Reviewer 1 Comments (27th August 2025)

Review of "Land subsidence dynamics and their interplay with spatial and temporal land-use transitions in the Douala coastland, Cameroon."

General comments:

The paper presents original research on land subsidence in a rapidly growing coastal region. This work is important as the paper notes, because "there have been no specific studies on land subsidence mechanisms for the coast of Cameroon, leaving it uncharted". The paper is generally well written. I am particularly interested by the analysis of how subsidence rates change following urbanization. However, I have concerns about how the InSAR analysis was performed, especially considering that it is the primary source of data supporting the authors' analysis and conclusions. The section describing the InSAR analysis is severely lacking detail and contains a number of erroneous statements. This casts doubt over the entire subsequent analysis and conclusion. In addition, I have some suggestions for how the data are presented, because they are not easily interpreted in their current form.

Specific comments (major):

1. No time series analysis or accompanying coherence matrices were provided in the either the article or the supplementary material. I find this rather problematic, as the entire premise of the paper revolves around analysing that data correctly. Particularly with regard to the non-urban to urban transition zones, it is very likely that no coherent interferometric combinations exist for these pixels which cross the transition to urban. The authors should show the coherence matrix for such a region. It is probable that two separate subsidence rates would need to be estimated, one preceding urbanization and one after.

Response: We thank the reviewer for their comment. To clarify, our study does not analyse simultaneous land-use change and land-subsidence dynamics. Instead, we investigated the correlation between past (1992–2015) to recent (2017–2022) land-use transitions and the contemporary subsidence rates observed during 2018–2023. Our hypothesis is that current subsidence rates and patterns can be related, at least partially, to antecedent land-use changes. As summarized in Table 6, all but one of the transition paths are built-up areas after 2017, confirming that the pixels included in the analysis correspond to coherent scatterers throughout the monitoring period. To further strengthen our study, we have added displacement time series for all land-use change classes listed in Table 6. In addition, a mean coherence map and representative coherence time series for interferometric pairs from urban, peri-urban, and discarded pixels are now provided in Supplementary Figures S4a, S4b and S4c.

2. Lines 138--139: "To improve the signal-to-noise ratio of the interferometric phase, a multi-looking factor was used to create a pixel dimension of approximately 75 m in the range and azimuth directions". A 75x75 m2 multilooking is approximately 55 pixels, which for S1 IW mode means approx. 35 looks/independent samples. Why was this number chosen? For DS regions 35 looks is likely insufficient to suppress noise, and for PS regions a 75x75m2 pixel is far too large for such a mixed environment.

Response: We thank the reviewer for raising this important point. The choice of ~75 m ground pixel spacing results from a multilooking factor of 32 (range) by 6 (azimuth), providing approximately 192 independent looks. This spatial averaging is widely employed in regional and localized InSAR studies utilizing Sentinel-1 IW time-series, with similar or larger pixel sizes used in comparable urban subsidence studies (e.g., Cigna & Tapete, 2021: Mexico City, ~75 m; Ohenhen et al., 2023: US East Coast, ~50 m; European Ground Motion Service, ~100 m; Payne et al., 2025: Iran, ~100 m). Additionally, we note that >80% of the InSAR pixels in our study fall within built-up environments during the 2018–2023 observation period, indicating that our study area is predominantly urbanized and characterized rather than a mixed environment (note the transition pixels discussed above). The 75 m resolution provides an appropriate balance between noise suppression and spatial detail for capturing subsidence patterns in this urban-dominated setting, while maintaining sufficient coherence for reliable time-series analysis. A summary of this reasoning has been added in the revised ms (lines …)

3. Lines 143--145: "To this end, the so-called noisy pixels with coherence less than 0.65 (for distributed scatterers) and amplitude dispersion more than 0.3 (for permanent scatterers) were discarded following Lee and Shirzaei (2023)."

a) Coherence is a time-varying quantity and depends on the combination of images used to form an interferogram. The text seems to imply that each pixel can be assigned a single static value of coherence. How was this implemented? And if it is per interferogram, how do you ensure a continuous time series of coherent phases?

b) 0.65 is a very high threshold for DS pixels in agricultural or urbanizing regions. I find it hard to believe that more than only a few pixels would pass this threshold spanning the entire archive of imagery used in this study.

c) The article makes no mention of a pixel-based PS algorithm being used, however the use of amplitude dispersion as a quality metric seems to imply a PS methodology. What is actually being done with these pixels? If a PS algorithm is used in combination with the DS, how are the two analyses integrated?

Response: We thank the reviewer for their comment. We have revised the Methods section (Lines 137–154) to clarify that our analysis implemented a SBAS-type framework following Lee and Shirzaei [2023], which applies a statistical procedure to identify and retain only stable pixels. In this framework, permanent scatterers (PS) were identified using an amplitude dispersion index <0.3, while distributed scatterers (DS) were evaluated using temporal mean coherence across the interferogram stack. DS pixels with

average coherence >0.65 and low coherence variance were retained and assigned to Voronoi cells around adjacent PS pixels. A Fisher's F-test then evaluated amplitude similarity between DS and PS within each cell. DS pixels passing this statistical test were reclassified as stable distributed scatterers, ensuring the final dataset comprised only reliable scatterers for time-series analysis (see Lee and Shirzaei, 2023 for additional details). Supplementary Figures S4a and S4c provide coherence maps and time series demonstrating the temporal stability of our selected pixels.

4. Lines 147--148: “A 2D phase-unwrapping algorithm was used to examine the complex interferometric phase noises and identify elite pixels (i.e., pixels with an average coherence greater than 0.7) (Shirzaei, 2013).” This is a very problematic statement. PU algorithms attempt to estimate relative ambiguity levels in adjacent pixels by applying spatial continuity constraints. They do not “examine noise”. The description provided in the reference is about low-pass filtering interferograms based on the values of some identified high-quality pixels (called “elite pixels”). This is not a standard approach, and the authors risk removing high frequency parts of the signal of interest by doing so. This is likely only going to be effective at finding slowly varying, deep-seated subsidence drivers, which is not the focus of this paper. I recommend that the authors discard this method in favour of approaches accepted by the community in general such as SqueeSAR (Ferretti 2011) or similar. If the authors insist on this method, they must at least provide strong justification for doing so.

Response: We thank the reviewer for this comment and for pointing out the need for clarification. We agree that our original description was misleading. In the revised manuscript (Lines 156–158), we now state: *“A 2D minimum cost flow phase unwrapping algorithm was applied to estimate absolute phase changes in each interferogram, using a sparse set of elite pixels selected as described above (Costantini, 1998; Costantini & Rosen, 1999).”* Thus, we do not use phase unwrapping to “examine noise,” but rather to unwrap interferometric phases on a network constrained by statistically selected elite pixels. The WabInSAR algorithm employed in this study has been validated in multiple studies for producing spatially continuous deformation time series in both urban and peri-urban settings.

5. Line 151--152: “….using a local reference point (longitude: 9.61, latitude: 4.22) located 20 km outside the study area” Why was this point chosen? How was the atmospheric phase correctly removed if the reference point was not part of the analysis?

Response: We thank the reviewer for their comments. We have revised the manuscript (Lines 160–164) to clarify the choice of reference point as a stable point outside the city. The reference point, while outside the urban center, remains within the same SAR scene coverage and experiences the same atmospheric corrections as the study area. The final deformation maps presented in the manuscript were subsequently trimmed using a polygon corresponding to the urban extent of Douala. We now show the location of the reference point in Figure 3.

6. Line 166: “Given $\{LOSA, LOSD\}$ and $\{\sigma A\text{^}2, \sigma D\text{^}2\}$ are the LOS displacement and variances for a given pixel” How are these variances obtained?

Response: We thank the reviewer for their comments. We have revised the manuscript (Lines 160–164) to clarify that the LOS velocity is obtained as the slope of the reweighted least-squares fit to the time series, and the associated variance is derived from the uncertainty of this regression slope.

7. Table 6: The extreme values reported in this table need to be checked. In particular, the cropland and wetland areas are prone to temporal decorrelation and phase unwrapping errors, which often results in overestimated subsidence rates (see Morishita and Hanssen 2015, Tampuu 2022). InSAR analysis often fails in regions like these and the authors need to take the dynamics of the region they are monitoring into account. Again, an analysis of the coherence matrices in these areas would be very beneficial.

Response: We thank the reviewer for their comments. The values reported in Table 6 correspond to the minimum, mean and maximum values of land subsidence in each of the following corresponding land-use change classes. Over the period covered by the InSAR images the areas consistently remained urbanized (see the 2017 and 2022 columns), with no issue in terms of temporal decorrelation. The land-use changes are not referred to the simultaneous changes of land use and land subsidence but correspond to the past and present change of land use within a specific area and how these changes correlate the current observed land subsidence value. Time series data for these changes are equally updated in the supplementary materials (Fig.S4a, b, c and d).

8. Line 370: The discussion on groundwater extraction is lacking. Are we talking about deep or shallow aquifers, and how does the urban data support the conclusion? "The land subsidence rates decreased with an increase in building height, suggesting the potential influence of foundation type on land subsidence" -- that is highly doubtful. More likely, deeply founded buildings are less prone to subsidence caused by draining the phreatic groundwater. i.e. we can't see the subsidence happening on the surface at those locations. This would suggest that the city is not obtaining water from a deep aquifer. Is that the case? Again, the lack of a real PS processing methodology casts doubt over the entire conclusion.

Response: We thank the reviewer for their comments. In the literature, we recalled that groundwater is one the main causes of land subsidence in numerous cities around the world including cities like Jakarta, Shanghai and Mexico. However, our objectives in this study were centred on understanding if a correlation exists between land subsidence measured over the period 2018-2023 and when the coastland was transformed from non-urban to urban zone over the past 3 decades. Also, the type of constructions has been investigated, and we agree with this reviewer about the fact that "deeply founded buildings are less prone to subsidence caused by draining the phreatic groundwater. i.e. we can't see the subsidence happening on the surface at those locations.**". Our original sentence has been rephrased to make clearer this concept. By the way, we agree with a previous reviewer comment that, the possibility to distinguish between the displacement of tall and low buildings would be better captured using a PS-based interferometric processing chain. The InSAR data used here provides first insights and indications, however they carry**

additional uncertainties due to the processing chain which provides a spatial smoothed signal. This limitation of our study has been highlighted in the Discussion (lines 440-446). We recognised the fact that groundwater pumping could be a factor significantly contributing to land subsidence especially because Douala is rapidly growing coastal city where more groundwater is needed for population and industrial needed. Unfortunately, information about groundwater pumping rates, drainage, recharge, and pressure evolution in the shallow and deep aquifer system is very limited in Douala. Therefore, it cannot be addressed in the present analysis. We have highlighted more strongly this important gap in the Discussion. Data completely lack or are not made available from governmental institutions and private companies. This challenge is not limited to the study area but extend to the whole region of sub-Saharan Africa, as recently highlighted by Avornyo et al., 2023 and Ikuemonisan et al., 2023. The need of establishing, using, and maintaining in-situ monitoring networks have been highlighted too (lines 449-458). Remote sensing quantification, e.g., through GRACE, cannot outpace the complete gap occurring nowadays.

9. Regarding the comparisons between LULC classes. The authors should include time series data, in order to demonstrate the differing dynamics of these types of regions, ideally at least one from each of the identified classes.

Response: We thank the reviewer for their comments. We have included the average InSAR time series plots for each land-use changes category as illustrated in the supplementary, Fig. S5.

Specific comments (minor):

1. Why are orbital and topographic phases removed after unwrapping? This should be done beforehand to reduce variability in the phases.

Response: We thank the reviewer for this observation. Our analysis follows the WabInSAR (Wavelet-based InSAR) framework, in which residual orbital ramps, DEM-related errors, and the topography-correlated component of atmospheric delay are corrected after unwrapping in the wavelet domain. All relevant studies and the corresponding methodological validation are cited in the methods section.

2. I find Table 6 very hard to interpret, and it is arguably the main result of the paper. It should be presented in a graphical way, preferably geographically. This would allow the reader to comprehend the scale of change over the region and study period.

Response: We thank the reviewer for this comment. Figure 9 was included to ease understanding of Table 6 by illustrating the boxplot of each category of land-use changes between 1992-2022, and their corresponding mean and median values. A geographical representation cannot be done without using 56 subpanels (14 trajectories x 4-time intervals), which resulted too large

3. I think the LULC figures and tables waste a lot of real estate in the paper. I suggest to keep one of them, and put the rest into supplementary. Put the InSAR results into the paper, as they are what the authors derive their conclusions from.

Response: We thank the reviewer for the comments. As InSAR is only one of the main "ingredients" of our contribution (which is not specifically focused on monitoring land subsidence using InSAR), we prefer to maintain LULC representation in the main text. However, to follow this reviewer's suggestion at least in part, we have included more information on InSAR such as coherence maps and behavior versus time, Line of Sight (LOS) displacement, and time series in the supplementary materials.

4. Figure 8: please provide a date corresponding to these maps. It would perhaps be more interesting to show how the urbanization has changed over the course of the study period.

Response: We thank the reviewer for this observation. Figure 8 refers to 2020 as provided in the figure caption. We have updated Table 6 by including the time period of the InSAR analysis into the table. We have equally included annual land use maps of the Douala coastland and urban city for the corresponding land subsidence time period (2018-2023).