SINKING CITIES IN INDONESIA: SPACE-GEODETIC EVIDENCE OF THE RATES AND SPATIAL DISTRIBUTION OF LAND SUBSIDENCE

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ABSTRACT

Land subsidence due to groundwater extraction, increased urban development, and natural consolidation of soil is known to occur in several cities of Indonesia. However most of the evidences of ground subsidence rely on point wise campaigns measurements, providing spatially and temporally limited data. Here we present a global D-InSAR survey combined with Small Baseline time series analysis using ALOS data between late 2006 and mid 2009, on the Indonesian islands of Sumatra and Java. We identified 6 major cities undergoing ground subsidence at vertical rates varying from 2 cm/yr to up to 24 cm/yr. In Sumatra we detected subsidence in Lhokseumawe and Medan, and in Java: in Jakarta, Bandung, Semarang and Sidoarjo. In five of these six cities we suggest that ground water extraction and building loads are the main cause of subsidence.

INTRODUCTION

Land subsidence corresponds to a differential lowering of the ground surface relative to the surrounding terrain or sea level. This major hazard has been identified in many metropolitan areas worldwide (Mexico city, Shangai, Tokyo, Venice, etc.). Land subsidence is often creating damages to structures, making its consequences costly. Moreover, when taking place in low-lying areas, it increases the risk of tides and storm surges flooding, and, considering the predicted sea level rise, it becomes an urgent problem.

Relatively slow subsidence can result from natural causes such as natural sediments compaction. More rapid subsidence is typically associated with sediments compaction due to loading, compaction of the aquifer system due to ground water extraction and organic soil drainage [2; 3; 4]. This is often causing a steady but decreasing with time subsidence as compaction limit is reached [5]. Traditional measurements of ground subsidence involve leveling surveys and, more recently, GPS campaigns. Although these methods provide precise measurements, they are spatially and temporally limited.

InSAR has demonstrated its capability for mapping sub-centimeter ground deformation over large-scale areas, on a pixel-by-pixel basis providing millions of measurements in each city [6]. Here we performed a global survey of Sumatra and Java, Indonesia, using differential SAR (D-InSAR) combined with Small Baseline (SB) time series analysis. This technique allows monthly measurements of deformation with precision of a few millimeters over regional scales [7]. We present an inventory of subsiding cities of Indonesia, and reveal the spatial distribution of subsidence within the cities for a continuous period of observation of 2 years.

1. DATA AND METHOD

We used 1500 SAR images from 35 ascending tracks of the ALOS satellite acquired between late 2006 and mid 2009. We performed over 3000 interferograms covering an area of about 500,000 km^2 on the islands of Sumatra and Java. ALOS has a recurrent cycle of 46 days corresponding to an average of 9 acquisitions per track. We removed acquisitions affected by strong atmospheric signal using pairwise logic and confirmed that the atmospheric signal remaining in the time series is small, by looking at the line of sight (LOS) displacements. The time history of LOS displacements and the LOS velocity averaged over the observation period is obtained from a network of interferograms using the Small Baseline (SB) technique [8]. Interferograms with a maximum spatial baseline of 1.5 km were phase-unwrapped, a plane was removed to subtract long wavelength signals (orbital errors, remaining atmospheric noise) and were inverted for the phase with respect to the first acquisition. Temporal coherence of each pixel is computed on the set of interferograms to select only reliable pixels (threshold of 0.7). InSAR-time series provides high spatial resolution, allowing to constrain precisely where the highest rates of subsidence are occurring, and provides continuous temporal coverage for the SAR observation period (Fig. 1).

The main limitation of InSAR using ALOS data lies in the fact that only LOS displacements can be retrieve. Ascending acquisitions contain both vertical and west motion components. Considering the incidence angle of the satellite, the vertical component of the deformation field is higher than the LOS one. Moreover, it has been suggested by GPS surveys in Indonesia that the horizontal component of the

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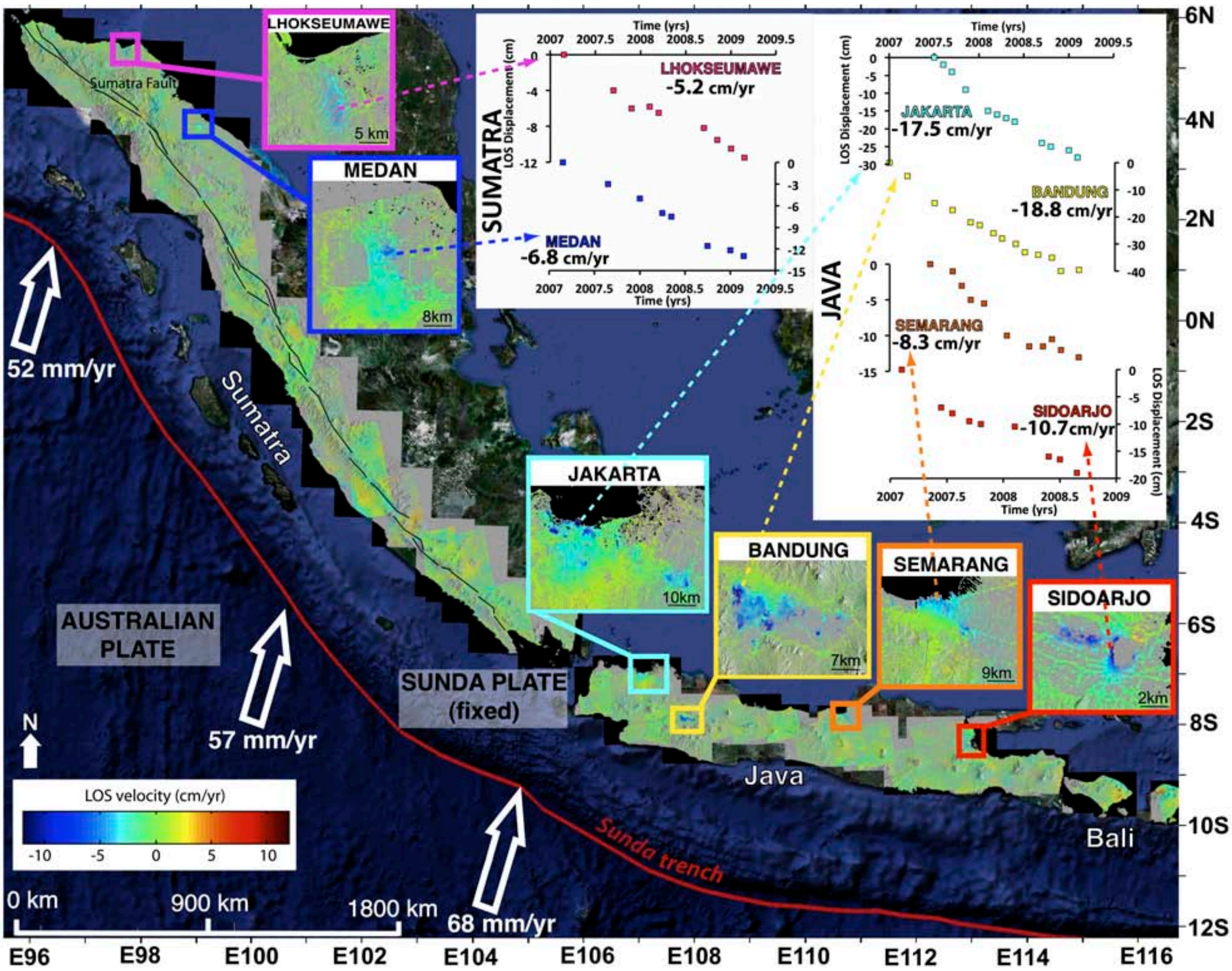

Figure 1: Averaged 2006-2009 LOS velocity map in Sumatra and Java, Indonesia, from ALOS InSAR time series, overlaying Google Earth imagery. Positive LOS velocity (red) represents movement towards the satellite (uplift) whereas negative LOS velocity (blue) represents movement away from the satellite (subsidence). Red line: subduction trench; white arrows: relative plate convergence rates. Insets: zoom on the subsiding cities (color coding kept throughout the paper). Top right: LOS displacement time series in each city for a pixel showing maximum subsidence. The corresponding linear subsidence rates are shown.

deformation is almost null [9]. This observation justifies the approximation that all the deformation observed in the LOS of the satellite occurs vertically. Correcting from the incidence angle of the satellite, 1 cm of LOS displacement corresponds to 1.25 cm of vertical displacement.

In order to identify the causes of ground subsidence, we superimposed time series results on Google Earth imagery to isolate the types of environments presenting the maximum rates of subsidence and evaluate the influence of recently developed areas (using Google Earth historical imagery; Fig. 2 to 7).

2. RESULTS: SUBSIDENCE IN 6 CITIES

We identified 6 major cities undergoing ground subsidence, in Sumatra we observed land subsidence in Lhokseumawe and Medan and in Java we detected subsidence in Jakarta, Bandung, Semarang and Sidoarjo (Fig. 1).

2.1. Lhokseumawe

Lhokseumawe is a city located in North Sumatra, it is the second largest independent city in the Aceh province and has a population of ~189,000 people (Indonesia 2000 census). The biggest LOS displacement observed in Lhokseumawe is 12 cm of subsidence during our observation period corresponding to a linear rate of 5.2 cm/yr (Fig. 1). The mean LOS subsidence observed is 5 cm corresponding to 2.5 cm/yr. If we consider that all the deformation is occurring vertically, the biggest subsidence is 15 cm (6.5 cm/yr). However a polynomial function of the second order gives a significantly better fit to the data than a linear regression (using F-test and AICC), suggesting that the rate of subsidence is decreasing in time (Fig. 2). The subsidence in Lokseumawe is mostly occurring in residential areas surrounding rice fields.

2.2. Medan

Medan is located on northeast coast of Sumatra, it is the capital of the North Sumatra province and the fourth largest city in Indonesia with 2.1 million people. Time series show that the maximum LOS subsidence at Medan is 13 cm, corresponding to a linear rate of 6.8 cm/yr (Fig. 1). The mean LOS subsidence is 5 cm, i.e. 2.5cm/yr. The corresponding maximum vertical subsidence rate is 8.5 cm/yr. Elevated rates of subsidence are located within industrial areas that were built recently (between 2003 and 2009). Polynomial functions of the second order give a significantly better fit to the data than linear regressions for the subsiding areas located in the southeast (Fig. 3). This suggests that the rate of subsidence is decreasing in time.

2.3. Jakarta

Jakarta is the capital and largest city of Indonesia with a population of about 9.5 millions. Jakarta is located on the northwest coast of Java in a alluvial plain. The maximum subsidence in Jakarta is observed on the coast with LOS displacement up to 28 cm during our observation period (Fig. 1). The average LOS subsidence varies spatially from 4 to 5 cm. The maximum LOS linear rate of subsidence reaches 17.5 cm/yr (21.9 cm/yr assuming all the deformation is occurring vertically). However, in some parts of the city with high subsidence rates, polynomial functions of the second order give a significantly better fit to the data than linear regressions (Fig. 4). Fast subsidence in Jakarta is located within 2 areas: near the coast, in industrial, residential and high-rise buildings areas, and in the southeast, on an industrial center.

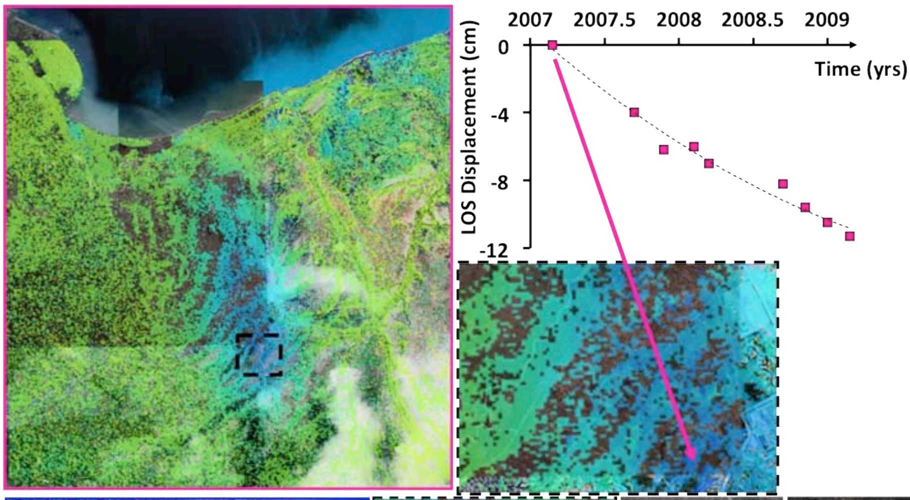

Figure 2: Averaged LOS velocity in Lokseumawe superimposed on Google Earth imagery. The scale is identical to the one displayed on figure 1 (extremes -/+ 12cm/yr). The subset on the bottom right represents the region of maximum subsidence (black dash square on the main image). LOS displacement time series is shown on the top right with the best fitting regression.

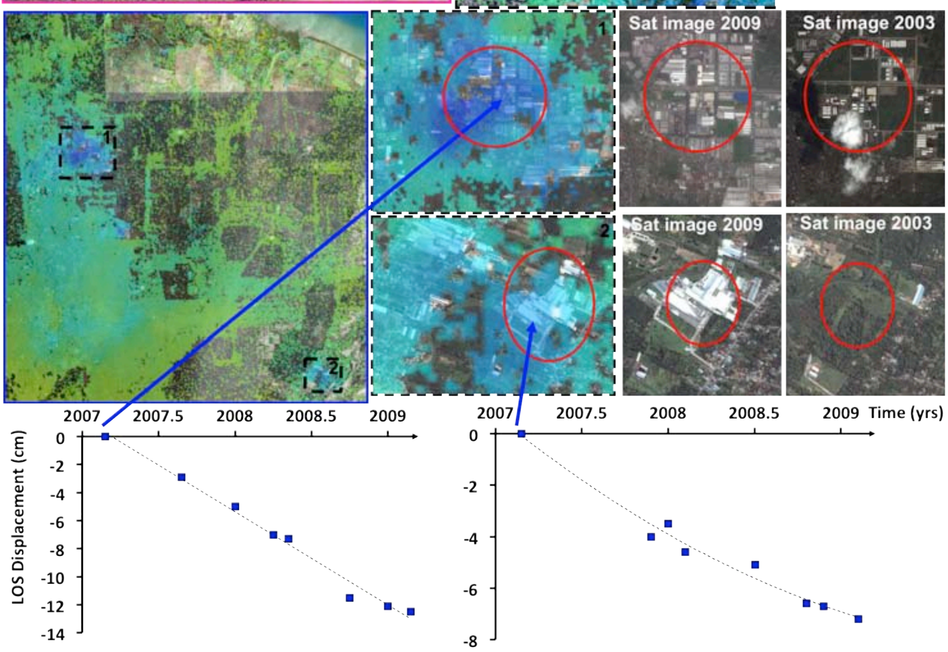

Figure 3: Averaged LOS velocity superimposed on Google Earth imagery in Medan (same scale as figure 1). The subsets show regions of maximum subsidence (black dash squares on the main image). The LOS displacement time series are shown at the bottom, with the best fitting regressions. The satellite images on the right show the difference in development of the areas between 2009 (left) and 2003 (right). The red circle outlines the areas that were built during this time interval.

2.4. Bandung

Bandung is the capital of the West Java province and the country's third largest city with 7.4 millions people. The city is located in a large intra-montane basin composed of 2 systems of aquifers [10]. The average LOS subsidence is about 10 cm within the entire basin (Fig. 1). The maximum LOS subsidence in Bandung reaches 40 cm during our observation period; corresponding to linear rates of 18.8 cm/yr. Assuming all the displacement is occurring vertically, the maximum vertical subsidence is 50 cm (linear rate of 23.5 cm/yr). However, the highest rates of subsidence are better explained by a second order polynomial function (Fig. 5). The high rates of subsidence are located in the northwest of the city and in the south, both in industrial areas.

2.5. Semarang

Semarang is located on the north coast of Java, with a population of 1.5 million, it is Indonesia's fifth largest city. The maximum LOS subsidence observed in Semarang is 13 cm and the average LOS subsidence is 3-4cm (Fig. 1). A linear regression gives a LOS subsidence rate of 8.3 cm/yr (10.4 cm/yr vertically). Assuming all the displacement is occurring vertically the maximum vertical subsidence is 16.3 cm (10.4 cm/yr). In Semarang the highest rates of subsidence are observed near the coast, in industrial areas and recently built areas (2003-2009), and in the southeast, in an industrial center (Fig. 6). Polynomial functions of the second order give a significantly better fit to the data than linear regressions in the coastal areas.

2.6. Sidoarjo

Sidoarjo is located on the north coast of Java, south of Surabaya. Since May 2006 Sidoarjo is experiencing the eruption of Lusi mud volcano. The subsidence observed in Sidoarjo is located around the edifice as well as few kilometers west. Uplift is also observed

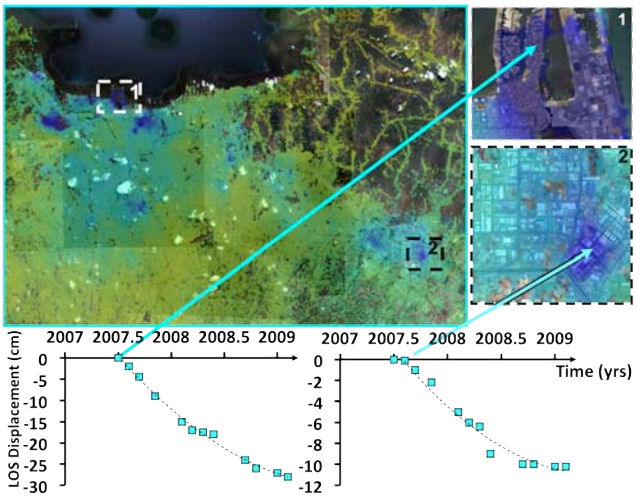

Figure 4 (up): Same as fig. 3 for Jakarta.

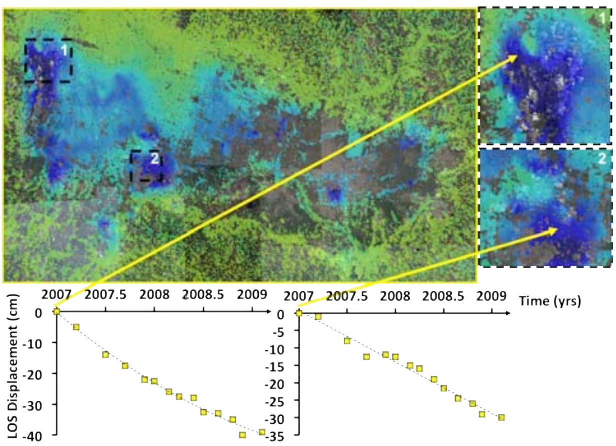

Figure 5 (up): Same as fig. 3 for Bandung.

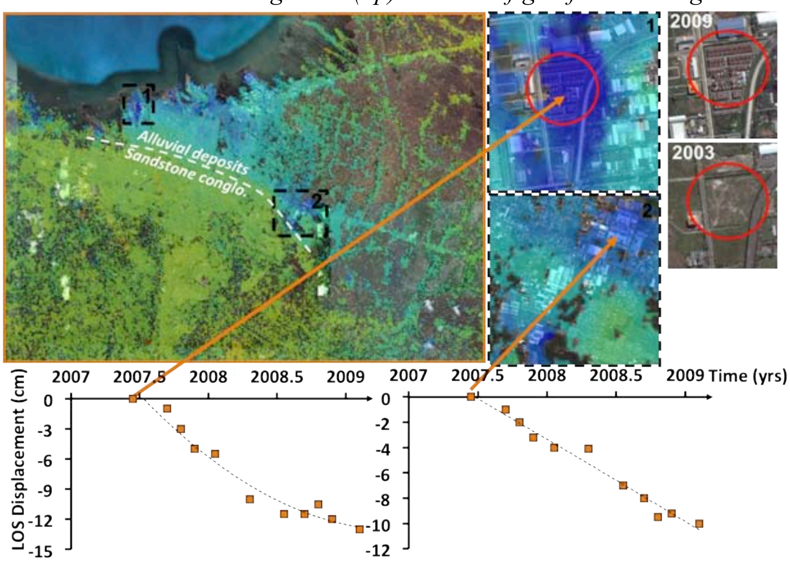

Figure 6 (Right): Same as fig. 3 for Semarang. The satellite images on the right show the difference in development of the areas between 2009 (top) and 2003 (bottom). The transition in sediments type is also shown with the white dash line.

northeast of the volcano. Subsidence around Lusi volcano has already been described using InSAR interferograms from ALOS [11], but no time series analysis has yet been produced. The maximum LOS subsidence is observed around Lusi volcano, with 19 cm of subsidence between 2007.1 and 2008.6 (Fig. 1). The average LOS subsidence observed west of Lusi is 14 cm. Assuming all the displacement observed in the LOS is occurring vertically, the maximum vertical subsidence is 23.8 cm and the average vertical subsidence is 17.5 cm. The subsidence around Lusi can be associated with a linear trend corresponding to a LOS rate of 13.5 cm/yr (16.9 cm/yr vertically). West of Lusi a linear trend give a LOS subsidence rate of 8.9 cm/yr (11 cm/yr vertically). We also observe uplift northeast of Lusi up to 9 cm. This uplift seems to be best fitted by a third order polynomial function.

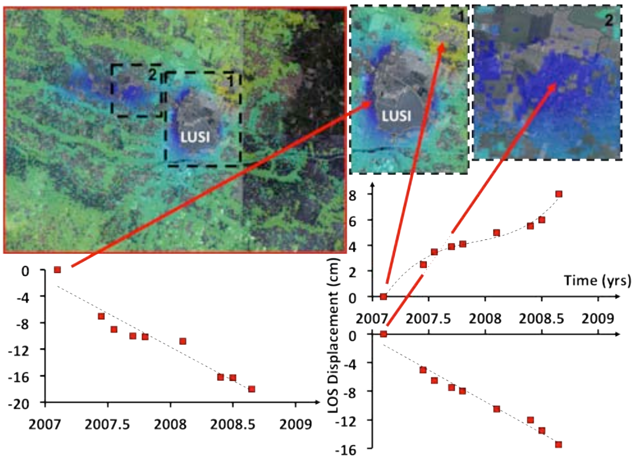

Figure 7: Mean LOS velocity around Lusi volcano superimposed on Google Earth imagery. The subsets represent the regions of maximum subsidence located around the mud volcano (image 1 and bottom left LOS displacement) and west of it (image 2 and bottom right LOS displacement). We also observe uplift located northeast of Lusi (image 1 and top left LOS displacement). The best fitting regressions are added to the LOS displacements plots.

3. DISCUSSION AND INTERPRETATION

3.1. Comparison between InSAR, GPS, gravity and leveling results.

There are no previous observations of subsidence in Lhokseumawe and Medan.

In Jakarta GPS surveys and leveling surveys were realized between 1997 and 2005 [12]. The estimated subsidence rates are 1-15 cm/yr and can be up to 20-25 cm/yr at certain locations and certain periods [12, 13, 14]. These rates are in global agreement with the ones obtained in our survey. GPS surveys also indicates that the subsidence in northern Jakarta is higher than in the southern part, in agreement with our results. Our study also reveals that the rates of subsidence are decreasing through time. This observation either reflects the fact that the subsidence rates started to decrease only recently or denote the limitation of using point-wise campaigns measurements.

In Bandung GPS surveys were realized between 2000 and 2005, revealing 12-24 cm/yr of subsidence with both temporal and spatial variability [10]. These rates are in good agreement with the rates obtained from our survey. We also confirm that the highest rates of subsidence are occurring in the northwest of the city, in agreement with previous works. Our survey reveals that the rates of subsidence are decreasing with time in the northwest of the city whereas GPS studies considered linear subsidence rates.

In Semarang GPS surveys were realized between 1979 and 2006 showing subsidence rates up to 17 cm/yr, the largest subsidence occurring along the coast [15]. PS-InSAR detected subsidence in areas close to the shoreline with rates of 8cm/yr [16]. Microgravity surveys between 2002 and 2005 indicate maximum rates of subsidence of 15 cm/yr [17]. Our survey indicates maximum vertical rates of subsidence of 14.4 cm/yr between 2007.4 and 2008.5, observed near the coast. Both the rates and the spatial distribution of the subsidence are in general agreement between our observations and previous works. However we suggest that subsidence rates are decreasing in time near the coast whereas previous studies considered linear subsidence.

Subsidence in Sidoarjo, associated to Lusi's eruption, has been described previously using ALOS interferograms [11, 18]. Since we used similar data our results are comparable, the time series is adding more confidence to the spatial and temporal characteristics of the subsidence.

In the Indonesian cities with previous subsidence monitoring we confirmed that the rates and spatial distribution of subsidence are in general agreement between our survey and previous works. This suggests that the rates of subsidence have been constant over many years. The spatial and temporal coverage of our study is un-preceded, providing millions of single data points in each city and measurements every 46 days for a period of more than 2 years. In 3 cities we suggest a decrease of the subsidence rate (Jakarta, Bandung and Semarang) that started after 2008. However this observation needs to be confirmed by studies extending further in time especially because this decrease in subsidence rate is very subtle. Moreover we consider that the noise associated with our measurements is +/- 1 cm/yr in LOS velocity (green-yellow colors on Fig. 1) varying along the survey area in function of the number of SAR acquisitions and of the atmospheric conditions. Thus the changes in subsidence rates are close to the detection threshold and need to be confirmed by time series extending further in time.

3.2. Causes of ground subsidence

The 3 main mechanisms suggested to explain ground subsidence in cities are natural consolidation of alluvium soil, subsidence induced by the load of constructions, and subsidence due to groundwater withdrawal [19]. We can expect different patterns of subsidence, both in rates and spatial distribution, depending on which of these mechanisms is dominating. If subsidence is mainly caused by natural compaction of alluvium soil we expect to observe subsidence located preferentially in areas with deposition of young sediments and limited to rates of millimeters per year to few centimeters per year [20]. Subsidence caused by load of constructions is likely to have rates of few centimeters per year and have a patchy distribution. This type of subsidence is expected to occur in areas with high-rise buildings, and in recently built areas on young alluvium sediments [21]. Subsidence due to ground water withdrawal and water drainage is expected to occur in cities with rapid expansion and urbanization. Rates of subsidence due to ground water extraction can reach tens of centimeters a year [22] and are often decreasing with time as compaction limit is reached [5]. In Indonesia groundwater extraction can be categorized in 2 types: shallow water extraction mostly done by individuals, and deep water extraction conducted by industries using drilled wells, with a higher extraction rate.

In Lokseumawe, the area of subsidence is correlated with an area of rice fields, alternating with residential areas. The absence of massive constructions excludes building loads from the potential causes. In We conclude that the subsidence is due to a combination of natural sediment compaction and pumping of water from shallow water tables for agriculture and households purposes.

In Medan, the subsidence is centered on the city center. This distribution cannot be explained by the natural compaction of alluvial deposits expected to be thicker near the coast. Moreover we observed that high rates of subsidence are located on industrial areas that were built recently (between 2003 and 2009). This observation suggests that the subsidence in Medan is due to load of buildings and ground water pumping, especially in relation with industrial activities.

In Jakarta we observe subsidence in 2 parts of the city. The first one is located near the coast and the city center, in areas with both industrial and residential activities, as well as in few areas with high-rise buildings. The mean rates of subsidence can be explained by a combination of both generalized ground water extraction and sediments compaction due to building loads. The coastal area is experiencing the highest rates of subsidence. Since only few massive buildings are present load of constructions is probably not of primary importance. The coastal location suggests that sediments compaction, maybe in relation with land reclamation, or related to organic matter compaction, might play an important role. Ground water extraction can also be part of the causes. The second area of subsidence is identified 40 km southeast from the coast, centered on an industrial area, suggesting that ground water pumping and building loads are the main sources of subsidence. Moreover a lowering of the piezometric level has been observed in Jakarta [13]. Sediments compaction due to building loads do not influence the phreatic level suggesting that, in Jakarta, the subsidence is mainly due to ground water extraction. Finally, rates of subsidence seem to decrease through time, which additionally supports this interpretation.

In Bandung we observe high rates of subsidence in the totality of the basin, between 10 cm/yr to up to 24 cm/yr, which cannot be explained by natural compaction of sediments. We also observed that the highest rates of subsidence are occurring in industrial areas, suggesting that building loads and groundwater withdrawal from deep aquifers for industrial purposes are the main causes of subsidence. Moreover the average annual drop of the water tables in the Bandung basin reaches from 1m to up to 2.5m [10], suggesting that water extraction is the main cause of ground subsidence. Finally rates of subsidence seem to decrease through time, supporting this interpretation.

In Semarang the spatial distribution of subsidence is homogeneous and coincide with the distribution of alluvium and coastal plain deposits [23] (Fig 6). The average rates of subsidence of 2-3 cm/yr can be explained by a combination of ground water withdrawal, natural sediment compaction and compaction due to load of buildings. The maximum rates of subsidence are observed on the coast and 10 km southeast, both on industrial areas and recently built areas. This observation suggests that ground water extraction in relation with industrial activities and building loads are the main causes for high subsidence rates.

In Sidoarjo we identified two distinct areas of subsidence. The one undergoing the fastest subsidence is located close to Lusi volcano, suggesting that the mud volcano is playing an important part in the subsidence. The causes of subsidence at Lusi have been investigated by *Fukushima et al.* 2009 [11], who concluded that pressure decreases and depletion of material at depth are likely to cause the observed subsidence. However the area of subsidence is limited to the surroundings of the mud volcano and does not extend laterally. This implies that the source of subsidence is located at very shallow levels, probably shallower than what was inferred by previous studies. Further modeling is necessary to clearly identify the source of subsidence at Lusi. The second zone of subsidence, located west of Lusi, is on the Wunut gas field area. The observed subsidence is interpreted as resulting from the depletion of the field with no relationship with Lusi's activity [12]. The uplift northeast of Lusi was interpreted as a reactivation of the Watukosek fault in relation with Lusi's activity [12].

CONCLUSION

InSAR time series provide unprecedented spatial resolution and continuous temporal coverage of the subsidence in western Indonesia. We identified 6 major cities undergoing subsidence at vertical rates up to 24 cm/yr.

The spatial variability of the subsidence in Jakarta, Bandung and Semarang, previously identified with GPS, leveling and gravity measurements, is confirmed by this survey. The temporal variability of GPS results doesn't exist in our time series.

We suggest that ground water pumping is the main cause of land subsidence in Lhokseumawe. In Medan, Jakarta, Bandung and Semarang we suggest that ground water extraction, especially for industrial purposes, combined with building loads are the main causes of subsidence. These interpretations are supported by the spare spatial distribution of high rates of subsidence, as well as the spatial agreement between soft sediments and subsidence distribution.

Subsidence due to water pumping is often associated with rates decreasing in time as compaction limit is reached. Statistical analysis reveals that second-order polynomial functions give a significantly better fit than linear regressions in some parts of the cities in Lhokseumawe, Medan, Jakarta, Bandung and Semarang, supporting our interpretations. However, to confirm this observation, this survey should be extended in time. The main limitation lies in the fact that no L-Band satellite is currently acquiring data. Similar surveys with C or X-Band data might suffer greater decorrelation.

A continuation of the current rates of subsidence would result in a catastrophic increase in exposure to risks, particularly considering that some of the highest rates of subsidence are found in coastal areas, where even small amount of subsidence pose a great danger.

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