Earth and Planetary Science Letters 473 (2017) 24–32

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Uncertainty of the 20th century sea-level rise due to vertical land motion errors

Alvaro Santamaría-Gómez[a,b,*,1], Médéric Gravelle[a], Sönke Dangendorf[c], Marta Marcos[d], Giorgio Spada[e], Guy Wöppelmann[a]

[a] LIENSs, Université de la Rochelle – CNRS, 2 rue Olympe de Gouge, 17000 La Rochelle, France
[b] School of Land and Food, University of Tasmania, Hobart, Australia
[c] Research Institute for Water and Environment, University of Siegen, Siegen, Germany
[d] Mediterranean Institute for Advanced Studies, UIB-CSIC, Esporles, Spain
[e] Dipartimento di Scienze Pure e Applicate, Università degli Studi di Urbino Carlo Bo, Urbino, Italy

ARTICLE INFO

Article history:
Received 8 November 2016
Received in revised form 22 May 2017
Accepted 24 May 2017
Available online 9 June 2017
Editor: P. Shearer

Keywords:
vertical land motion
GPS
GIA
reference frame
tide gauges
sea-level reconstruction

ABSTRACT

Assessing the vertical land motion (VLM) at tide gauges (TG) is crucial to understanding global and regional mean sea-level changes (SLC) over the last century. However, estimating VLM with accuracy better than a few tenths of a millimeter per year is not a trivial undertaking and many factors, including the reference frame uncertainty, must be considered. Using a novel reconstruction approach and updated geodetic VLM corrections, we found the terrestrial reference frame and the estimated VLM uncertainty may contribute to the global SLC rate error by ± 0.2 mm yr^{-1}. In addition, a spurious global SLC acceleration may be introduced up to $\pm 4.8 \times 10^{-3}$ mm yr^{-2}. Regional SLC rate and acceleration errors may be inflated by a factor 3 compared to the global. The difference of VLM from two independent Glacio-Isostatic Adjustment models introduces global SLC rate and acceleration biases at the level of ± 0.1 mm yr^{-1} and 2.8×10^{-3} mm yr^{-2}, increasing up to 0.5 mm yr^{-1} and 9×10^{-3} mm yr^{-2} for the regional SLC. Errors in VLM corrections need to be budgeted when considering past and future SLC scenarios.

1. Introduction

For nearly two hundred years, the sea level has been observed directly by self-recording instruments named tide gauges (TG) even though they actually record other processes than the oceanic tide (Pugh and Woodworth, 2014). In particular, on decadal to centennial timescales, TGs record climate-related changes in sea levels associated with ocean heating, land–ice melting or water mass redistribution. They also record changes in the shape of the Earth's crust associated with Glacio-Isostatic Adjustment (GIA) and dynamic topography, plate-tectonics or compaction processes. Not surprisingly, long TG records can provide reliable constraints to better probe climate or geophysical models (Munk, 2002; Smith-Konter et al., 2014). Since the basic quantity recorded with a TG is the local sea level relative to the local solid Earth, one should be cautious when dealing with signals in the TG records that can be considered either a sea-level process or a solid-Earth process. These signals can indeed display similar magnitude and temporal variability in a TG record, including the long-term trend, and are thus difficult to disentangle without independent supplemental information.

The sea-level observations from TG records can be described as:

$$RSLC = ASLC - VLM \tag{1}$$

where *RSLC* represents the observed relative sea-level change (SLC), *ASLC* represents the absolute SLC with respect to the Earth's center of mass and *VLM* represents the vertical land motion. Eq. (1) is often called the sea-level equation; see e.g. Spada (2017) for a review. Further separating the different contributions in Eq. (1) we obtain:

$$RSLC = ASLC_{GIA} + ASLC_{atm} + ASLC_{clim} - VLM \tag{2}$$

where $ASLC_{GIA}$, $ASLC_{atm}$ and $ASLC_{clim}$ represent the GIA-induced absolute SLC, the impact of the atmospheric/oceanic dynamics and the climatic-related SLC, respectively.

In this study, we adopt the climate-related sea-level perspective in which $ASLC_{clim}$ is the quantity sought from the *RSLC* observations after accounting for all the other terms in Eq. (2). In

---

* Corresponding author.
E-mail address: alvaro.santamaria@get.omp.eu (A. Santamaría-Gómez).

[1] Now at: GET, Observatoire Midi–Pyrénées, Université de Toulouse, CNRS, IRD, 14 avenue Edouard Belin, F-31400 Toulouse, France.

http://dx.doi.org/10.1016/j.epsl.2017.05.038
0012-821X/

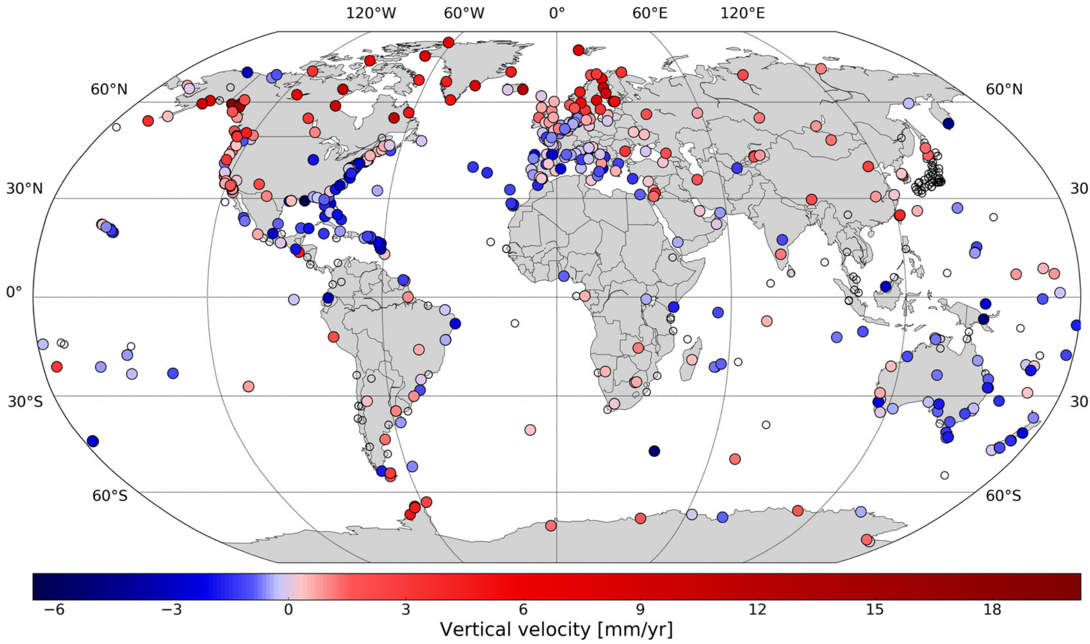

Fig. 1. GPS tracking network used in the ULR6 solution (circles) with the estimated vertical velocities (color bar). Small open circles indicate that a robust velocity estimate could not be obtained due to insufficient data, velocity discontinuities or clear non-linear series. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

particular, we focus on how a limited knowledge of the VLM at TGs can affect the estimate of $ASLC_{clim}$ at global and regional scales. $ASLC_{GIA}$ and $ASLC_{atm}$ need also to be accounted for in order to obtain $ASLC_{clim}$, but we will not discuss these terms here or how uncertainties in these terms propagate into $ASLC_{clim}$ estimates. Henceforth, we will refer to $ASLC_{clim}$ as SLC for simplicity.

Within this context, it is worth noting the following two remarks. First, the temporal information evidencing 20th century SLC comes primarily from individual TG trends (Douglas, 1991; Spada and Galassi, 2012) or from sea-level reconstructions (Church and White, 2006; Hay et al., 2015; Jevrejeva et al., 2006; Ray and Douglas, 2011). Second, VLM corrections are obtained mostly from GIA models, assuming both the linearity of VLM over the TG record and a negligible non-GIA linear VLM. Recently, an alternative probabilistic method has been proposed to minimize the impact of non-GIA VLM in global SLC estimates (Hay et al., 2015, 2017).

Faced with the difficulty of accurately modeling all the relevant geophysical processes causing VLM at TGs, the alternative approach of measuring VLM using space geodesy techniques has been advocated for several decades (Carter et al., 1989). The use of the Global Positioning System (GPS) has demonstrated promising results at local (Sanli and Blewitt, 2001), regional (Teferle et al., 2009) and global scales (Wöppelmann et al., 2009). However, the lack of direct GPS co-location at TGs and the lack of available data and estimates, among other issues, have prevented scientists from using GPS velocities in most SLC studies (Wöppelmann and Marcos, 2016). Here, we build upon a new GPS solution (section 2), completed with altimeter-derived VLM estimates, to investigate how uncertainty in the VLM corrections at the TGs propagates into the estimates of the SLC rate and acceleration using a robust, recently developed, sea-level reconstruction (section 3). For the sake of completeness, the impact of errors in modeled GIA VLM is also investigated.

2. Vertical land motion estimates

The GPS vertical velocity fields produced at the University of La Rochelle (ULR) are intended to correct the VLM from multi-decadal TG records in the Revised Local Reference data set of the Permanent Service for Mean Sea Level (PSMSL; Holgate et al., 2013). Within the frame of the second reprocessing campaign of the International GNSS Service (IGS repro2; Rebischung et al., 2016), the University of La Rochelle completed the last solution, named ULR6. For this solution, we included GPS stations within a radius of 15 km from a TG record longer than 60 yr in the PSMSL database. For those TGs with no GPS station at 15 km, we included the nearest GPS station regardless of its distance to the TG. For 95% of the GPS-TG pairs, the separation distance was less than 20 km and the maximum was 60 km. In total, the ULR6 network includes 757 GPS stations globally distributed (Fig. 1) with data between January 1995 and December 2014. The estimated velocity field together with the mean station coordinates, the station position discontinuities and the residual position time series are provided in SONEL[2] as part of its commitment to the UNESCO/IOC Global Sea Level Observing (GLOSS) program (IOC, 2012).

The velocity estimation process is divided into three main steps: the estimation of the daily GPS station positions (see the supplementary material), the estimation of their velocity with respect to a well-established, conventional and Earth-centered reference frame (section 2.1) and then the estimation of the velocity formal errors taking into account the autocorrelation of the residual series (section 2.2).

2.1. Estimation of GPS velocities

The estimated daily station positions (see the supplementary material) were stacked into time series defining a long-term solution by estimating the translation, rotation and scale transformation parameters together with the station mean position (at a given reference epoch), annual signal and velocity. The long-term terrestrial frame, in which the estimated velocities are expressed, was aligned to the last realization of the International Terrestrial Reference Frame (ITRF2014; Altamimi et al., 2016) by applying minimal constraints on all the transformation parameters (trans-

---

[2] http://www.sonel.org.