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Is land subsidence increasing the exposure to sea level rise in Alexandria, Egypt?

Guy Wöppelmann,[1] Gonéri Le Cozannet,[2] Marcello de Michele,[2] Daniel Raucoules,[2] Anny Cazenave,[3] Manuel Garcin,[2] Susan Hanson,[4] Marta Marcos,[5] and Alvaro Santamaría-Gómez[1,6]

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[1] Delta margins are subject to relatively high rates of land subsidence and have the potential to significantly exacerbate future changes in sea levels predicted by global warming models used in impact studies. Through a combined analysis of GPS and persistent scatterer interferometry data, we determine that most of the coastline of Alexandria has been subject to moderate land subsidence over the past decade (0.4 mm/yr on average and up to 2 mm/yr locally). This contrasts to previous studies that suggested subsidence in excess of 3 mm/yr. Based on our findings, we infer that on multi-century to millennia timescales, land subsidence in the area of Alexandria is dominated by tectonic setting and earthquakes or gravitational collapse episodes of a growth fault, whereas on shorter interseismic decadal to century timescales, subsidence rates are likely steady and moderate, in agreement with natural compaction and dewatering of the observed Holocene sediment layer. **Citation:** Wöppelmann, G., G. Le Cozannet, M. de Michele, D. Raucoules, A. Cazenave, M. Garcin, S. Hanson, M. Marcos, and A. Santamaría-Gómez (2013), Is land subsidence increasing the exposure to sea level rise in Alexandria, Egypt?, *Geophys. Res. Lett.*, *40*, 2953–2957, doi:10.1002/grl.50568.

1. Introduction

[2] The primary source of sea level change data over multi-decadal to century timescales is tide gauge records, some of which date back to the early eighteenth century [e.g., *Wöppelmann et al.*, 2008]. A critical issue in using this data source to estimate the climate-related contributions to sea level change is the correction of vertical land motion signals in tide gauge records, whichever subset of records is used or data analysis strategy devised. In particular, the virtually identical rates of 1.7–1.8 mm/yr global mean sea level rise estimated from tide gauge records over the past 100 years or so, using either averaging techniques of individual linear trends [e.g., *Douglas*, 1991] or advanced statistical methods of global sea level reconstructions based on the spatial variability observed in satellite altimetry data [e.g., *Church and White*, 2011], are based solely on vertical land movement associated with glacial isostatic adjustment (GIA). Regardless of the accuracy of GIA models, other geophysical processes can cause vertical displacements on the coast. For instance, delta regions are prone to subsidence processes, often attributed to sediment compaction and removal of underground water or hydrocarbons [*Ericson et al.*, 2006].

[3] The use of continuous Global Positioning System (GPS) offers an alternate approach to measuring vertical displacements at tide gauges, whatever their geophysical origin [*Blewitt et al.*, 2010]. Nonetheless, despite the first promising results obtained from global GPS data reanalysis [*Wöppelmann et al.*, 2009], the long-term sea level application is demanding in terms of metrology; vertical GPS velocities at tide gauges need to be determined with greater accuracy than the climate-related signals of about 2 mm/yr sea level rise. In addition, two working hypotheses are necessary when using GPS data to correct vertical land movements in sea level records. The first hypothesis requires that the linear vertical land movement estimated from the GPS data is consistent over the multi-decadal to century timescale of the tide gauge operation. The second requires that the land motion detected by the GPS antenna is consistent with that affecting the tide gauge at the level of a few tenths of a millimeter per year, or that their local differential motion is monitored to that level of accuracy.

[4] The second hypothesis constitutes a major issue in the use of GPS velocities for studies of long-term sea level trends. Less than 14% of the tide gauge stations from the global sea level observing (GLOSS) program are equipped with a GPS station installed directly on top of the tide gauge [*Santamaría-Gómez et al.*, 2012]. This situation places severe demands on the measurement of the connection between the GPS antenna and the tide gauge at an accuracy of less than 0.5 mm/yr. This level of accuracy is challenging even for the highest-precision spirit leveling over distances of up to several kilometers. The most likely alternate means to address this challenge in the future is likely to be the emerging space-borne techniques of Interferometric Synthetic Aperture Radar (InSAR). Remarkable progress in the quality of the InSAR results has been obtained with the persistent scatterer interferometry (PSI) technique [*Ferretti et al.*, 2001]; for instance, relative velocity uncertainties of the order of 1 mm/yr have been reported [*Brooks et al.*, 2007]. Interestingly, whereas the GPS provides a geocentric point-wise measurement, InSAR techniques provide ground surface relative velocity estimates with a dense spatial resolution [e.g., *Raucoules et al.*, 2008].

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[1]LIENSs, Université de La Rochelle—CNRS, La Rochelle, France.
[2]BRGM, Orléans, France.
[3]LEGOS, Toulouse, France.
[4]Faculty of Engineering and the Environment, University of Southampton, Southampton, England, UK.
[5]IMEDEA (CSIC—UIB), Esporles, Spain.
[6]IGN, Observatorio de Yebes, Guadalajara, Spain.

Corresponding author: G. Wöppelmann, LIENSs, Université de La Rochelle - CNRS, 2 rue Olympe de Gouges, FR-17000 La Rochelle, France. (gwoppelm@univ-lr.fr)

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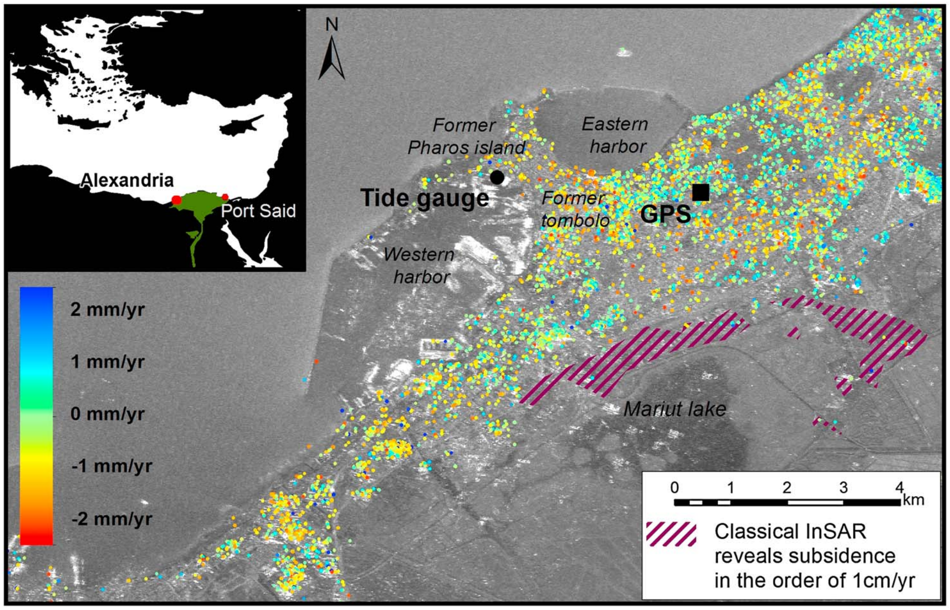

Figure 1. Study area of Alexandria (Egypt) showing the tide gauge (circle) and the continuous GPS station from the CEAlex (square) used in our analysis. Linear line of sight velocities over the period 2002–2010 from the PSI results are given with respect to the GPS station. Positive velocities indicate site uplift, whereas negative velocities indicate subsidence.

[5] In this study, the potential of the PSI technique is explored to assess whether the 3 km distant continuous GPS station and the main tide gauge in Alexandria can be considered stable within the 0.5 mm/yr precision required by the long-term sea level application. The reliability of the PSI velocities is appraised against independent space geodetic techniques using the most recent results from the available continuous GPS data [*Santamaría-Gómez et al*., 2012] and the advanced method of combining tide gauge and satellite altimetry data [*Kuo et al*., 2004; *Wöppelmann and Marcos*, 2012]. The resulting calibrated and spatially dense vertical velocity field in the coastal region of Alexandria is then used to assess the importance of land subsidence, which is suspected to exacerbate the exposure of population and assets to future sea level related hazards [*Hanson et al*., 2011]. The most likely causes of subsidence are investigated, and their relative importance discussed.

2. Data and Methods

[6] We used 49 SAR descending scenes acquired by the Envisat satellite from 2003 to 2010 and processed them by means of two complementary InSAR methods, both implemented in the Gamma software. On the one hand, we applied an advanced version of the approach based on interferogram stacking [e.g., *Le Mouelic et al*., 2005] to detect and map linear ground deformations in a range of a few centimeters per year. On the other hand, we relied on PSI [e.g., *Ferretti et al*., 2001] to estimate slower and quasilinear deformations. The principle of the method is to select resolution cells containing target objects with radiometric properties which are stable over time and to estimate iteratively the different components (displacement, height, and atmospheric phase screen) of their phase evolution. As a result, persistent scatterer (PS) deformations are measured with respect to an arbitrary location, which was chosen in this study close to the continuous GPS station from the Centre d'Etudes Alexandrines (CEAlex). Finally, considering the sub-millimeter per year precision required for our application, we selected a high threshold of temporal amplitude stability (ratio between the temporal mean and its standard deviation, for a given pixel) to retain only the most reliable PS.

3. Results

[7] The results obtained from the InSAR analysis over the period 2003–2010 are presented in Figure 1. The interferogram stacking reveals that the areas located around the shallow waters of the Mariut Lake are affected by a subsidence of about 1 cm/yr. By contrast, the other areas of the city center appear stable or are slightly subsiding. Indeed, the PSI results highlight ground movement of the order of 1 mm/yr, in particular at the former sandy tombolo which connects the palaeo-island of Pharos to the continent and today constitutes a heavily urbanized peninsula [*Marriner et al*., 2008]. The mean ground motion for all the PS represented in Figure 1 is −0.39 mm/yr (median: −0.37 mm/yr) with respect to the continuous GPS station, and the standard deviation is 1.05 mm/yr; 78% of the PS velocities are comprised within one standard deviation. The uncertainty of the PS velocities was estimated at 0.7 mm/yr by considering the standard deviation of the velocities in homogeneous areas (see supporting information).

[8] The vertical velocity of the continuous GPS station from the Centre d'Etudes Alexandrines was estimated to be 0.05 ± 0.29 mm/yr with respect to the global international terrestrial reference frame [*Santamaría-Gómez et al*., 2012]. The GPS vertical velocity showed no significant land movement over the observation period 2001–2008, hence validating the choice of the nearest point scatterer as a reference for the PSI analysis. The GPS velocity uncertainty takes into account the temporal correlation in the weekly position time series using a power law plus variable white noise model. In Figure 2a, the weekly GPS position time series are projected into the InSAR satellite line of sight and overlain with that of the nearest PS, highlighting their consistency.

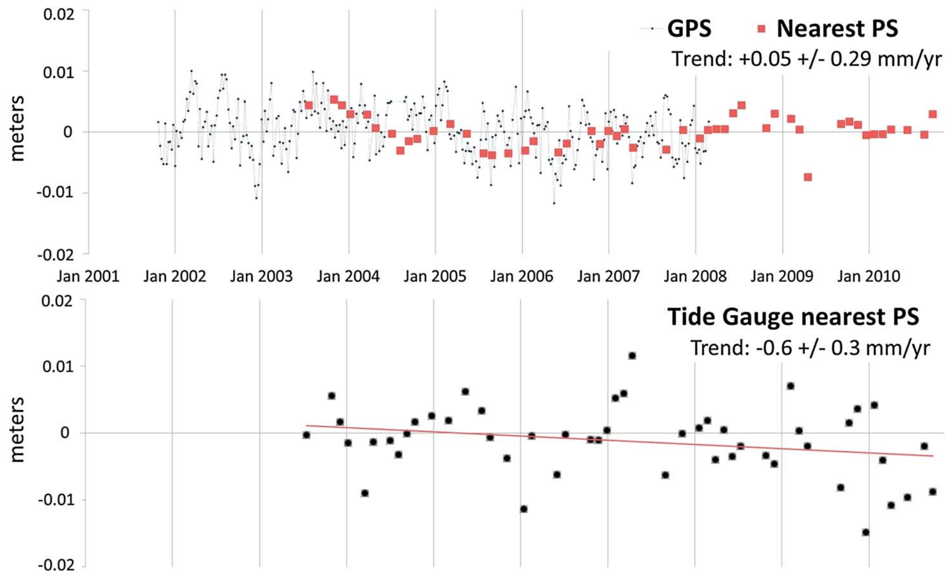

Figure 2. PSI and GPS time series projected along the satellite line of sight with (a) the persistent scatterer nearest to the continuous GPS antenna and (b) the persistent scatterer nearest to the tide gauge. The red line shows the best linear fit.

[9] Our PSI results indicate a subsidence of 0.6 ± 0.3 mm/yr at the nearest persistent scatterer to the tide gauge (Figure 2b). The regression analysis was performed robustly by taking into account the temporal correlation in the PSI time series. The resulting subsidence uncertainty was confirmed by examining the PSI results within a radius of about 120 m around the tide gauge, in which five point scatterers were found. They show consistent velocities with a similar dispersion (standard deviation) of 0.35 mm/yr. The supporting information further describes the error bar assessment in the PSI velocity estimates. An additional external validation was obtained here from the advanced method of combining tide gauge and satellite altimetry data over the period 1993–2010 [*Wöppelmann and Marcos*, 2012]. From this independent space geodetic approach, a vertical velocity of -0.40 ± 0.23 mm/yr was obtained at the tide gauge in the global international terrestrial reference frame.

4. Considerations and Consequences

[10] Recent studies have indicated that the Nile Delta coast is subject to relatively high rates of subsidence of 4 to 5 mm/yr [*Ericson et al.*, 2006; *Stanley and Toscano*, 2009]. However, the results of our combined GPS and InSAR analyses reveal that most of the Alexandria coastal region can be considered stable or undergoing moderate subsidence, with only a few areas of the coastline experiencing subsidence of up to 2 mm/yr (Figure 1). This finding is supported by the data obtained using the independent space geodetic method, combining satellite radar altimetry and tide gauge data [*Wöppelmann and Marcos*, 2012], at the Alexandria tide gauge (-0.40 ± 0.23 mm/yr), which is in excellent agreement with the PSI result (-0.60 ± 0.35 mm/yr). The high spatial resolution of ground deformation from the PSI results further indicates that the observed low rate of subsidence is not restricted to the immediate tide gauge or GPS locations. How then to reconcile our geodetic findings with the previous results?

[11] First, stratigraphic analyses of numerous radiocarbon-dated sediment cores point to an uneven lowering of the coastal plain due to natural compaction and dewatering of Holocene sediments of varying thicknesses [*Stanley*, 1990]. Hence, the highest subsidence rates of about 5 mm/yr were obtained in the northeastern part of the Nile delta, where Holocene deltaic deposits can attain a thickness of up to 60 m, for example, at the Manzala lagoon or Port Said [*Stanley and Warne*, 1993]. In contrast, Alexandria is positioned at the western margin of the Nile delta on a cemented Pleistocene sandstone ridge covered by a thin layer of Holocene sediments, except in locally specific areas such as the short stretch of the tombolo toward the palaeo-island of Pharos and the former southern wetlands [*Stanley and Toscano*, 2009]. Accordingly, the Alexandria coastal plain is considered to be relatively stable, with estimates of 0 to 0.5 mm/yr land subsidence [*Frihy et al.*, 2010], in good agreement with our findings.

[12] Second, the temporal difference between the values calculated from Holocene radiocarbon-dated sediments and the modern rates based on space geodetic data from the past decade or so. Our findings are in close agreement with Holocene sediment compaction rates, but do not preclude the possibility that other processes occur on longer timescales. Such processes might possibly explain the higher rates of about 4–5 mm/yr subsidence inferred from archeological data in Alexandria by *Stanley and Toscano* [2009]. Interestingly, the earthquake activity in the Nile delta region is considered of moderate magnitude [e.g., *Frihy et al.*, 2010]. To our knowledge, no earthquake of a magnitude higher than 5–6 with significant associated surface displacement has been identified during the past century (only two events of magnitude 5–6). Nonetheless, *Marriner et al.* [2008] indicate that seismic displacement accounted for the submergence of some parts of the ancient city, suggesting that the largest values of about 4–5 mm/yr subsidence reported on millennia timescale for Alexandria are likely due to tectonic activity and abrupt subsidence episodes occurring at intervals of hundreds of years or more rather

than to Holocene sediment compaction and dewatering. In between these major episodes, no substantial land subsidence is affecting Alexandria and the coastal plain westward of Alexandria. Of the other possible processes, groundwater extraction is mostly limited to the southern and central portions of the delta [*Research Institute for Groundwater*, 1992] and can subsequently be discarded here as a significant factor of subsidence. Similarly, GIA can be discarded as its crustal radial effect is estimated to be −0.51 mm/yr [*Tsimplis et al*., 2011].

[13] Finally, the Nile delta margin has been affected by a complex pattern of geophysical processes, which hampers the use of an average rate of land subsidence for the entire delta margin. Subsidence rates of the Alexandria coastal plain are however lower than the rates of 3–10 mm/yr reported at the northeastern part of the Nile delta and other Mediterranean deltas such as the Rhone and Po deltas [*Stanley*, 1997].

[14] The consequences of the reduced subsidence rates determined here for impact studies can clearly be seen in the calculation of exposure to flood events carried out by *Hanson et al*. [2011]. In this global study, uniform subsidence of 50 cm between 2005 and 2070 was used to account for subsidence which might occur due to groundwater extraction, compaction, and lack of sediments. As a result, Alexandria was ranked the eleventh most vulnerable city in terms of population exposure to future coastal flooding. However, our findings reveal a moderate land subsidence of about 20 times lower on average (2.6 cm in 2070) that would not significantly exacerbate sea level rise due to climate change. If the reduced subsidence is used, and assuming no major seismic event prior to 2070, then the population exposed to the 1 in 100 year flood event for Alexandria in 2070 drops by approximately 300,000 and asset exposure by 35 billion USD; these are important considerations for local planning and policy development. Nonetheless, when considering vulnerability, it should be kept in mind that other natural processes have affected Alexandria in the past such as tsunamis [*Shaw et al*., 2008], earthquakes [*Marriner et al*., 2008], and local sediment instability [*Stanley et al*., 2006].

5. Conclusions

[15] In this study, we highlight the importance of evaluating the relative contribution of each process to the estimated rates of vertical land motion, and subsequently to the projected sea level changes, in relation to its characteristic timescale. Based on our combined space geodetic results and the analysis of the geological context as described in the literature, we infer that on multi-century to millennia timescales, land subsidence in the coastal region of Alexandria is primarily dominated by tectonic setting and earthquakes or gravitational collapse episodes of a growth fault, whereas on shorter interseismic decadal to century timescales, subsidence rates are probably steady and moderate, in agreement with sediment thickness and compaction. In addition, the Nile delta coastal plain should definitely not be treated as one unit in terms of land subsidence, in particular due to its general northeast tilting [*Stanley*, 1990].

[16] Our findings also confirm that PSI methods are now mature enough to address the major issue of using GPS data from relatively distant stations for the accurate correction of vertical land movements at tide gauges. Of course, there are limitations such as the availability of sufficient SAR images, which indeed may not be available for island stations. Nonetheless, the new implementation plan of the Global sea level observing system (GLOSS) calls for an important upgrade to its core network of installing continuous GPS stations in the vicinity of the tide gauges [*Intergovernmental Oceanographic Commission*, 2012]. Thus, we recommend that whenever the GPS station is not installed at the very tide gauge, PSI data should be considered both for precisely monitoring the differential land motion between the GPS antenna and the tide gauge areas, and for supplementing high spatial resolution data to properly assess relative sea level changes along the coastal area beyond the point-wise GPS data. Although the resources have been substantially reduced in most agencies and past data are not readily accessible, precise leveling remains a useful method for monitoring local and regional vertical land motions [*Hudnut and Beavan*, 1989], and subsequently to assess PSI results.

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