ANTHROPOGENIC DRIVERS OF RELATIVE SEA-LEVEL RISE IN THE MEKONG DELTA – A REVIEW

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Abstract: The Mekong Delta is sinking and shrinking. This is because of the absolute sea-level rise, and because of the subsidence of the land. The absolute sea-level rise originates from the thermal expansion of the ocean waters and the melting of ice on land, plus other factors including changes in winds and ocean circulation patterns. The subsidence originates from the construction of dams in the river basin upstream of the Delta, that has dramatically reduced the flow of water and sediments, and excessive groundwater withdrawal, plus other factors including riverbed mining, infrastructural extension, and urbanization. The origin of alluvial delta created by a continuous supply of water and sediments and the natural subsidence of uncompacted soils is relevant background information to understand the current trends. Another factor affecting the sinking and shrinking include the degradation of the coastal mangrove belt. It is concluded that the subsidence due to the reduced flow of sediments and water, and the withdrawal of groundwater more than the replenishment of aquifers is more than one order of magnitude larger than the absolute sea-level rise estimated by satellite and climate models, or the value estimated from tide gauges, that is much less. The current sinking and shrinking trends are not sustainable, as the low-lying Delta may disappear before the end of this century.

Key words: Mekong Delta, Vietnam, land subsidence, thermosteric sea-level rise

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Introduction

River Deltas are created by deposition of sediments carried by the river flow leaving its mouth and entering the ocean waters. The extension of a Delta is controlled by the balance between processes supplying sediment, and processes redistributing, sequestering, and exporting the sediments (Blum, Törnqvist 2000, Pasternack et al. 2001). One of the largest Asian mega Deltas is the Mekong Delta, south of Ho Chi Minh City, in Viet Nam (Fig. 1). The Mekong river flows for 4,630 km through Southeast Asia, then entering the South China Sea south of Ho Chi Minh City. The Mekong Delta is a 40,000 km^2 maze of rivers, swamps, and islands of elevation about sea level, that is home to 20 million peoples, and one of the most productive areas of Asia for agriculture. Most of the rice of Vietnam, that is a heavy consumer and a similarly important exporter (Vietnam is also the world's second-largest rice exporter) comes from the Mekong Delta. The Mekong Delta is also an important centre for aquaculture and offshore fisheries. The Mekong Delta is characterized by a growing population and economy, the same of the other countries along the Mekong River.

The Mekong Delta is at the centre of growing interest because of the relative sea-level rise

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(Newswise 2019). In addition to the thermosteric rise of sea levels, because of thermal expansion of warming oceans and mass addition for melting of ice on land, the Mekong Delta is facing excessive groundwater withdrawal-induced subsidence. Since the late 1980s, agricultural production, population, consumption, and urbanization have been dramatically growing, and with them the water withdrawal in the area. Additionally, the delta is built by the flow of water and sediments, and this flow has been dramatically reduced by the constructions of dams along the river, and the growing water uses upstream, to answer the energy and food needs of a growing population. Riverbed mining or infrastructure extension in the Delta has also contributed to worsening the issue. As a result, the delta is sinking and shrinking, putting at risk the existence of the delta in the present form, by as early as 2100.

Here we survey the information available to quantify the relative contributions of the three main drivers of relative sea-level rise in the Mekong Delta, excessive groundwater withdrawal-induced subsidence, and reduction of flow of water and sediments caused by the many dams built along the river, and upstream water uses, that are strongly connected each other, and thermosteric sea level rise.

The relative sea levels rise (or fall) because of one land and one sea component. The land component is due to subsidence or isostasy, originating from global (for example glacial isostatic adjustment), regional (for example groundwater withdrawal) and local (for example soil compaction, infrastructure extension) phenomena. The sea component includes the thermosteric sea level rise, due to the expansion of the ocean waters and the melting of ice on land, as well as other phenomena, such as changes of circulation. A tide gauge supplies a local measure of the relative sea-level rise, the sum of one sea and one-land components.

The land component of the relative sea-level rise

The major drivers of the subsidence in the Mekong Delta are the excessive groundwater withdrawal within the delta and the reduction of the flow of water and sediments because of the upstream dams. Added factors affecting the land component are urbanization and infrastructure extension, riverbed sand mining, and change of land use. To be considered, also the geological framework of the Delta, with a soil subjected to

Fig. 1. Aerial view of the Mekong River Delta, south of Ho Chi Minh City, Vietnam. Image is reproduced modified from (Bing 2019).

natural subsidence only worsened by the depletion of aquifers and the reduced flow of sediments. The literature on the subject is here reviewed.

Excessive groundwater withdrawal

Excessive water withdrawal has worsened the subsidence of a soft, shallow soil, with the growth in infrastructure an extra burden (Erban et al. 2014, Minderhoud et al. 2017, 2018, Zoccarato et al. 2018, Minderhoud 2019). The relative sea level rises fast because the land is significantly sinking. The saltwater is pushing farther inwards the land, and the delta faces the problem of salinization of soil and aquifers. The effect of groundwater withdrawal is coupled with the reduction of water and sediment delivery to the delta plain (Zoccarato et al. 2018). Van Manh et al. (2015) suggested that hydropower dams are the dominant driver. Nhan and Cao (2019) pointed out as the degradation of the Mekong Delta is due to several factors including poor water management schemes, hydropower dams in the river basin, sediment starvation, increased pollution, infrastructural extension, riverbed mining, delta subsidence, thermosteric sea level rise, degradation of the coastal mangrove belt, gaps in governance of the Mekong basin. Especially the effects of dams and groundwater extraction are much larger than what was thought.

Subsidence rates from excessive groundwater withdrawal are more than one order of magnitude larger than the predicted thermosteric rates of rising of the sea level (Erban et al. 2014). The combined effect of water withdrawal coupled to the reduction of the flow of water and sediments is also discussed in Ziv et al. (2012), Smajgl, Ward (2013), Cosslett, Cosslett (2014), Pokhrel et al. (2018). As discussed in Winter (1998), Bui et al. (2017) or Reba et al. (2017), the status of an aquifer is based on a balance between recharge and withdrawal. Thus, the reduction of water flow because of upstream dams and irrigations, and withdrawals are unbalanced, and this produces a reduction of the aquifers. In addition, the reduced permeability of the river bed, the channelization of the river, the increased speed of the water, all affect the excessive groundwater extraction induced subsidence.

Groundwater exploitation is a major cause of land subsidence. Compounded by thermosteric sea-level rise, this poses a flood inundation hazard in coastal areas. Over-exploitation is inducing widespread hydraulic head declines in the aquifers. The average rate of head decline is ~300 mm a^{-1}, based on time-series data from 79 nested monitoring wells at 18 locations (Erban et al. 2014). The compaction of sedimentary layers at these locations is estimated to cause land subsidence at an average rate of 16 mm a^{-1}. (Erban et al. 2014). Interferometric synthetic aperture radar (InSAR) subsidence rates, as shown in Figure 2, are consistent with compaction-based rates calculated at monitoring wells, and ~10–40 mm a^{-1} over large regions 1000s of km^2 size (Erban et al. 2014). If groundwater pumping continues at present rates, ~0.88 m (0.35–1.4 m) of land subsidence is expected by 2050, posing at risk of inundations large areas of the low-lying delta.

Minderhoud et al. (2015) coupled the multi-aquifer subsurface of the delta and the complex sedimentary architecture of the heterogeneous subsurface to the groundwater extraction through a 3-D geo-hydrological model based on lithological borehole data, geophysical sedimentary properties, paleogeography, and conceptual models of delta evolution. Drops of hydraulic

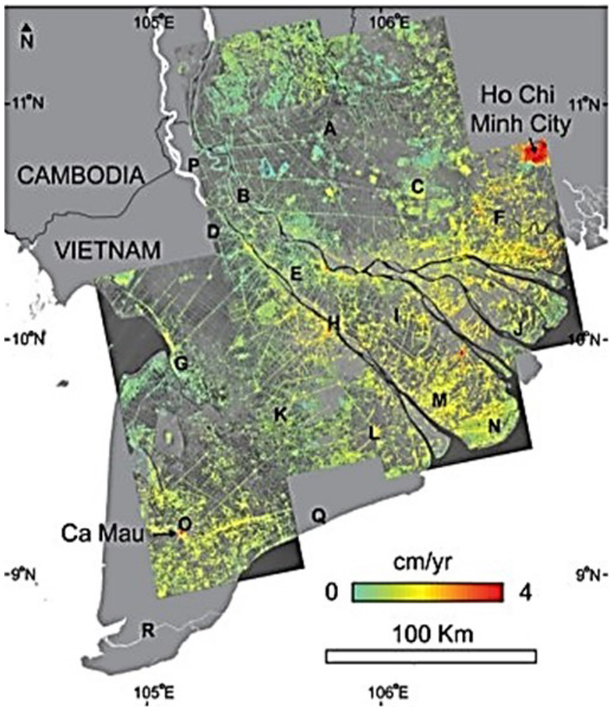


Fig. 2. InSAR-based land subsidence. Data are from JAXA, METI. These land subsidence rates are annual averages from 2006 to 2010. The image is reproduced modified from (Erban et al. 2014).

heads in aquifers were on average 0.3–0.7 m a^{-1}. Minderhoud et al. (2015) found land subsidence rates of ~ 10–40 mm a^{-1}. attributed to groundwater extraction, increased for growing domestic, agricultural, and industrial demands.

Higgins (2016) discussed as not only the Mekong, but most of the world's major river deltas are sinking. Subsidence produces aquifer salinization, infrastructure damage, vulnerability to floods and storm surges, and permanent inundation of low-lying land. Higgins (2016) confirmed that subsidence associated with groundwater extraction may outpace thermosteric sea-level rise by up to two orders of magnitude, producing relative sea-level rise one-hundred times faster than the global average rate.

Subsidence rates up to several centimeters per year have been reported by many for the Mekong Delta. Excessive groundwater extraction is always suggested as the main driver. When the groundwater levels drop, then aquifer compaction produces subsidence. In the Mekong Delta, groundwater extraction has increased dramatically over the past 25 years, producing a situation with increasing aquifer depletion. Minderhoud et al. (2017) show that subsidence related to groundwater extraction has gradually increased in the past decades. During the past 25 years, the total subsidence was on average ~18 cm. Current average subsidence rates amount to 11 mm a^{-1}. Presently, some areas are subsiding over 25 mm a^{-1}. The presently increasing trends in groundwater extraction are expected to further increase this subsidence (Minderhoud et al. 2017).

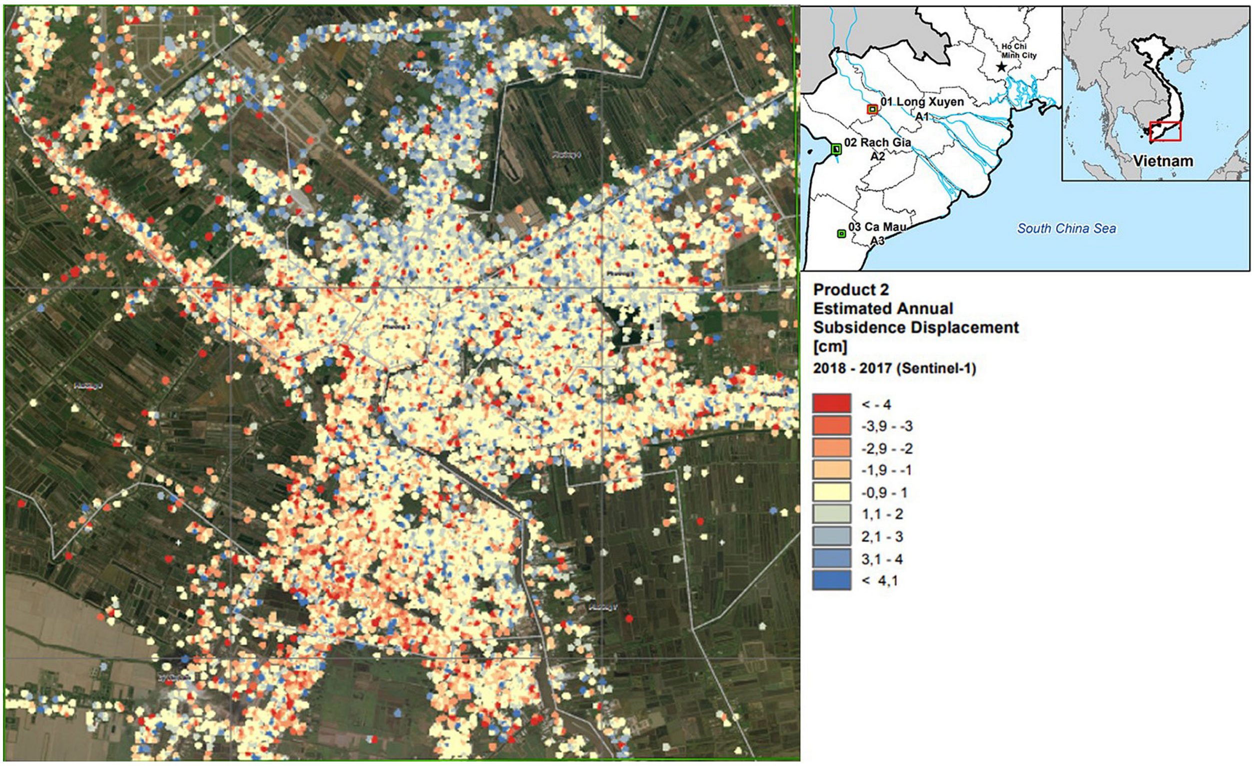
Minderhoud et al. (2018) pointed out as the Mekong delta is subsiding due to a combination of natural and anthropogenic causes. Land-use changes have taken place because of increased agricultural production, as well as population growth and urbanization. These land-use changes have altered the hydrological system and increased the loading of the surface, amplifying natural subsidence processes and creating new anthropogenic subsidence. InSAR-derived subsidence rates for the various land-use classes are proposed. Lowest subsidence rates are found for undeveloped land-use, like marshland and wetland forest (~6–7 mm a^{-1}). Highest subsidence rates are found for areas mixed-crop agriculture and cities (~18–20 mm a^{-1}). The land-use-based approach predicted 65–92% of the spatially varying subsidence rates within the measurement error range of the InSAR observations (RMSE of 5.8 mm).

The Mekong Delta was formed by deposition of unconsolidated, fine-grained (clayey) sediments transported by the river flow. These sediments were undergoing high compaction rates. Groundwater pumping, infrastructural loading, sand mining, and dam construction have worsened the effects of natural consolidation (Zoccarato et al. 2018). The natural compaction of the Holocene deposits following the delta evolution has reached unprecedented high rates (up to ~20 mm a^{-1}). This subsidence threatens the lower plains with permanent inundation and reduces the service life of coastal flood defence structures.

Copernicus EMS (2019) now provides subsidence maps of the Mekong Delta. Subsidence in the Mekong Delta is a naturally occurring phenomenon, accelerated through human activities such as groundwater extraction and infrastructure loading. This accelerated rate of degradation exacerbates flood severity, coastline regression, and salinification of soil and water, and therefore need adequate monitoring. Satellite monitoring is certainly the best avenue to infer subsidence rates across the Mekong Delta, with policies adaptively built and checked based on continuous measurements. Figure 3 presents the estimated annual subsidence displacement of 2018 and displacement change 2018–2017 around Ca Mau. Clearly showed are areas of subsidence up to 5 cm a^{-1}, subject to acceleration.

The reduced flow of water and sediments

The exploitation of transborder freshwater resources (Wolf 1999, Rahaman 2012) has been historically resulted in damage to the downstream population often leading to conflicts. Kite (2001) discusses, as the Mekong basin will be affected by proposed developments in the basin by using a model of the hydrological cycle of the Mekong and its tributaries. The proposed dams will translate into dramatic environmental changes. Le et al. (2007) noted as the Mekong Delta was severely affected recently by a series of unusually large floods. In the dry season, the delta is affected by salinity intrusion and tides. For mitigation, many engineering structures have been built in the delta. The flood levels in the delta depend on



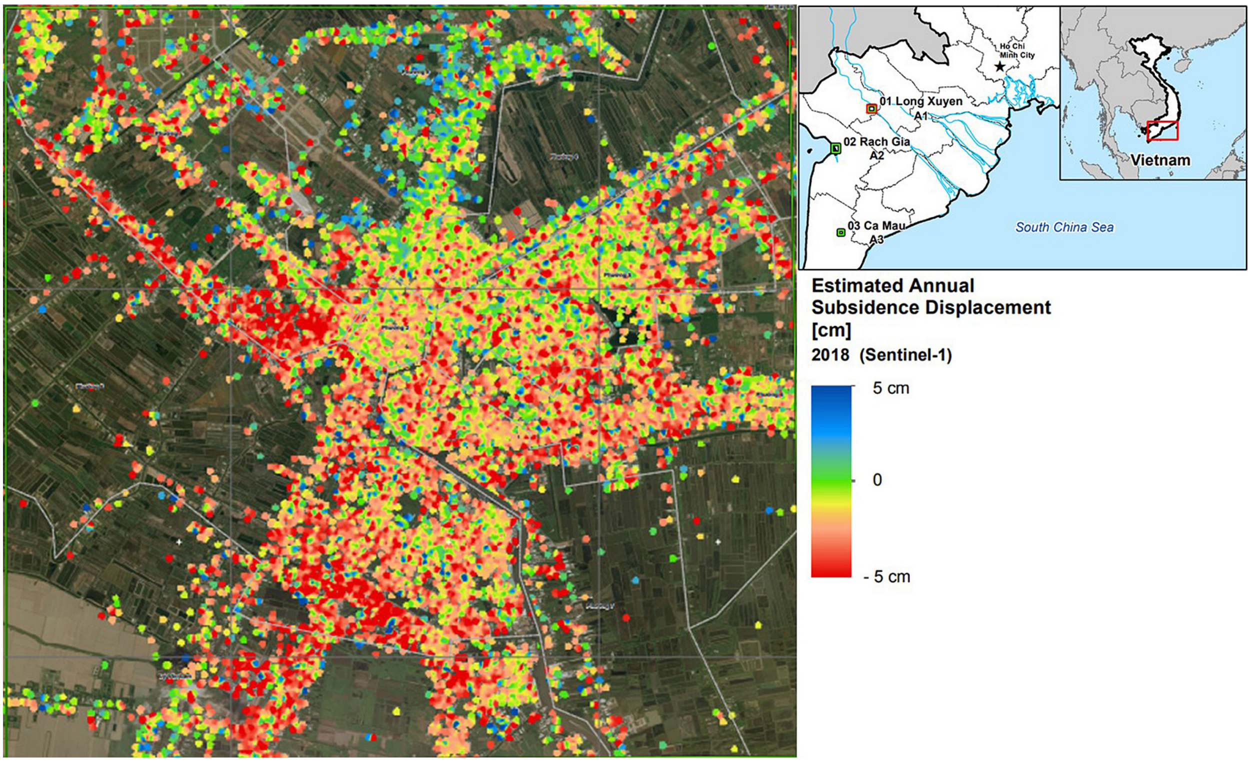


Fig. 3. (a) Estimated annual subsidence displacement of 2018 around Ca Mau, in the Mekong Delta. (b) Estimated annual subsidence displacement change 2018–2017 around Ca Mau, in the Mekong Delta. Images reproduced modified from (Copernicus Emergency Management Service 2019). Copyright European Union, 1995–2019.

flows in the Mekong River, storm surges, sea-level rise, and the possible siltation of the estuary. Construction of dams in China and the remaining river catchment affect the floods. According to Le et al. (2007), the engineering structures in the delta increase the flow velocities, thus increasing bank erosion, and producing deeper rivers and canals. Engineering structures thus increase flooding in the non-protected areas and increases the risk of failure of the dikes in the protected areas.

Kondolf et al. (2014) noted the massive rapid dam construction along the Mekong. 7 dams are under construction in China, and 133 proposed for the Lower Mekong River and tributaries. The cumulative sediment trapping by these dams is estimated to be significant. In the case of the 38 dams built at the time or already under construction at the time, the cumulative sediment reduction is 51%. Under completion of all planned dams, the cumulative sediment trapping will be 96%. Only 4% of the pre-dam sediments are thus expected to reach the Delta. This will affect the persistence of the Delta landform itself. Rubin et al. (2015) also expect substantial changes along the alluvial reaches, though stripping of thin sediment deposits in bedrock reaches.

Anthony et al. (2015) also discussed how the Mekong Delta, affected by subsidence and coastal erosion, will be further damaged by the too many dams constructed upstream. Their analysis of high-resolution satellite images between 2003 and 2012 supplied erosion and land loss affecting over 50% of the more than 600 km-long shorelines of the Delta. The erosion is consistent with a reported significant decrease in suspended sediment from the Mekong River linked to dam retention, large-scale sand mining in the river and channels, and groundwater extraction induced subsidence. According to Van Manh et al. (2015), the hydropower dams are the dominant driver on floodplain sediment dynamics, while sea level rise is as a second-order impact effect.

Fawthrop (2016) discussed as the environmental costs of the dams in the Mekong have been underestimated. The delta is both shrinking and sinking as a result. The large dams trap sediments. The delta is suffering from sediment loss, already 50% less than the regular flow. Sand-mining aggravates the sediment shortage. The most dangerous dams are those of Don Sahong, Xayaburi and Pak Beng in Laos, and the 6s more dams upstream in China.

Schmitt et al. (2017) discussed the effect of hydroelectric dams, sand mining, dyking of floodplains, groundwater induced subsidence and sea-level rise. If sediment supply to the delta will be nearly completely cut off, as it will be the case with all the planned dams completed and current rates of sediment mining, and the groundwater pumping will continue at the present rates, they forecasted that the delta will disappear by the end of this century due to increased rates of subsidence and the rising sea levels.

Zoccarato et al. (2018) stressed as groundwater induced subsidence and sediment delivery both determine the future elevation of the Delta and its vulnerability to thermosteric sea level rise. Nhan and Cao (2019) recently discussed as the Mekong Delta is shrinking and sinking, with its ecosystem and environment seriously degraded. Much of this degradation is due to hydropower dams in the Mekong river basin but particularly the big dams in China in the Upper Mekong Basin. By comparison with the period before the 1990s, construction of these big dams has decreased 50%–60% the sediment load, the flood discharges have also decreased; low flow events are now common. The seasonal regime has shifted resulting in earlier and more severe salinity intrusion into the delta. Flooding from storms at sea is not blocked by the river discharge. The riverbed is deeper by 1.3 m on average, also because of the sand mining. Erosion of riverbanks has increased, affecting 400 locations, and erosion of the coast has also increased, affecting 66% of the foreshore.

Li et al. (2017) used 43-year Landsat images from 1973 to 2015 to investigate the changes to the Mekong Delta's shoreline. They found a significant decrease in the shoreline progradation rate and a present 66% of erosion of the shoreline is under erosion. Most of this erosion occurs on the East side of the Ca Mau Peninsula and in the North West side of the delta in the Gulf of Thailand. This is an indication that also changes in the sea conditions affect the erosion processes. They found that most parts of the shorelines in the estuary are however still growing, despite the reduction of the sediments' flow. They evidenced a shift from growing to shrinking around the year 2005, phased with the construction of the dams along the river.

Thermosteric sea level rise

While it is common to assume that thermosteric sea level rise is the major threat to the Mekong Delta, (Mainuddin et al. 2011, Toan 2014, Smajgl et al. 2015, Hoang et al. 2016, Allison et al. 2017, Cinner et al. 2018, Dang et al. 2018), even at the accelerated rate claimed by the Intergovernmental Panel on Climate Change (IPCC 2013), the thermosteric sea level rise is a second-order driver vs. the effect of groundwater withdrawal and construction of upstream dams. The latest global mean sea level rate of rise and acceleration are 3.1 mm a^{-1} and +0.096 mm a^{-1} (Colorado University (CU) Sea Level Research Group 2019).

The long-term-trend (LTT) tide gauges of the world are free of significant acceleration over the length of their recording (Mörner 2004, 2013, Houston, Dean 2011, Boretti 2012, Parker, Ollier 2015, 2017). This suggests considering more than the theoretical global thermosteric rate of rising of the sea level, the actual local rate of rising of the sea levels (Parker and Ollier 2015). Integration with subsidence data from GPS or other means, the analysis of the tide gauge records may supply a good representation of the sea and land contributions to the relative sea-level signal recorded by the tide gauges.

The tide gauges record the sea level movements relative to the instrument. Cleared of the natural oscillations of periodicities up to quasi-60 years (Chambers et al. 2012), the relative sea-level may rise or fall because the absolute sea level is rising or falling, by the thermosteric effect, for thermal expansion or the addition of mass by melting of ice on land, or other causes, for example changes of circulation, or because the land is subsiding or uplifting, due to global glacial isostatic adjustment, regional subsidence, tectonic movements, or other causes, such as compaction.

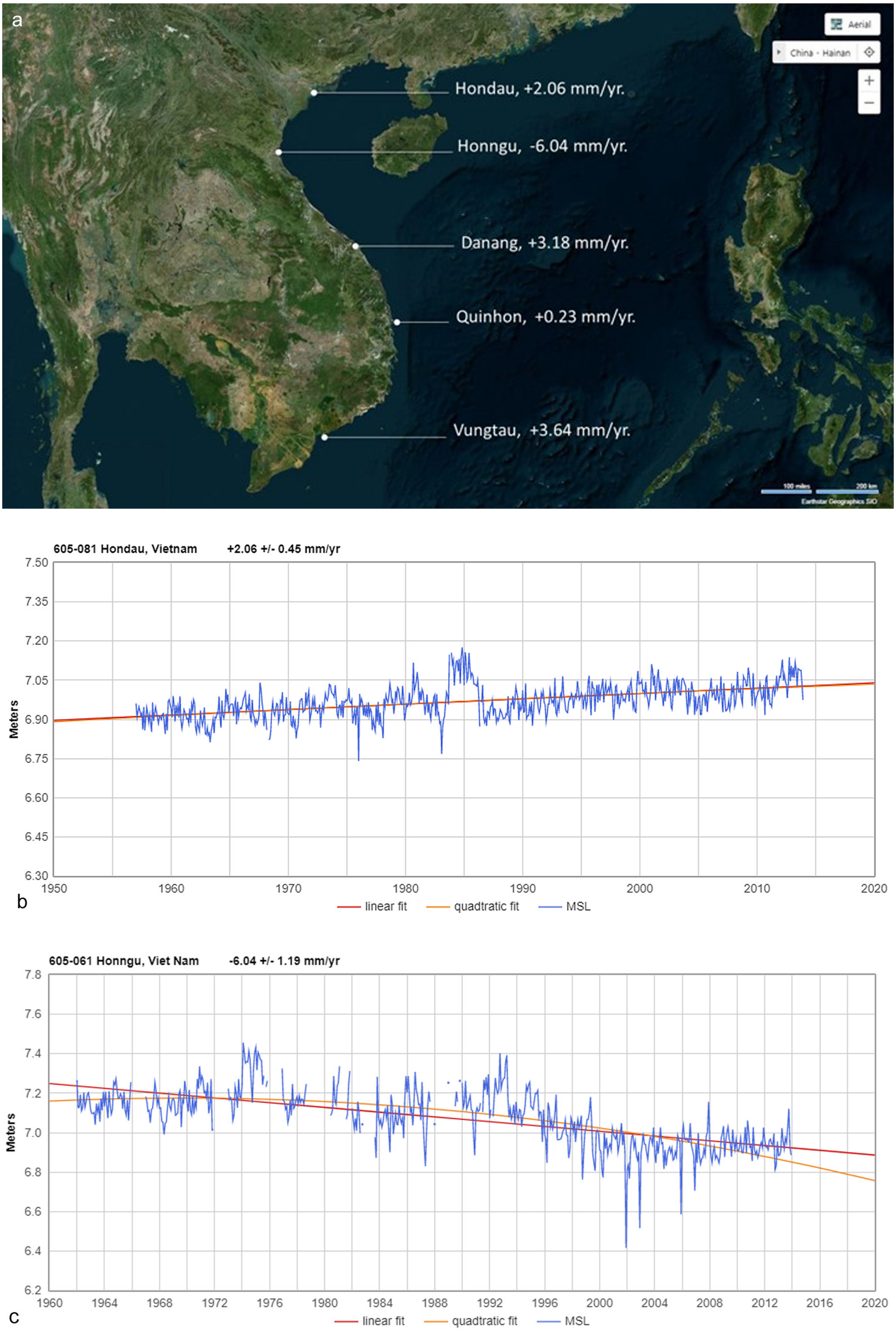
The sea levels of Vietnam are not covered by any LTT tide gauge. There are 5 tide gauges listed in the PSMSL database (PSMSL, n.d.), Table 1. Moving north to south, they are Hondau, Honngu, Quinhon, Danang, and Vungtau. Hondau is located in front of Hanoi. Vungtau is located in front of Ho Chi Minh City, on the northern boundary of the Mekong Delta. The tide gauges of Quinhon II and Vungtau II have recently replaced the historical tide gauges of Quinhon and Vungtau.

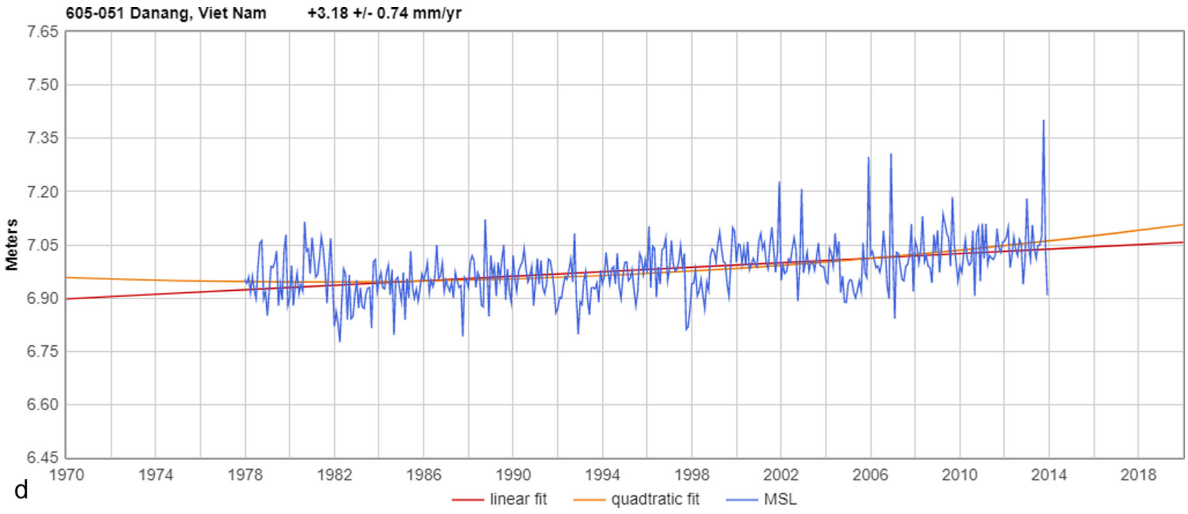
None of these tide gauges has record length exceeding 60 years, a minimum to infer a proper rate of rise cleared up of the multidecadal oscillations. The data available is summarized in Figure 4. Figure 4a is the location of the tide gauges of Vietnam. Figures 4b to f are the analyses of the monthly average mean sea levels (MSL) time series by linear and parabolic fittings. The relative rate of rise is strongly variable from +3.64 to -6.18 mm a^{-1}, because of the short records and variable sea and land contributions to the relative sea-level rise. Apparent accelerations – the records are too short – are largely positive in two cases, large negative in two other cases, and small negative in the longer record.

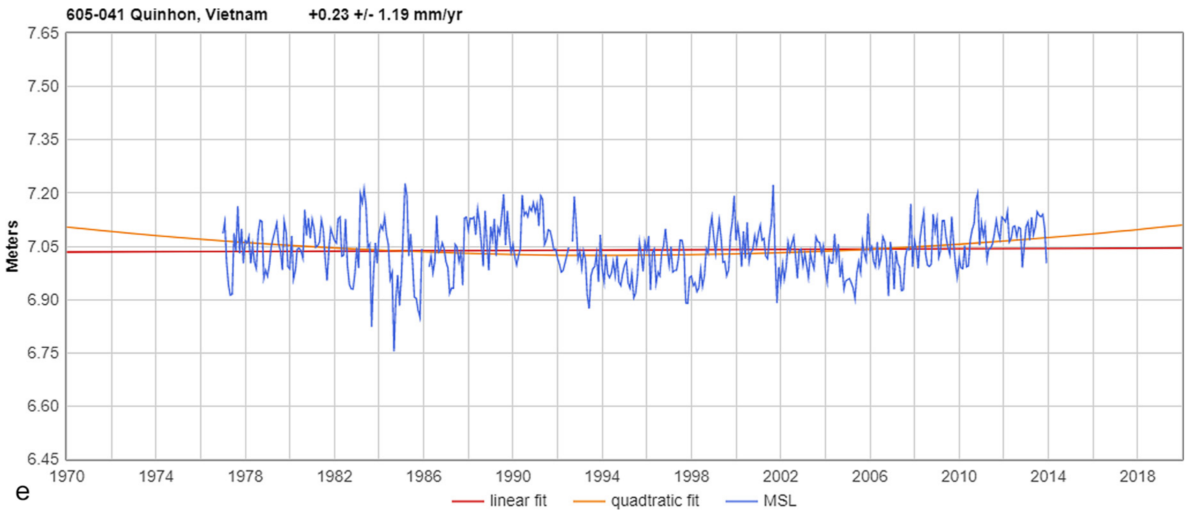
Vietnam has no tide gauge of enough length to infer a proper rate of rise and acceleration. However, 2 of the 5 tide gauges, Hondau and Honguu, are spanning more than 50 years. The other 3, Danang, Quinhon and Vungtau, are shorter. The MSL trend at Hondau is +2.06 mm a^{-1}. The date range is only 56 years. The slope is much more realistic than the acceleration. The apparent acceleration is −0.01059 mm a^{-2}. The apparent MSL trend at Honngu is -6.04 mm a^{-1}. The date range is only 51 years. The slope is much more realistic than the acceleration. The apparent acceleration is −0.33 mm a^{-2}. The apparent MSL trend at Danang is +3.18 mm a^{-1}. The date range

Table 1. Rate of rise and acceleration of the relative sea levels measured at the tide gauges of Vietnam.

Tide gauge	PSMSL Id.	Latitude	Longitude	Years of measurements		Rate of rise of the relative sea levels	Acceleration of the relative sea levels
				start	end	[mm a^{-1}]	[mm a^{-2}]
Hondau	841	20.667	106.8	1957/1	2013/12	2.06	−0.0106
Honngu	1003	18.8	105.767	1962/1	2013/12	−6.04	−0.33
Quinhon	1449	13.767	109.25	1977/1	2013/12	+0.23	0.264
Danang	1475	16.1	108.217	1978/1	2013/12	+3.18	0.212
Vungtau	1495	10.333	107.067	1979/1	2013/12	+3.64	−0.096
Quinhon II	2267	13.775	109.255	2007/11	2016/11	NA	NA
Vungtau II	2268	10.34	107.072	2007/11	2016/11	NA	NA


a
Aerial
China - Hainan
Hondau, +2.06 mm/yr.
Honngu, -6.04 mm/yr.
Danang, +3.18 mm/yr.
Quinhon, +0.23 mm/yr.
Vungtau, +3.64 mm/yr.
605-081 Hondau, Vietnam +2.06 +/- 0.45 mm/yr
Meters
7.50
7.35
7.20
7.05
6.90
6.75
6.60
6.45
6.30
1950 1960 1970 1980 1990 2000 2010 2020
b
linear fit
quadtratic fit
MSL
605-061 Honngu, Viet Nam -6.04 +/- 1.19 mm/yr
Meters
7.8
7.6
7.4
7.2
7.0
6.8
6.6
6.4
6.2
1960 1964 1968 1972 1976 1980 1984 1988 1992 1996 2000 2004 2008 2012 2016 2020
c
linear fit
quadtratic fit
MSL





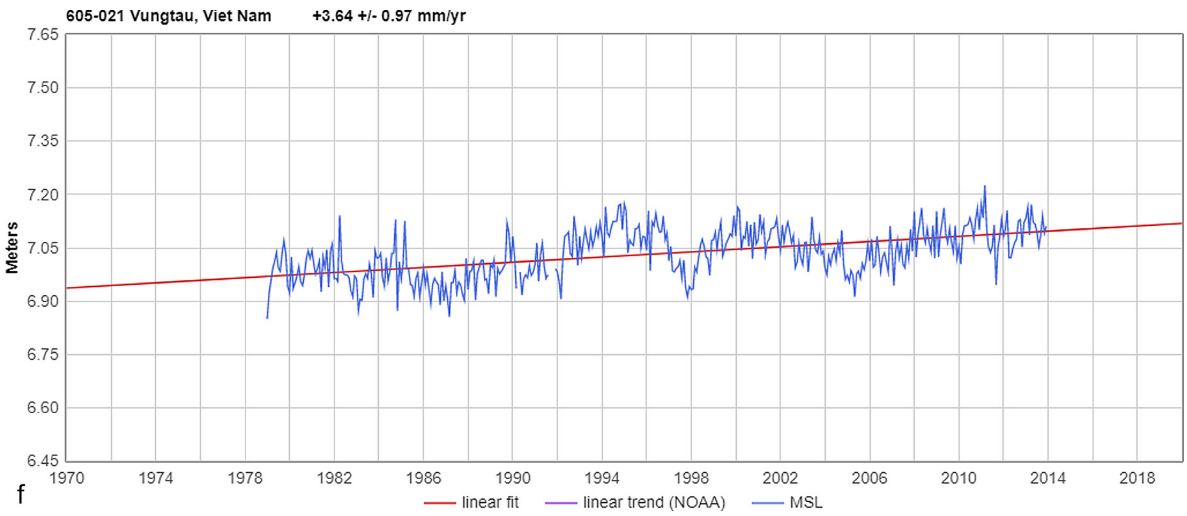


Fig. 4. (a) Tide gauges of Vietnam and (b) to (f) their monthly average mean sea level analysis. Image (a) is reproduced modified from (Bing 2019). Images (b) to (f) are reproduced modified from (SeaLevel.info, n.d.).

is only 35 years. Also, the slope is in this case not realistic. The apparent acceleration is +0.212 mm a^{-2}. The apparent MSL trend at Quinhon is +0.23 mm a^{-1}. The date range is only 35 years. The slope is, also in this case, not realistic. The apparent acceleration is +0.264 mm a^{-2}. The apparent MSL trend at Vungtau is +3.64 mm a^{-1}. The date range is only 34 years. The slope is in this case not realistic. The apparent acceleration is –0.0960 mm a^{-2}.

Figure 5 presents a further analysis of the MSL of Vungtau and Vungtau II, plus an image of the area, subjected to heavy construction. Figure 5a presents the MSL in Vungtau and Vungtau II, while Figure 5b presents their difference Data are from (Permanent Service for Mean Sea Level PSMSL, n.d.). The aerial view of the area of Vungtau evidences heavy construction. While the area in front of Vungtau in the Mekong delta is affected by significant subsidence, the area of Vungtau was previously stable (bedrock). There is however some sign that the heavy construction may contribute to recent subsidence. The latest Vungtau II is likely subsiding vs. the older Vungtau tide gauge, as shown by the difference between the two signals reducing. This may be an artifact of different sea exposure or compaction induced subsidence.

According to Choblet et al. (2014), the tide gauge of Honngu is uplifting being located along with the active Red River-Ailao Shan fault system (Pedoja et al. 2011, 2014). Conversely, they indicate the Vungtau tide gauge is subsiding, outlining the effect of the Mekong Delta subsidence, although its relocation to Vungtau II during this century has also contributed to the anomalous record.

The sea levels of Vietnam thus appear to be characterized by strongly variable local relative sea-level rise, suggesting an overwhelming contribution by local circulation patterns and subsidence, and a likely small thermosteric contribution. The relatively small regional thermosteric contribution has been shown for the area by Parker (2018 or 2019), at slightly more than half a millimetre per year and about constant. As shown by Japan Meteorological Agency (2018) for Japan, the sea level rate of rise since 1906 in tide gauge locations affected to a lesser extent by crustal movements is 0.29 mm a^{-1}, subjected to an acceleration of 0.010 mm a^{-2}.

Figure 6 presents the MSL around Japan as proposed by the Japan Meteorological Agency (2018). Figure 6a is the sea level anomaly. Figure 6b are the locations of the stations affected to a lesser extent by crustal movements of the survey. As noted by Parker (2019) the correct rate of rise and acceleration for Japan are even less than the 0.29 mm a^{-1}, subjected to an acceleration of 0.010 mm a^{-2} that may be inferred from the linear and parabolic analyses of the data in Figure 6a. In Figure 6a, the anomaly 1906 to 1960 is computed based on the result for the 4 tide gauges of Figure 6b on the left, but the anomaly 1960 to present is computed based on the results for the 16 tide gauges of Figure 6b on the right, that is in principle incorrect, as different tide gauges may have different relative rates of rise not only because of the different crustal motion. By considering the 4 individual tide gauges of Figure 6b, they are all free of any sea-level rise or acceleration since the end of the 1800s until the present time, as noticed by Parker (2019). The Geospatial Information Authority of Japan (2019) provides the data of Hosojima since Jan. 1894, Wajima since Jan. 1894 and Oshoro since Nov. 1905. The tide gauge of Hamada is unfortunately discontinued. Data are updated to July 2019. Figure 6c, d and e present the MSL of Hosojima, Wajima, and Oshoro. Clearly, there has been no sea-level rise since the end of the 1800s. Figure 6f presents the short time windows rates of rise for Hosojima, to show once more how misleading can be the cherry-picking of short tide gauge records to assess the sea level rate of rise and the acceleration. With data since 1894, the present sea level rate of rise is 0.00137 mm a^{-1}, i.e. zero (Fig. 6c). With 10, 20, 30 or 60 years of data, the latest sea-level rates of rise are -0.66593, 2.08034, 2.07795, and 0.66658 mm a^{-1}. Obviously, the sea level rates of rise computed over short time windows also largely oscillate in time (Fig. 6f). The SLR_{10}, $SLR_{20,}$ and SLR_{30} oscillate because of the natural oscillations very well known in the tide gauge signals, having many periodicities of relevance. Even the SLR_{60} is significantly different from the SLR computed by using the full record length. Figure 6.g is the periodogram of the MSL in Hosojima (analysis from Wessa 2017). Clearly, there are many periodicities of interest, with particularly relevant the quasi-60 years and a 25.6 years periodicity. To complete the picture for the Hosojima tide gauge,

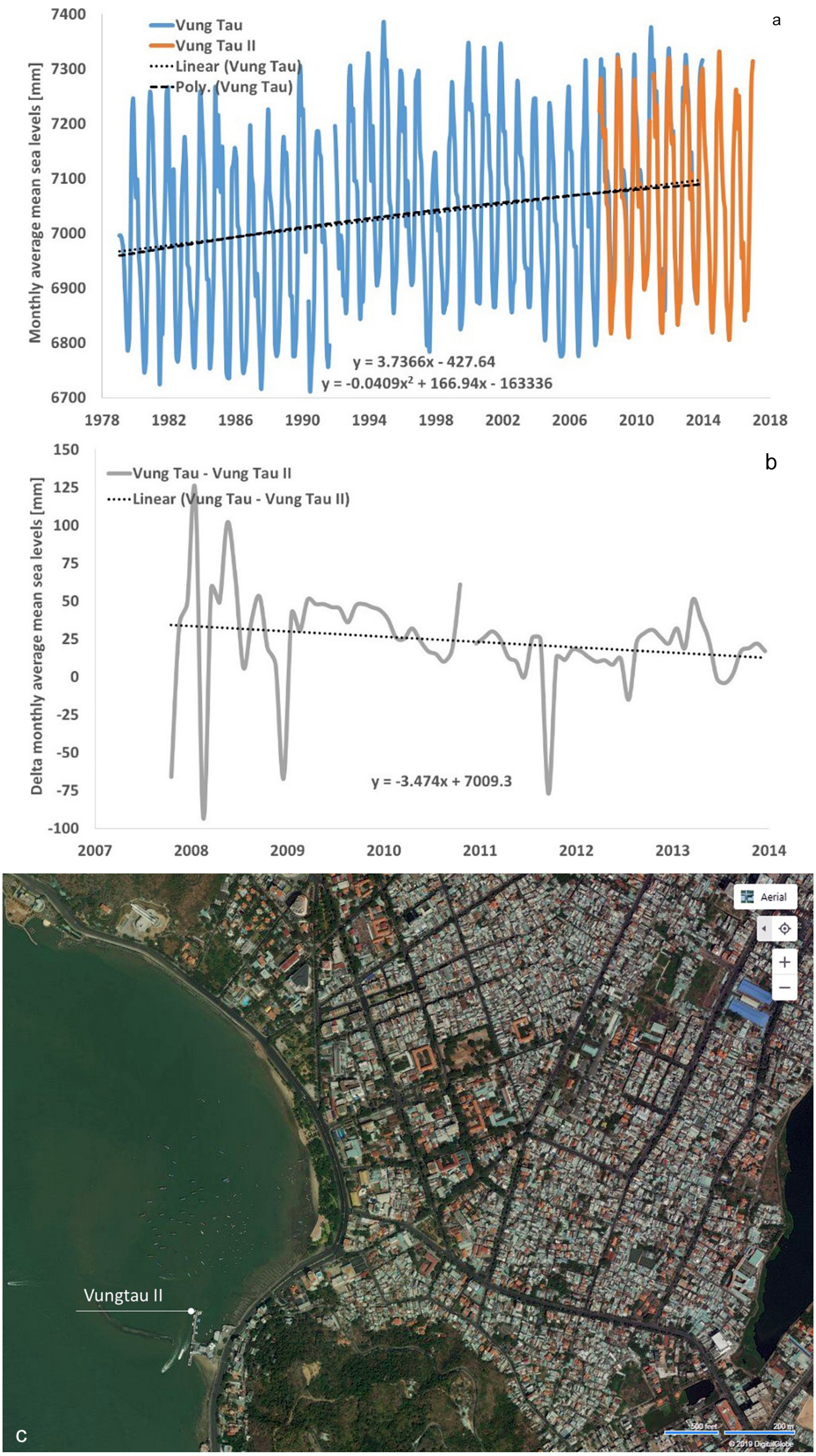
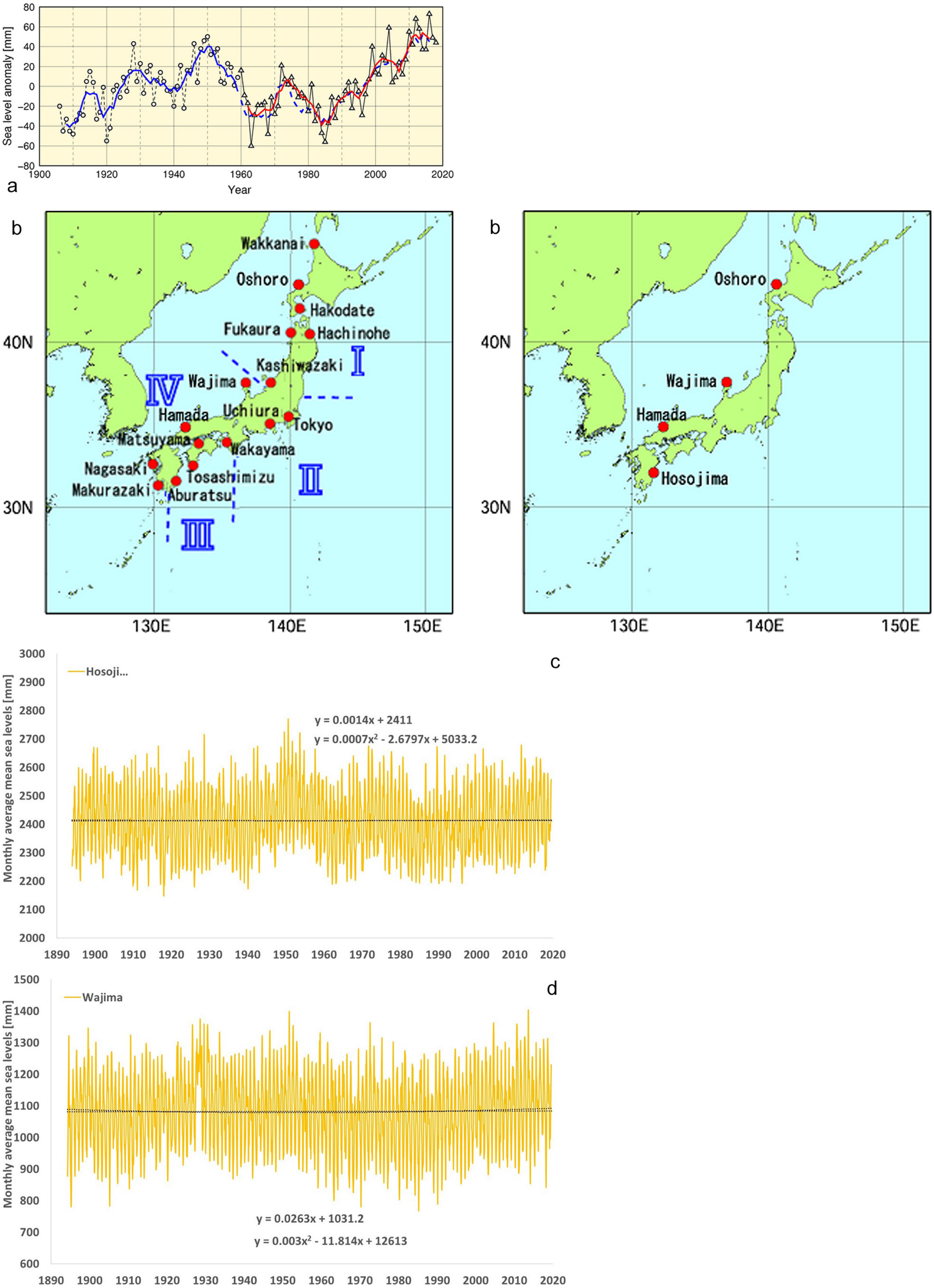


Fig. 5. MSL in Vungtau and Vungtau II (a), and their difference (b). data from (PSMSL, n.d.). (c) aerial view of the area of Vungtau, with evidenced the heavy construction. Image reproduced modified after (Bing 2019).


a
Sea level anomaly [mm]
Year
b
Wakkanai
Oshoro
Hakodate
Fukaura
Hachinohe
Kashiwazaki
Wajima
Hamada
Uchiura
Tokyo
Matsuyama
Wakayama
Nagasaki
Tosashimizu
Makurazaki
Aburatsu
I
II
III
IV
40N
30N
130E
140E
150E
b
Oshoro
Wajima
Hamada
Hosojima
c
Hosoji...
Monthly average mean sea levels [mm]
y = 0.0014x + 2411
y = 0.0007x² - 2.6797x + 5033.2
d
Wajima
Monthly average mean sea levels [mm]
y = 0.0263x + 1031.2
y = 0.003x² - 11.814x + 12613

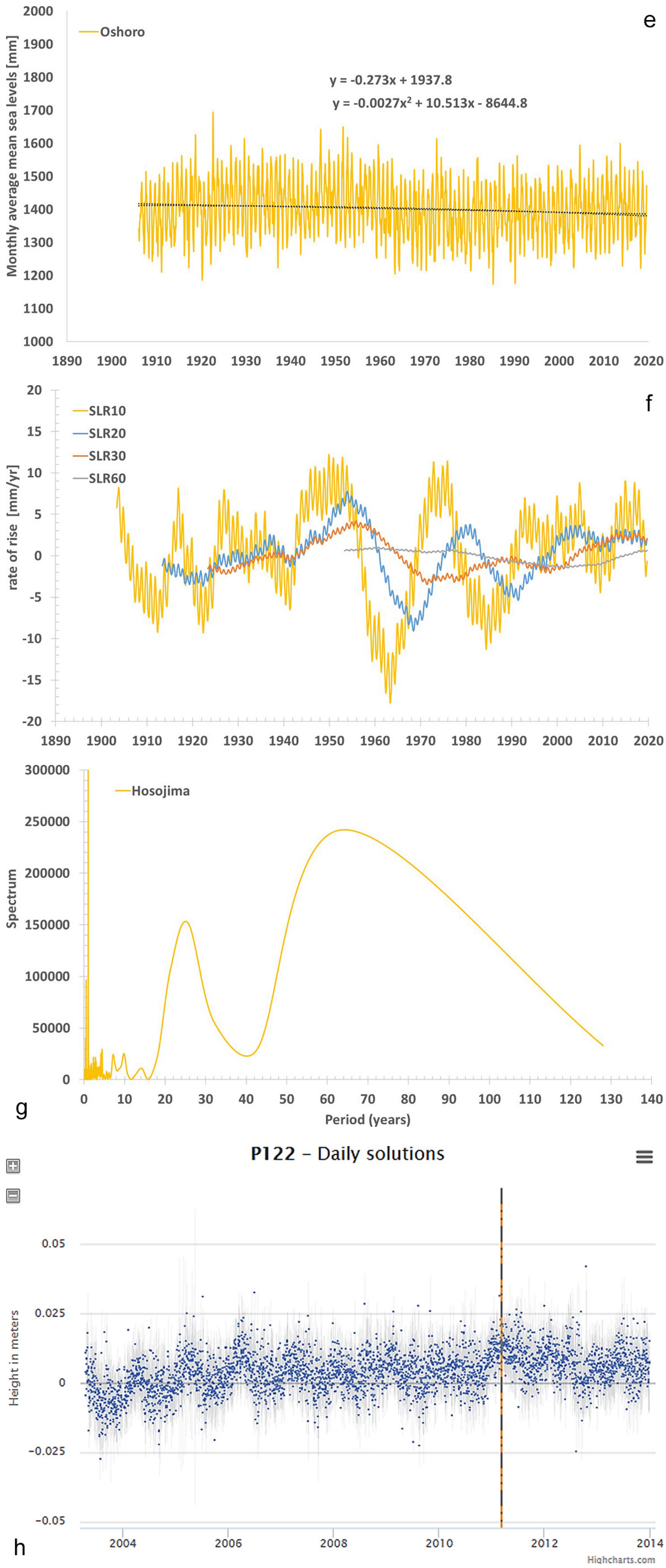


Fig. 6. MSL around Japan according to Japan Meteorological Agency (2018): a) sea-level anomaly, b) locations of the stations affected to a lesser extent by crustal movements. Images (a) and (b) reproduced modified after Japan Meteorological Agency (2018); c), d) and e) MSL of Hosojima, Wajima, and Oshoro. In Hosojima, Wajima and Oshoro there is no sea-level rise and there is no sea-level acceleration; f) short time windows rates of rise for Hosojima; g) position of the GPS antenna close to the Hosojima tide gauge. Image reproduced modified from Système d'Observation du Niveau des Eaux Littorales (n.d.).

this tide gauge has a nearby GPS antenna, P122, at a distance to Tide Gauge of only 5 meters that is operational since 2003. The absolute position of this antenna is presented in Figure 6f (analysis Système d'Observation du Niveau des Eaux Littorales, n.d.). While this signal is considered not robust enough to compute a trend for the subsidence, the land appears to be fairly stable, and certainly not subjected to extreme uplift.

The result of Japan is the only quality long term trend tide gauge result available for East Asia. The average relative rate of rising at the LTT world tide gauges is similarly less than half a millimetre per year with a negligible average acceleration of few micrometres per year squared (Parker, Ollier 2015, 2017). The individual LTT tide gauge records are all characterized by minimal accelerations, sometimes positive and sometimes negative. The lack of any acceleration in the LTT tide gauges' signals is well known in the literature (Douglas 1992, Douglas, and Peltier 2002, Houston, Mörner 2004, 2013, Dean 2011, Boretti 2012, Parker, Ollier 2015, 2017, Fasullo et al. 2016). Other indicators, such as the increasing, rather than shrinking, areas of the emerged atoll islands in the Pacific or the Indian ocean also well-known in the literature (Webb, Kench 2010, Kench et al. 2015, Aslam, Kench 2017, Duvat 2018), support this stable sea level pattern.

Conclusions

The Mekong delta suffers from many issues, the more relevant are the sinking and shrinking. The Mekong Delta reached the present extension about 3.5 ka, with large supplies of water and sediments perfectly balancing the losses. It should not be a surprise that reducing the flow of sediments and water and extracting from the ground more water than what is replenished, an alluvial delta may suffer by soil compaction and eventually collapse. The sinking and shrinking are the results, in minimal extent, of the thermosteric sea level rise, and in a much larger extent, of the subsidence generated by excessive groundwater withdrawal and construction of dams in the upper basin that is limiting the flow of water and sediments to the Delta. The subsidence is more than an order of magnitude larger than the thermosteric sea level rise, even at the rates predicted by the Intergovernmental Panel on Climate Change, that are likely overrated., as shown by the tide gauges' result. While other anthropogenic factors are also considerable, their influence is certainly less. It is the control of the two main drivers, excessive groundwater withdrawal, and reduction of the flow of water and sediments that will eventually determine the future of the delta within this century.

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