Contribution of vertical land motions to coastal sea level variations: A global synthesis of multisatellite radar altimetry, tide gauge and GPS measurements

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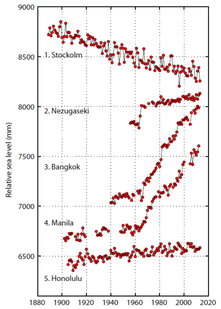
Scientific questions

In coastal areas, vertical land motions are a source of noise that can mask sea level signals induced by climate change. Since tide gauges are bound to the coasts, their records are directly affected by vertical land motions, which contributes to the considerable scatter of the rates of global mean sea level rise so far assessed using the few long records available[1].

In addition, vertical land motions contribute actively to the sea level changes felt by coastal populations, as they can amplify, diminish or counter the effects of climate-induced sea level changes[2]. In many cases, vertical land motions have been recognized as a dominant component of the total relative sea level variations observed at coasts.

Various geophysical processes impact tide gauge records. They may have a tectonic, volcanic or anthropogenic origin such as groundwater pumping. Vertical land motions also arise in response to the redistribution of sea, air, ice or inland water masses at the Earth surface.

An accurate determination of the vertical land motions occurring at coasts is therefore necessary to understand the processes which contribute to sea level rise, to appraise its impacts on coastal populations and make future predictions.



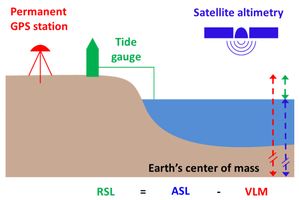
Geophysical signals in tide gauge records (http://www.psmsl.org).

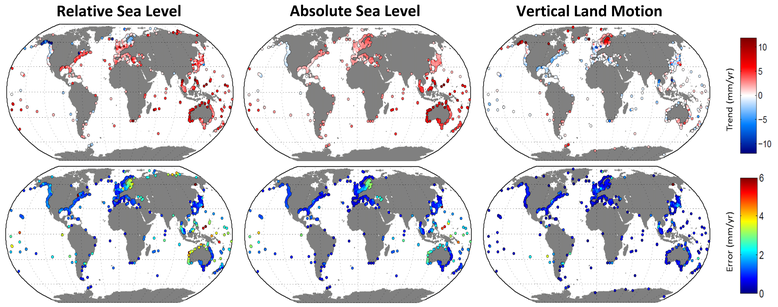
ALTIGAPS: Altimetry, Tide Gauges and GPS

ALTIGAPS combines multisatellite radar altimetry, tide gauge and GPS data acquired in coastal areas from November 1992 until July 2013. Data are processed to extract linear trends and their uncertainties:

- **Relative sea level changes (RSL)** are the changes in sea level with respect to the coast. They are measured at tide gauges and evaluated at GPS stations as the difference between altimetry and GPS data.
- **Absolute sea level changes (ASL)** are the changes in sea level with respect to the center of mass of the Earth. They are measured by multisatellite radar altimetry over all the oceans except at very high latitudes.
- **Vertical land motions (VLM)** are the vertical displacement of the coast itself observed with respect to the center of mass of the Earth. They are directly measured at GPS stations and can be evaluated as the difference between altimetry and tide gauge data.

Sea level budget at coasts





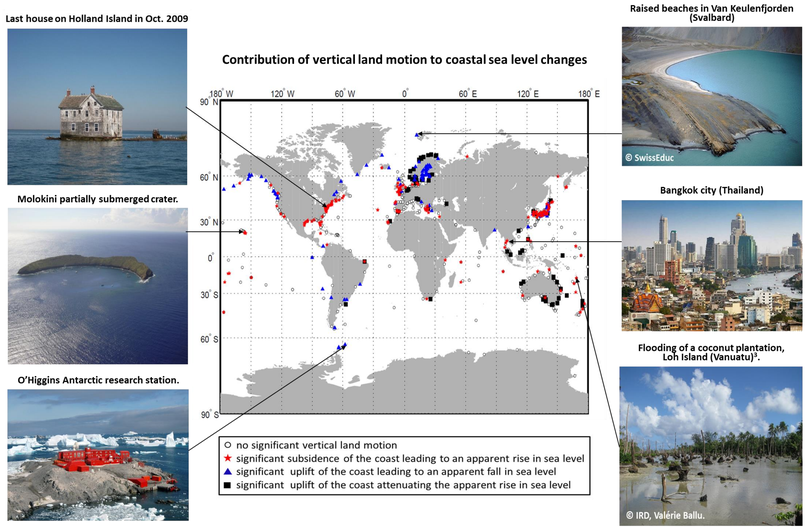
Relative Sea Level	Absolute Sea Level	Vertical Land Motion
Signal range: - 20 to 17 mm/yr	**Signal range:** - 2 to 12 mm/yr	**Signal range:** -13.5 to 16 mm/yr
Global average: +2.5 mm/yr	**Global average:** +2.8 mm/yr	**Global average:** +0,1 mm/yr
Error range: 0.4 to 12.2 mm/yr	**Error range:** 0.3 to 8.4 mm/yr	**Error range:** 0.1 to 7.4 mm/yr
Median error: 1.2 mm/yr	**Median error:** 1 mm/yr	**Median error:** 0.6 mm/yr

Why use ALTIGAPS?

- Global coverage: network of 886 stations, including 628 tide gauges and 258 permanent GPS stations.
- Longer period of observation: from November 1992 to July 2013 (update coming in July 2016).
- Multivariate approach: information about absolute sea levels, relative sea levels and vertical land motions.
- Multitechnique approach: data from multisatellite radar altimetry, tide gauges and GPS stations.
- Improved accuracies: median errors ~ 1.2 mm/yr, 1 mm/yr and 0.6 mm/yr for RSL, ASL and VLM trends.
- Data are published[2] and freely available online (e.g. http://julia-pfeffer.weebly.com).
- New applications for the investigation of sea level changes, crustal deformation and coastal hazards.

Coastal sea level changes: climate change or tectonic activity?

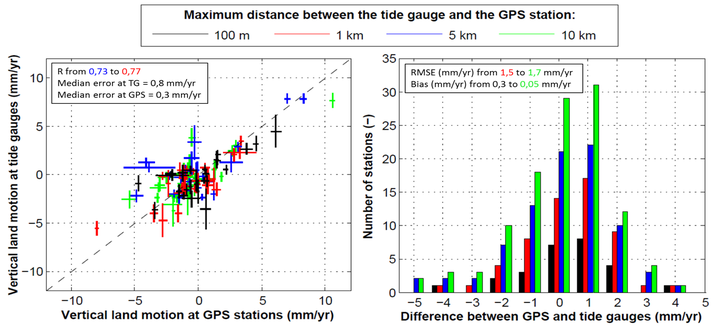
Here, geodetic data are used to better assess and understand the natural hazards associated with sea level rise in coastal areas. Vulnerable coastal areas are identified by positive relative sea level trends, i.e. an apparent rise of the sea relative to the coast, which can either be due to an absolute rise of the sea or to the subsidence of the coast. We evidence here the role of crustal motions, which are often neglected because they are considered local. Their evaluation constitutes however a global issue because all coasts are affected by local deformation processes with various origins.



The role of the crust in coastal hazards is highly heterogeneous: it can amplify, restrict or counter the effects of climate-induced sea level rise. Worldwide, vertical land motions dominate 30 % of observed coastal trends. A set of 182 potential vulnerable localities are identified by large coastal subsidence which increases by several times the effects of sea level rise.

Comparison of trends at colocated stations

VLM trends are compared at neighboring tide gauges and GPS stations. A maximum distance of 10 km is fixed to pair trend estimates, which results in 113 couples of values. The agreement between tide gauge and GPS estimates is good.



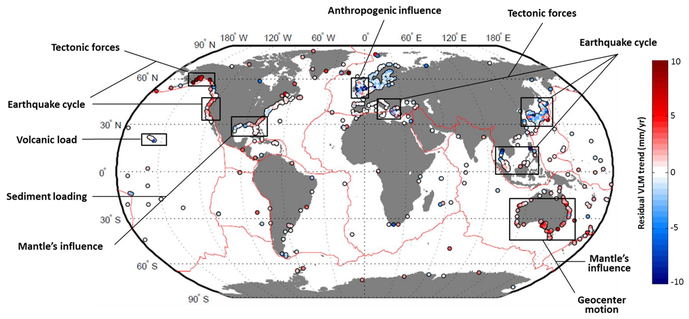
The comparison of trends in vertical land motions at colocated tide gauge and GPS stations is considerably better than previous studies, probably due to the use of a longer data records and to the larger number of sites compared.

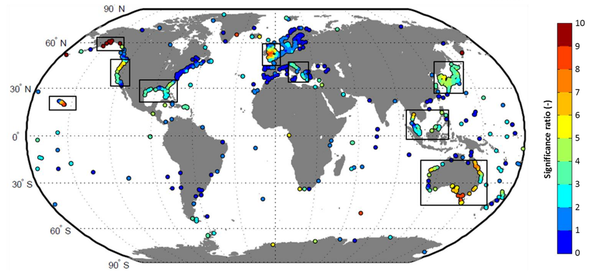
Trend computed as altimetry - tide gauge	No. of sites in the database	Method of comparison	Period of observation (yr)	No. of sites compared	R (-)	RMSE (mm/yr)
ALTIGAPS[2]	886	GPS	20.75	113	0.77	1.7
Ostanciaux et al., 2012[4]	634	DORIS	17	14	0.08	1.16
Ostanciaux et al., 2012[4]	634	GPS	17	57	0.40	2.65
Ray et al., 2010[5]	28	DORIS	16.5	28	0.56	2.7
Nerem & Mitchum, 2002[6]	114	GPS	7.5	33	0.35	-

Causes of vertical land motions observed at coasts

Some of the causes of the vertical deformation of the continental coastal platforms are studied by modeling. The deformation of the crust due to global atmospheric (ECMWF), oceanic (ECCO) and hydrological (ERA-Interim) circulation are modeled using elastic transfer functions coupled with global circulation models. Particular attention is paid to the effects of glacial isostatic adjustment (GIA) related to past deglaciations and current ice-melting. Different GIA models are tested, taking into account a wide range of Earth rheological parameters and a wide range of current ice-melting rates[7,8]. That way, we provide a group of scenarios, with a mean model output and a standard deviation associated with the range of variability of VLM predictions. The effects of glacial isostatic adjustment caused by current ice-melting and past deglaciations can explain up to 80% of observed VLM variance at scales larger than 300 kilometers and in well instrumented regions.

Local residual VLM signal is evidenced worldwide, in particular along plate boundaries due to the earthquake cycle. To identify significant residual vertical land motions, we compute an adimentional significance ratio (SR) as the residual VLM signal by the cumulative uncertainty on models and observation. Significant residual VLM signal is observed over nine well instrumented regions, forming observations windows on the geodynamical processes responsible for the vertical deformation of the Earth's surface. Such processes are not necessarily limited to these areas, but will elsewhere be masked by inaccurate VLM predictions and observations.





Take home messages

ALTIGAPS takes full advantage of the data acquired with **multisatellite radar altimetry, tide gauge and GPS** in coastal areas over the past 20 years.

Vertical land motions and **absolute sea level variations** are estimated simultaneously for a network of 886 ground stations with median individual accuracies of about 0.6 and 1 mm/yr respectively.

Recent climatic processes responsible for the sea level changes can be studied independently of the subsidence or uplift of the coast.

New constraints are brought on the vertical deformation of the coastal continental platforms, mainly due to the on-going effects of the glacial isostatic adjustment and the plate tectonics activity.

ALTIGAPS can help to evaluate, understand and predict the natural hazards associated with changing sea levels in coastal areas.

Acknowledgments

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The release of free tide gauge, multisatellite radar altimetry and GPS data by PSMSL (www.psmsl.org), Aviso (www.aviso.altimetry.fr) and SONEL (www.sonel.org) was essential to complete this work and we warmly thank these services.

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