which is also the dominant cause underlying the rapidly sinking cities in China (Ao et al., 2024) and Indonesia (Chaussard et al., 2013). In contrast, Thiéblemont et al. (2024) found that the dominant factor governing coastal VLM in European flood-prone cities is the GIA effect rather than human-induced subsidence. They also highlight several notable subsidence hotspots where contemporary VLM rates are considerably higher than the European average. The higher VLM rates in these places are, indeed, driven by human activities, such as in the Netherlands (subsidence driven by drainage-induced peat oxidation (Erkens et al., 2016)) and gas exploitation-driven reservoir compaction (Van Thienen-Visser & Fokker, 2017) and Po river plain in Northern Italy (subsidence driven by surface loading, drainage-induced peat oxidation and compaction, groundwater pumping (Tosi et al., 2016)). Although the VLM rates for these hotspots (between −5 and −10 mm/yr and in some spots <−10 mm/yr) are well above the average VLM (−1 mm/yr), and surpass the local contemporary rates of climate-induced SLR, they are nonetheless overshadowed by the staggering subsidence rates, primarily attributed to groundwater extraction, observed in sinking cities and rivers deltas elsewhere in the world (Bagheri-Gavkosh et al., 2021; Gambolati & Teatini, 2015).

The relatively lower rates of human-induced land subsidence in European coastal cities can be attributed to various factors, including biophysical and environmental characteristics (e.g., geological composition, hydrological setting, climate, freshwater availability and groundwater dependency, etc.) and socio-economical conditions (e.g., development state, wealth, culture, tradition, etc.). This disparity between coastal cities across different continents highlights the need for future research into the underlying causes, focusing on equitable solutions that address environmental and socioeconomic factors. Understanding these differences can offer valuable insights into how coastal cities and deltas can be managed and developed in ways that prevent further coastal subsidence, particularly in marginalized communities that are disproportionately impacted. Such research can help ensure that adaptation strategies promote environmental justice and protect vulnerable populations from the worsening effects of subsidence and SLR.

4. Importance of InSAR-Data Calibration

Besides providing a first continent-scale quantification of coastal subsidence rates, Thiéblemont et al. (2024) also address the fundamental issue of proper referencing InSAR-based VLM data to a unified reference frame. The geodetic reference frame used in EGMS influences the VLM estimates. They write that "*the geodetic reference frame used to calibrate EGMS strongly influences coastal vertical land velocity estimates at the millimeter per year level and this needs to be considered with caution*." After adjusting EGMS vertical velocities to the more accurate International Terrestrial Reference Frame (ITRF2014), the study provides a clearer picture of subsidence across Europe. This underscores the need to critically evaluate the reference frame of satellite observations for the purpose that it is being employed. Biases or inaccuracies of underlying geodetic reference frames may significantly influence the results, especially when VLM rates are in the same order of magnitude (mm scale). In fact, this calls for rigorous processing throughout the whole data chain, encompassing initial data retrieval by satellites, interferometric processing of satellite images (e.g., removal of atmospheric noise, phase unwrapping, etc.), estimation of VLM and, in a follow-up step, connect coastal subsidence to sea-level change to assess *relative* SLR. As the processing, post-processing and correct interpretation of InSAR data requires high levels of expert knowledge across several disciplines, from remote sensing and space geodesy to several Earth sciences fields, omission or errors easily creep into a workflow. One such issue is highlighted by Thiéblemont et al. (2024) on geodetic referencing when using the EGMS data, previously also underscored by Wöppelmann and Marcos (2016).

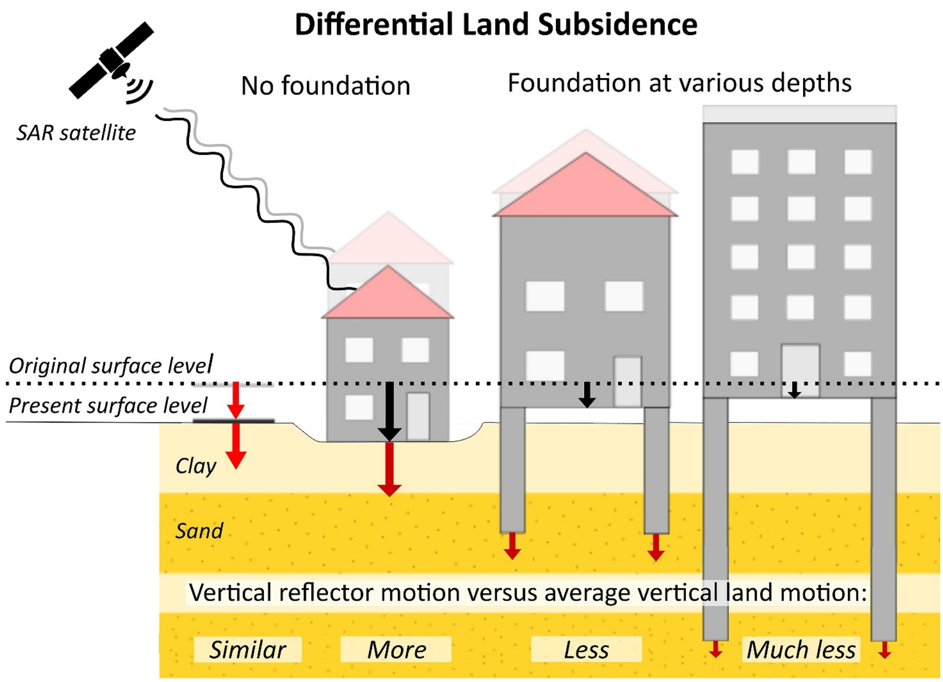

Figure 2. Differential land subsidence in a build-up environmental. Interferometric Synthetic Aperture Radar (InSAR)-observed reflector motion may not represent average vertical land motion (VLM) or land subsidence. These implications should be considered when using InSAR data to (a) determine VLM and (b) create spatio-temporal aggregation (i.e., averaging signal in time and space) to properly create relative sea-level change assessments (modified after P. S. J. Minderhoud, Hlavacona, et al. (2020) and de Wit et al. (2021), CC BY 4.0).

5. Call for Rigor—From InSAR Observations to Relative Sea-Level Rise Interpretation

After correctly processing and referencing InSAR-derived VLM, the interpretation of VLM requires careful consideration, which is often overlooked or oversimplified in many current InSAR-based studies. When deriving VLM from the processed InSAR products, relevant questions are: what kind of movement is registered and quantified by InSAR satellites, and how do these relate to the actual VLM of interest? The answer lies in knowing how InSAR works. SAR satellites send radar signals to the Earth and register returning signals as they bounce off our planet's surface back into space. Only objects or surfaces that cause a reflection back to the satellite are registered. Analyzing these returning signals, specifically the changes in the phase of the returning radar wave provides information on the change of the distance between the reflector and the satellite. Quantifying the changes in consecutive satellite passes makes it possible to determine the motion of the scatterers on the Earth's surface with respect to the satellite's position. When observations from different viewing geometries (i.e., from ascending and descending satellite tracks) for a given scatterer are combined, the observed motions can be split into horizontal and vertical directions, and InSAR-based vertical motion can be obtained for individual reflectors or as aggregate for a larger area (in case of the EGMS data the pixel resolution is 100×100 m). One fundamental aspect to realize is that InSAR-based data on vertical motion, although often directly labeled as VLM, actually provide information on the vertical movement of *scatterers* and/or *reflecting surfaces*, which may not always represent the actual vertical movement of the land itself.

Using InSAR-based vertical motion data directly as a measure of VLM is currently a common practice in InSAR studies, assuming that the vertical motion of the reflectors or the aggregate pixels equals the vertical movement of the land surface. This is indeed valid in case the reflectors themselves represent the land surface (e.g., bare rock surface or a pavement), but invalid in case the reflector movement differs from land surface motion (e.g., structure with a piled foundation, prevalent in areas with high subsidence rates like the west of The Netherlands). While the reflecting bare rock surface provides a direct measure of land surface motion, a building in a coastal city or a river delta may experience a different vertical movement as it is founded on deeper, more stable layers than the surface (Figure 2). And this difference can be as high as several cm/yr, for example, revealed by urban differential

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subsidence in different sinking cities in the Mekong Delta (de Wit et al., 2021) and the Netherlands (Koster et al., 2018; Van Asselen et al., 2018; Verberne et al., 2023). As a rule of thumb, the difference between the land surface and reflector movements increases with higher differential settlement between nearby reflectors. When these effects are ignored, for example, while applying spatial averaging to all InSAR motion data, the aggregated result may underestimate (or in specific cases overestimate) the actual vertical motion of interest (Keogh & Törnqvist, 2019). Therefore, the correct consideration and interpretation of InSAR data become especially important when assessing the risk of coastal cities to coastal subsidence and relative SLR. Especially in populous urban centers located in low-elevation, unconsolidated coastal plains and river deltas, which are the global hotspots of coastal subsidence, the proper interpretation of InSAR products is challenging as spatial average or median rates of InSAR-based data may not resemble the actual VLM taking place.

The recent advancements in open science have significantly increased the availability of InSAR-based data and processing algorithms, creating an unprecedented opportunity for researchers to access, analyze, and innovate in this field. However, this easy-to-access specialized data and algorithms also come with risks, as unsupervised use by non-experts may create results containing processing errors and/or biases. Additionally, disciplinary researchers sometimes use InSAR-derived VLM, (a) assuming it always provides an estimate of total VLM, (b) directly linking it to sea-level change without consideration of reference frame issues, and (c) linearly extrapolating its rates throughout the 21st century to obtain estimates of future relative SLR. These often unintentional oversimplifications in post-processing, interpretation, and application can introduce unknown and unquantified uncertainties, thereby limiting the overall utility and reliability of VLM data sets.

Another potential risk emerges in the downstream application of InSAR-derived VLM data sets by non-specialist researchers, such as those who use these data sets to train machine-learning algorithms or AI models for upscaling or projecting VLM trends (e.g., Davydzenka et al., 2024). This can result in the propagation of inaccuracies or errors in an unknown, unquantified, and often opaque "black-box" manner, undermining the reliability of subsequent analyses or predictions. As such, as a scientific community, we must ensure that designing a transparent, robust, and collaborative open science framework for democratizing access to InSAR-based VLM products balances openness with rigorous quality control, transparency, and accountability (Spellman et al., 2017; Vicente-saez & Martinez-fuentes, 2018). To this end, we propose an open science framework to comprise (a) Data quality and curation standards, (b) Transparent documentation of methods and assumptions, (c) Clear guidelines for ethical use and attribution, (d) Uncertainty quantification and transparent reporting, (e) Access and licensing, (f) User training and community education, (g) Robust infrastructure for collaboration, (h) Transparency and accountability mechanisms, and (i) Incentives and recognition for open science.

With the massive increase in SAR data volume (e.g., from Sentinel-1 and upcoming NiSAR satellites), the number of InSAR studies, and public data platforms like the EGMS,it is important to ensure accurate and transparent data interpretation to maintain the integrity of future research and its outcomes. To overcome these issues in the future, our scientific practices need to evolve in a similar way as sea-level science transformed in their use of tide gauge records. Similar to how tide gauge measurements may not directly reflect the sea-level change, and the time series may need correction for other factors (e.g., VLM effects, Raucoules et al., 2013), InSAR-based products should be scrutinized likewise to arrive at a correct interpretation of VLM, especially when assessing coastal cities in river deltas or alluvial plains. In response to the recent widespread availability of InSAR-based products through services like the EGMS, the scientific community now faces the critical challenge of establishing reproducible and standardized (post-)processing workflows for which the intermediate steps and assumptions are properly accounted. This requires cross-disciplinary collaboration and knowledge exchange, championed for new global initiatives like the International Panel on Land Subsidence (www.IPLSubsidence.org) (P. Minderhoud et al., 2024). Only through these rigorous standardization efforts we can achieve reliable integrated products on VLM and coastal subsidence. Such achievements will enable the crucial next step of integrating coastal VLM and climate-induced SLR, advancing toward the much-needed accurate quantifications and projections of relative SLR, informing governments, and supporting the development of effective coastal adaptation and mitigation strategies.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

10.1029/2024EF005539

Data Availability Statement

Data were not used, nor created for this research.

Acknowledgments
We thank Törbjörn Törnqvist for proof-reading and constructive comments that helped improve this manuscript. Luuk Minderhoud was thanked for providing meaningful distractions to the lead author during the preparation of this manuscript. PSJM is supported by the Dutch Science Foundation (NWO) under the NWO Veni TTW 2022 (Applied and Technical Sciences) call with the project: "Drowning Deltas—Why deltas sink and what to do about it" (nr: 20231). A fund from the US Department of Defense supports MS's contribution.

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