Sea Level Trends Around Indonesia From Altimetry and Tide Gauge Data

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Introduction

Indonesia consists of thousands of islands with large populations inhabiting the low-elevation coastal areas. The global sea level rise (SLR) in response to ocean warming and ice melting has locally important impacts. Therefore, an understanding of the past and future changes in sea level is here of utmost importance.

Sea Level Change in 1993-2011

Data

- The tide gauge stations (TG) installed by the Coordinating Agency for Surveys and Mapping (BAKOSURTANAL) (80) as well as by IOC (Intergovernmental Oceanographic Commission) and the JASL (Joint Archive for Sea Level) (Fig. 1) are monitoring sea level. One-minute data is available the IOC real-time monitoring facility (http://www.ioc-sealevelmonitoring.org/). Within the German Indonesian Tsunami Early Warning System (GITEWS) project and as a contribution to the Indonesian Tsunami Early Warning System (InaTEWS), Germany has provided 10 GPS-controlled tide gauges, installed on sites at the islands of Sumatra, Java, Sumba, and Rote facing the Indian Ocean (Fig. 1).

Methodology

- Four tide gauge stations (Benoa, Jakarta, Sibolga and Surabaya) have been selected based on the data availability over 1993-2011. Hourly tide gauge data are from UHSLC (http://ilikai.soest.hawaii.edu/uhslc/rqds.html) and from BAKOSURTANAL, the National Coordinating Agency for Surveys and Mapping in Indonesia. Monthly averages are computed.
- Multi-mission satellite data have been merged in monthly grids of 0.2 degree spacing (Gaussian weighted method, half-weight of 1 degree and search radius of 150 km). The linear trend has been estimated at each grid point (Fig. 5).
- At each grid point the linear trend (T) and the annual (A) and semi-annual (SA) signals have been evaluated separately for the altimeter and TG time-series through a least-squares (LSQ) procedure.
- For each TG a co-located altimeter time-series has been selected corresponding to the nearest point in the multi-mission altimeter grid.
- The jumps in TG time-series are corrected by considering the difference before and after the discontinuity.

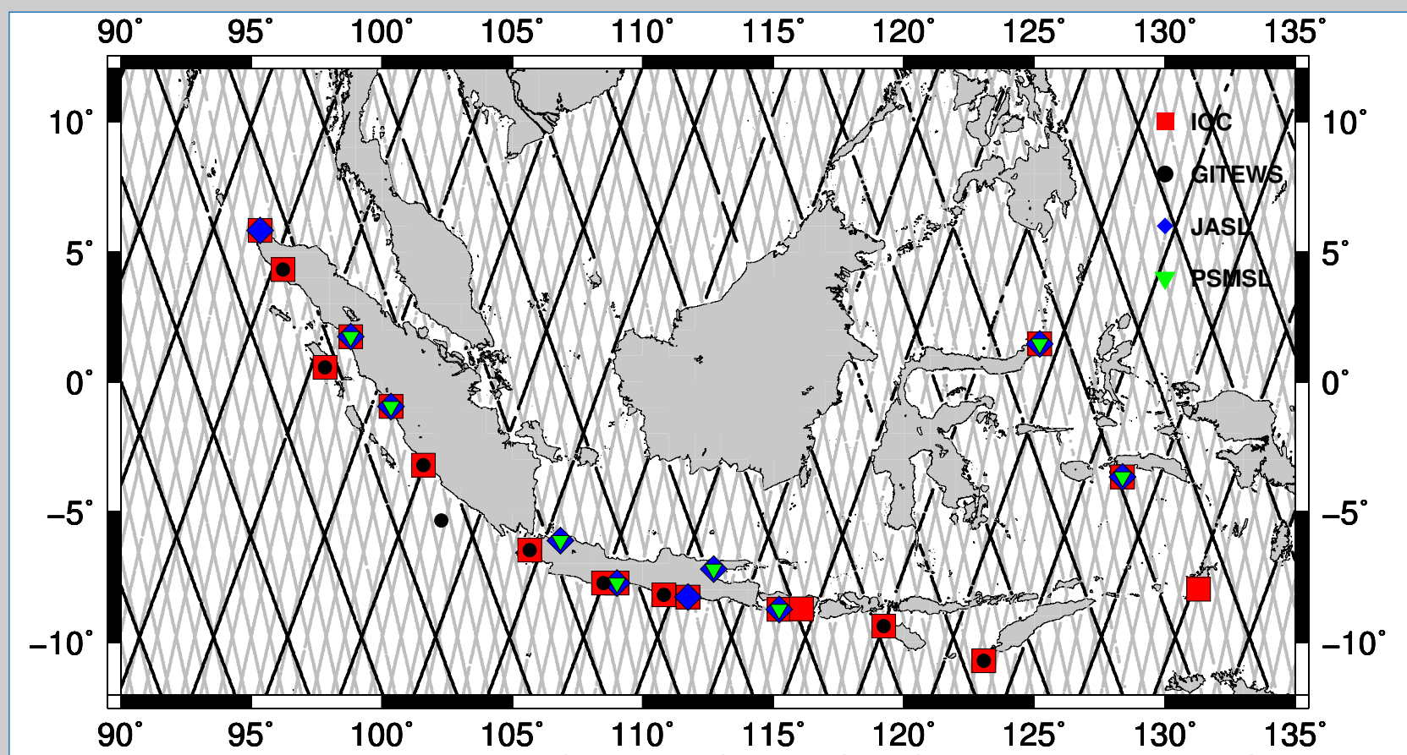

Fig. 1 Tide gauges of IOC, JASL, PSMSL and GITEWS

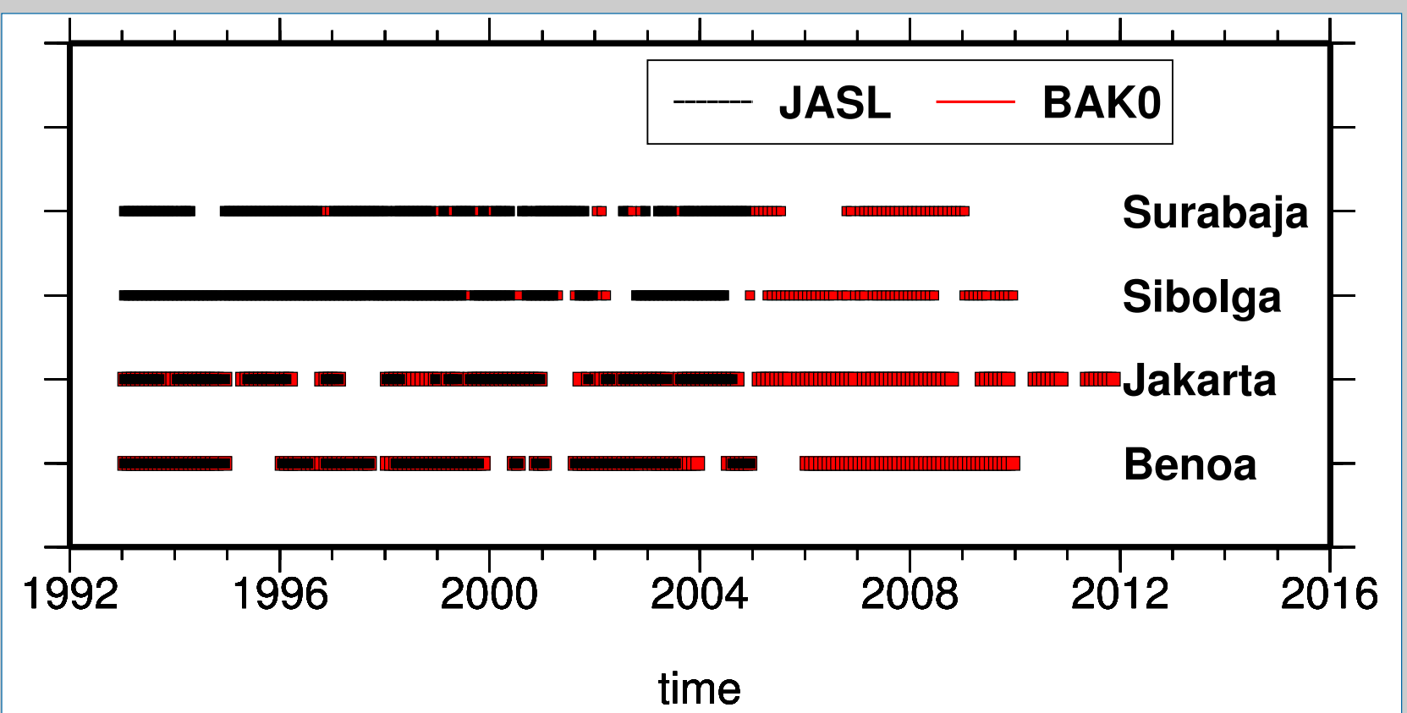

Fig. 2 Time availability of the tide gauge data from the JASL and BAKOSURTANAL databases used here in combination

Results

- Satellite altimetry indicates a positive sea level rise with mean of 4 mm/yr, which is higher than the global averaged mean sea level rise. The rates of sea level change computed from multi-mission altimeter data are positive and vary spatially from 1 to 16 mm/yr. In the open sea the trends are higher than in the marginal seas (Fig.5)
- Common oceanic signals characterize all time-series (Figs. 2-3). The strong signature of the El-Nino Southern Oscillation (ENSO), a forcing mode of the coupled Atmosphere-Ocean system, dominates the inter-annual variability. Its signature is characteristic for the sea level in the entire Indonesian region, as shown by the PCA decomposition of the de-seasoned and de-trended sea level time-series. The first four modes are statistically significant and explain together 81% of the variance of sea level during 1993-2011 in the selected region. The first mode, that accounts approximately for 60% of the total variance, corresponds to an oscillation in phase of the entire basin (Fig. 4). Its temporal pattern (Fig. 3) has a correlation 0.62 with the inverted Global-SST ENSO index, which captures the low-frequency frequencies of the ENSO phenomenon

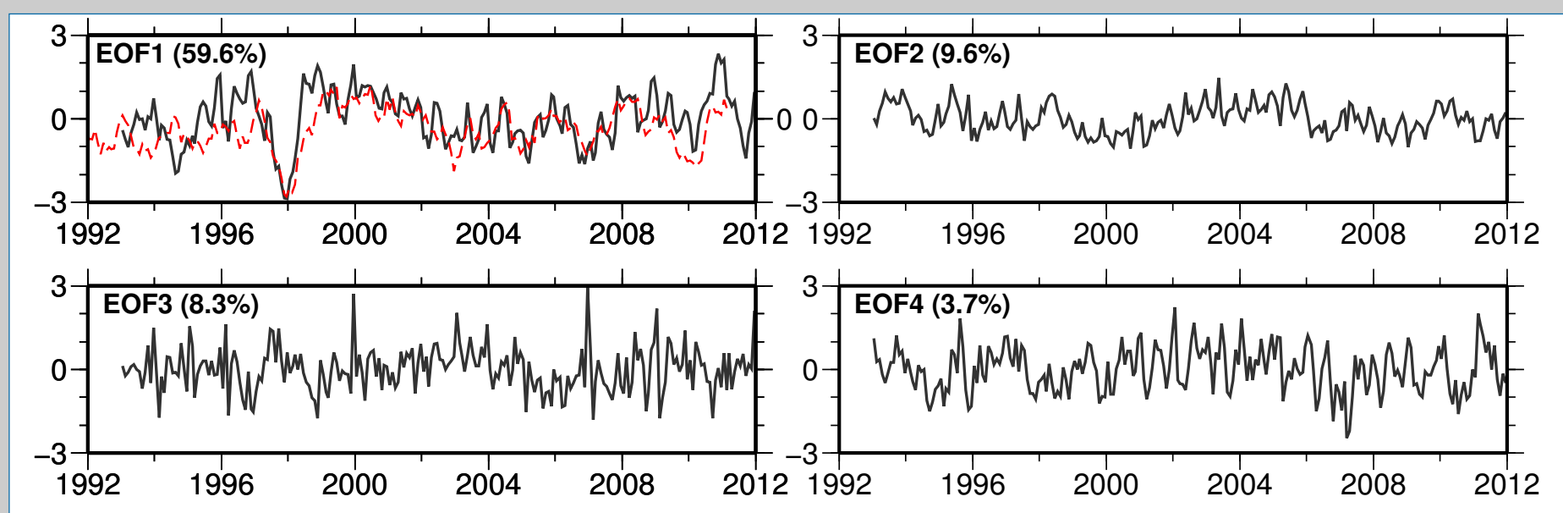

Fig. 3 First temporal coefficients of PCA decomposition of sea level

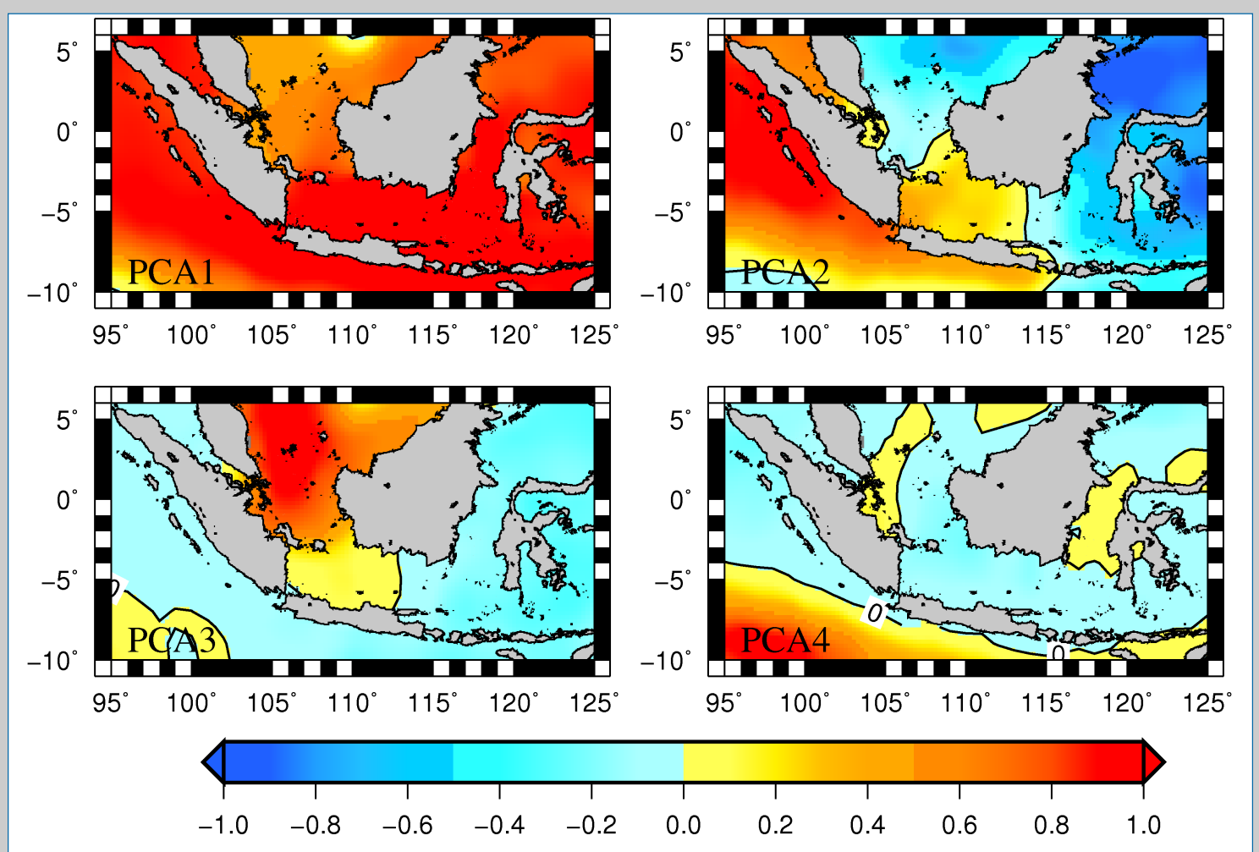

Fig. 4 Spatial patterns corresponding to Fig. 3

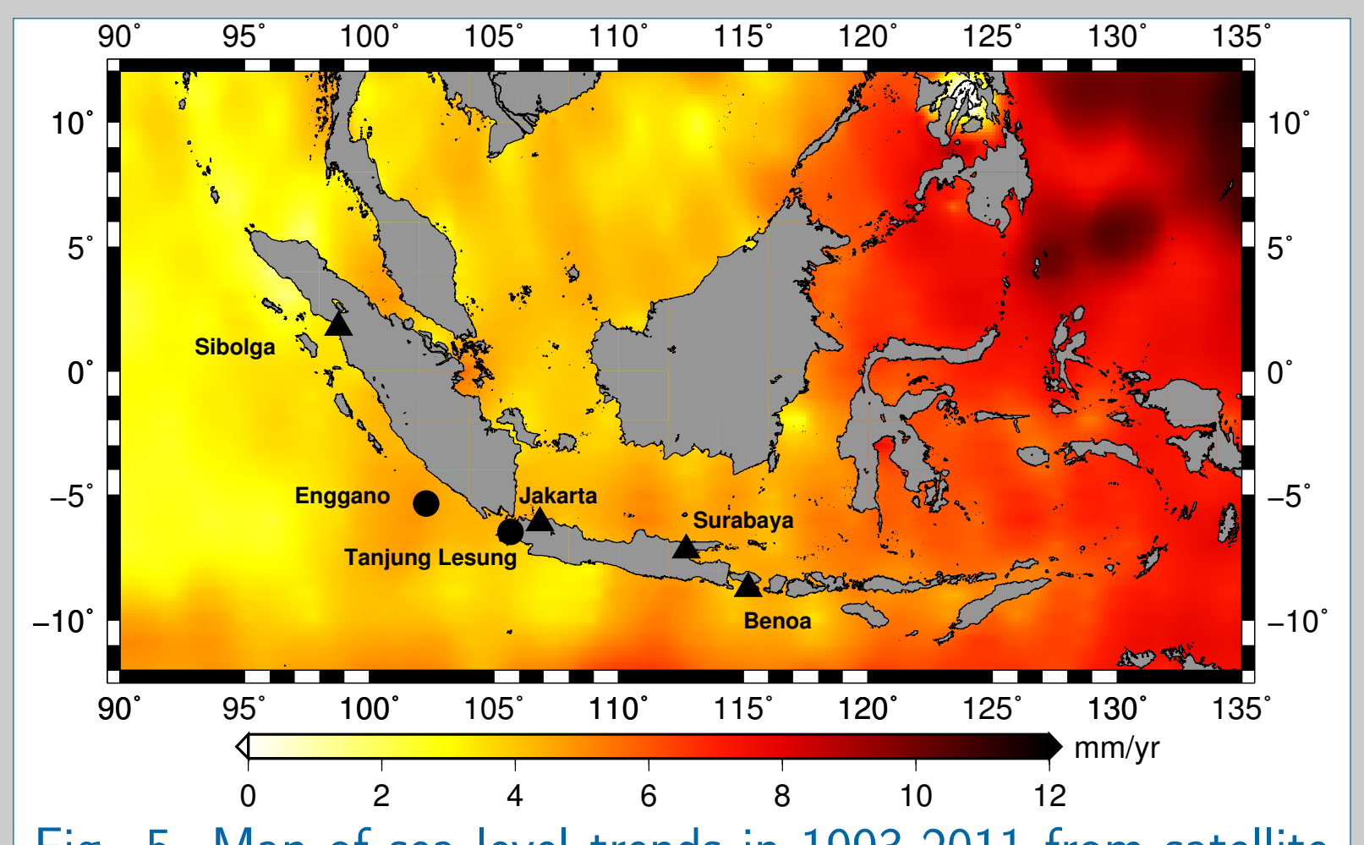

Fig. 5 Map of sea level trends in 1993-2011 from satellite altimetry

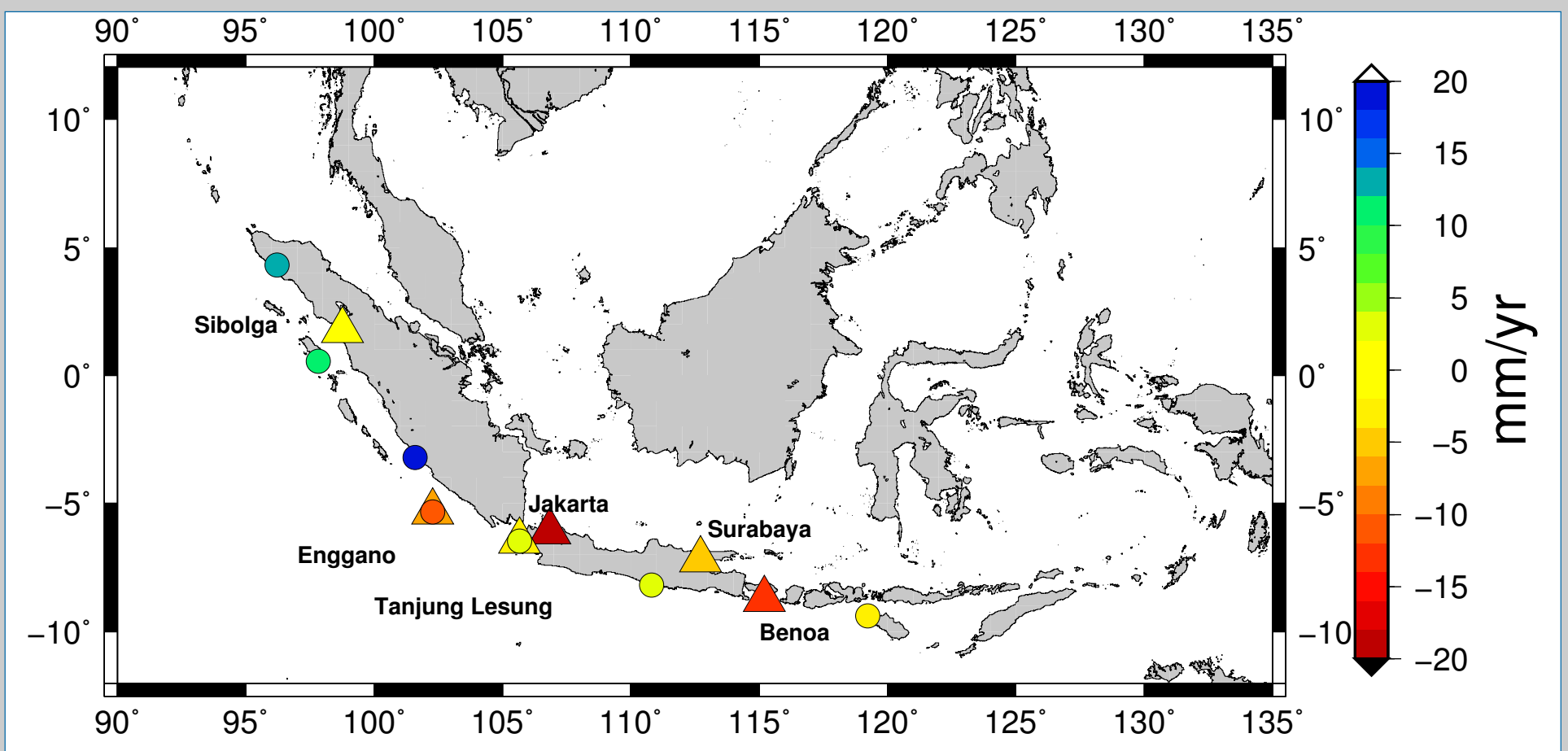

Fig. 6 Land vertical motion from altimetry minus tide gauges (triangle) and from GPS (circle).

Station	Altimetry (mm/yr)	Tide Gauge (mm/yr)	AL-TG (mm/yr)	Distance (km)	Correlation Correlation	RMSD (mm)	CI percent
Benoa	3.2 ± 1.1	14.8 ± 4.3	-11.9 ± 1.4	6.7	0.687	124	94
Jakarta	3.8 ± 1.0	23.1 ± 1.5	-19.7 ± 1.6	14.4	0.48	146	94
Sibolga	2.4 ± 1.2	0.6 ± 1.3	1.9 ± 1.3	25.2	0.70	73	94
Surabaya	3.8 ± 1.0	8.8± 1.2	-5.3 ± 2.3	8.9	0.65	66	89

Tab 1: Vertical land motion from monthly time-series at tide gauge and corresponding nearest altimeter point grid, correlation, root mean square differences (RMS) and completeness index (CI)

Sea Level Change in 1993-2011

- Fig. 7 shows jumps in reference level of the tide gauge records.
- Also after correction for jumps (Fig. 8, Tab. 1), the difference of the sea level trends from tide gauge and co-located satellite altimetry is in general greater than 3 mm/yr. In Sibolga altimetric and in-situ sea level have the highest correlation (0.7) and the most similar trends.
- Gaps in tide gauge data are significant, see completeness index (CI) in Tab.1
- the residual difference between the sea level measured by TG and altimetry is caused by vertical movements and/or by small unknowns jumps in the zero reference level of the tide gauge

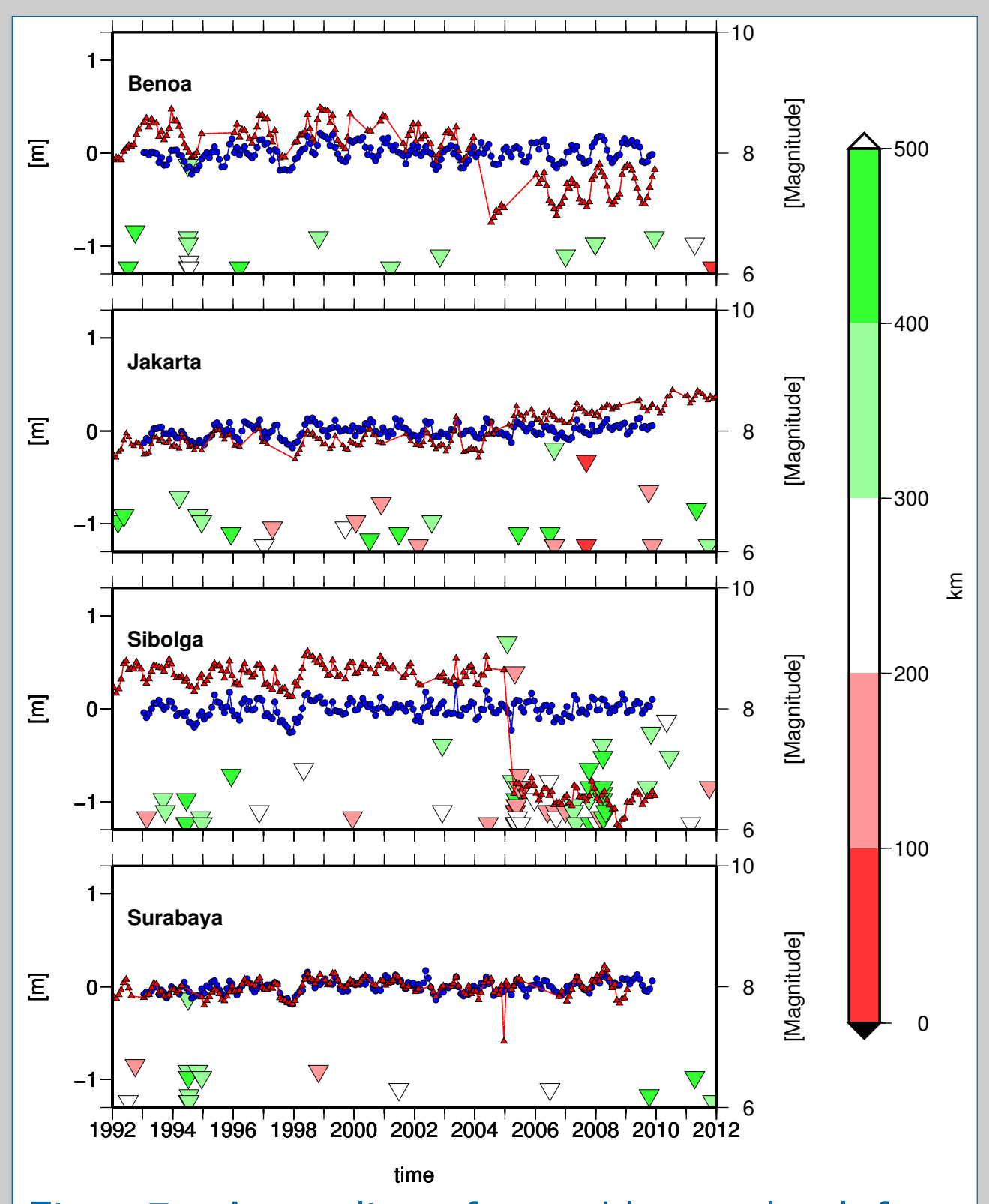

Fig. 7 Anomalies of monthly sea level from tide gauge (triangle) and from co-located altimetry (circle) data. Inverted triangles indicate earthquakes of magnitude higher than 6 in a radius of 500 Kilometers from the station.

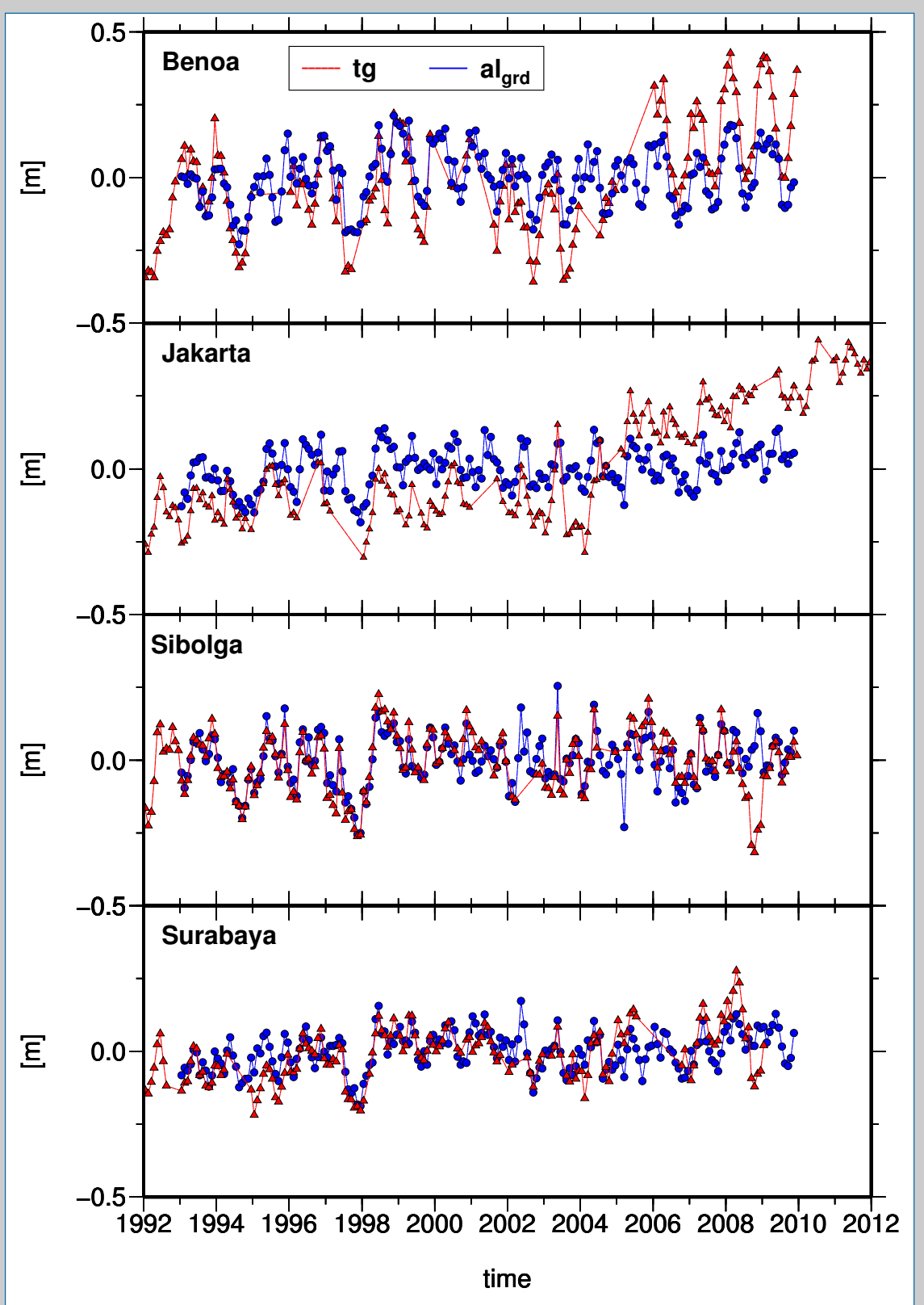

Fig. 8 Anomalies of monthly sea level in Figure 6, here corrected for jumps in the records using Eq. 3.

Sea Level at GPS-controlled tide gauges

- The GPS-controlled tide gauge stations allow a continuous monitoring of both sea level (with automated alert in case of rapid sea level change) and of the (vertical) movement of the tide gauge station itself.
- Table 2 provides GPS rates for additional GITEWS stations, computed taking into account the gaps +/- 0.6 mm/yr in Sadeng) than for stations in Sumatra (uplift of 10.1 +/- 0.4 mm/yr in Teluk Dalam, 13.9 +/- 4.1 mm/yr in Meulaboh, 19.2 +/- 1.7 mm/yr in Seblat).

  Table 3 compares vertical rates derived from both sea level differences (altimeter - tide gauge) (Fig. 9) with the GPS values at two stations. In Enggano the vertical land subsidence computed as al-tg rate, is -7.2 +/- 2.4 mm/yr, which is in agreement with the GPS-derived rate of -11.1 +/- 0.5 mm/yr. In Tanjung Lesung the al-tg rate is not significant (-3.9 +/- 4.6 mm/yr) and also the GPS-derived rate (2.2 +/- 0.5 mm/yr) does not indicate a high vertical land movement. At both stations the agreement between altimeter and tide gauge time-series (correlation higher than 0.93 and RMSD smaller than 30 mm for monthly time-series) is higher than for the four stations in Table 1. In Fig. 6 the GPS-derived rates (circle) and the a-tg rates (triangle) are compared.

Station	North	East	Up
MEUL	-34.5 ± 1.35	-15.51 ± 1.46	13.94 ± 4.06
GANO	8.06 ± 0.19	20.9 ± 0.16	-11.13 ± 0.51
SADE	-7.56 ± 0.21	28.92 ± 0.17	3.6 ± 0.61
SEBL	-34.34 ± 0.85	-20.48 ± 0.81	19.20 ± 1.76
TDAL	1.46 ± 0.19	5.19 ± 0.2	10.09 ± 0.44
TJLS	-5.48 ± 0.17	25.8 ± 0.16	2.2 ± 0.49
WAIK	16.72 ± 0.23	31.07 ± 0.19	-2.85 ± 0.56

Tab 2: GPS rates (mm/yr) at the cGPS@TG stations

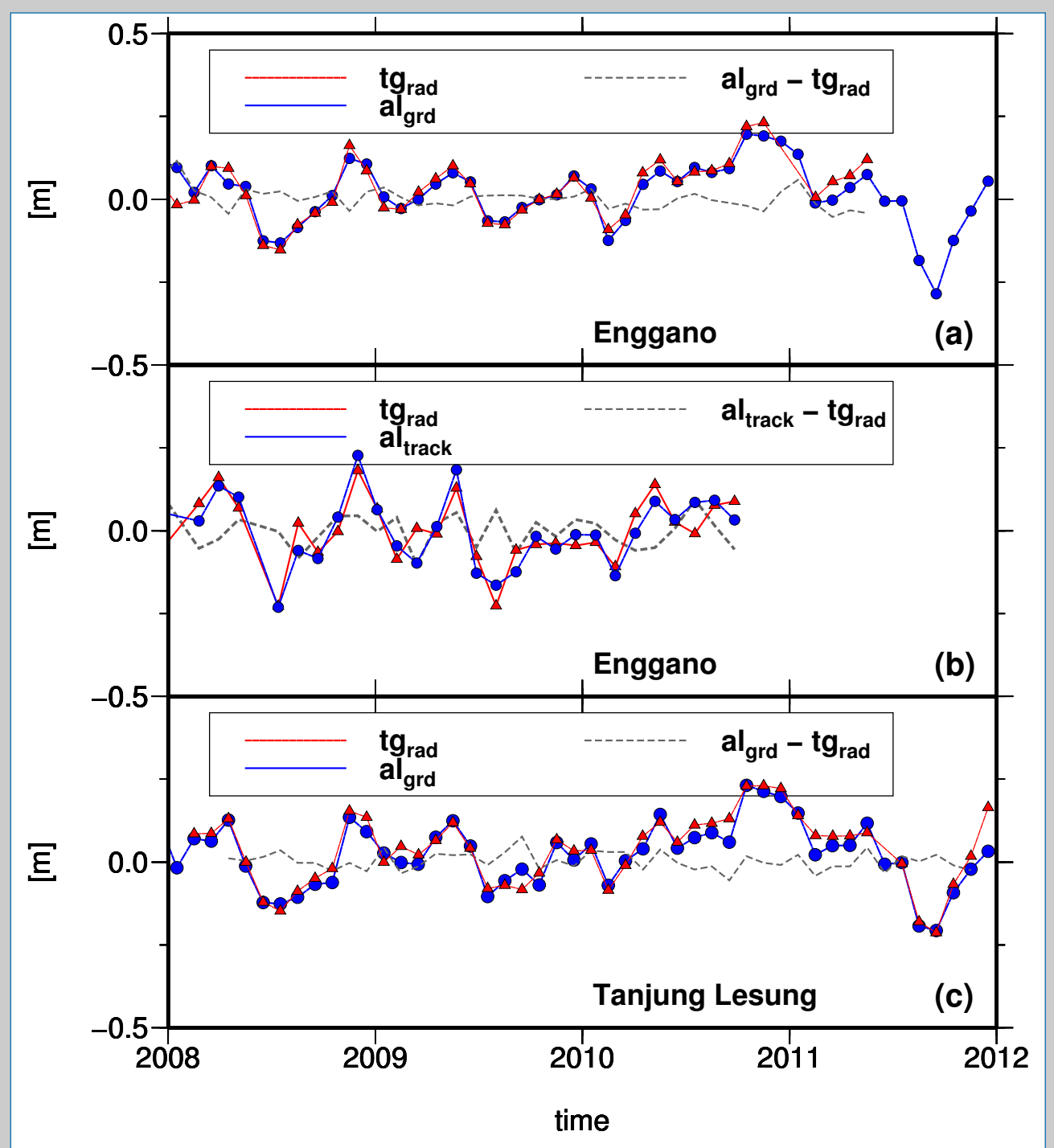

Fig. 9 Anomalies of sea level from altimetry, tide gauge (triangle) data and their difference in Enggano (a,b) and Tanjung Lesung (c). For Enggano results are shown from both gridded monthly (a) and along-track daily analysis (b).

Station	AL-TG (mm/yr)	Distance (km)	Correlation	RMSD (mm)	CI	GPS up (mm/yr)
Enggano	-7.2 ± 2.4	20.0	0.95	29	99	-11.1 ± 0.5
Tanjung Lesung	-3.9 ± 4.6	22.0	0.97	30	99	2.2 ± 0.5

Tab 3: Vertical land motion from tide gauge and nearest altimeter point grid, the same from GPS

Conclusions

- In 1993-2009 satellite altimetry shows a positive sea level trend larger than the global mean.
- Local geodynamic activity affects changes in the reference level of tide gauge data at many stations
- subsidence at various location is detected from both altimetry minus tide gauge and by GPS observations
- climate-related sea level rise is reinforced by vertical land movements of similar or even larger magnitude and therefore its impact on coastal areas should be seriously considered.

References

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