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Rates of sea-level change over the past century in a geocentric reference frame

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[1] The results from a carefully implemented GPS analysis, using a strategy adapted to determine accurate vertical station velocities, are presented. The stochastic properties of our globally distributed GPS position time series were inferred, allowing the computation of reliable velocity uncertainties. Most uncertainties were several times smaller than the 1–3 mm/yr global sea level change, and hence the vertical velocities could be applied to correct the long tide gauge records for land motion. The sea level trends obtained in the ITRF2005 reference frame are more consistent than in the ITRF2000 or corrected for Glacial-Isostatic Adjustment (GIA) model predictions, both on the global and the regional scale, leading to a reconciled global rate of geocentric sea level rise of 1.61 ± 0.19 mm/yr over the past century in good agreement with the most recent estimates. **Citation:** Wöppelmann, G., C. Letetrel, A. Santamaria, M.-N. Bouin, X. Collilieux, Z. Altamimi, S. D. P. Williams, and B. Martin Miguez (2009), Rates of sea-level change over the past century in a geocentric reference frame, *Geophys. Res. Lett.*, *36*, L12607, doi:10.1029/2009GL038720.

1. Introduction

[2] Estimates of global-scale sea level rise over the past century are mainly based on long tide gauge records. The range of estimates published in the literature is rather wide (1 to 3 mm/yr), with figures converging towards 1.8 mm/yr [e.g., Church and White, 2006; Douglas, 2001; Holgate, 2007; Jevrejeva et al., 2008]. To a large extent the origin of the differences lies in the methods used to correct the tide gauge records for vertical displacements of the land upon which they are located [e.g., Woodworth, 2006]. While most analyses have included corrections for Glacial-Isostatic Adjustment (GIA) effects, many other land motion processes, for example, associated with plate tectonics, volcanism, sediment compaction, or underground fluid extraction, have not been accounted for, except by excluding the possibly affected tide gauge records from consideration in the studies. Furthermore, the GIA models contain uncertainties in the knowledge of some geophysical parameters, which can yield to large differences in the magnitude and sign of the vertical displacement predictions [e.g., Woodworth, 2006].

[3] Encouraging results were recently obtained on global scales [e.g., Steigenberger et al., 2006; Wöppelmann et al., 2007], showing that the GPS technique in continuous mode and the reference frame realization have reached the maturity to provide useful information to account for land motion in tide gauge records. However, the issue remains challenging. To be useful site displacements at tide gauges should be monitored with standard errors several times smaller than the estimated 1–3 mm/year rates of global sea level rise. The use of a consistent analysis strategy throughout the whole observation data span is demonstrated to be mandatory [e.g., Steigenberger et al., 2006] to prevent GPS products (in particular GPS velocities) from being contaminated with spurious signals that make questionable any geophysical interpretation [e.g., Penna et al., 2007]. In this study, we extended the Wöppelmann et al. [2007] results, providing consistent position time series at tide gauges over a longer data span of up to 10 years, based on the recent ITRF2005 reference frame [Altamimi et al., 2007].

2. Data Analysis

2.1. GPS Observations and Processing

[4] We analyzed GPS observations from a global network of 227 stations using a consistent processing strategy over the whole period from January 1997 to November 2006. Among the stations, 160 are co-located within 15 km of a tide gauge, and 91 are used by the International GNSS Service (IGS) for the reference frame implementation. The electronic supplement provides a map showing the stations distribution (Figure S1¹). We used the GAMIT software version 10.21 [King and Bock, 2006], estimating station coordinates, satellite orbits, Earth orientation parameters (EOPs), and zenith tropospheric delay parameters as a piecewise linear model with nodes every 2 hours. Daily observation files were grouped into five subnets with up to 50 stations each. To ensure the optimal estimation of satellite orbital parameters, as well as the alignment to the ITRF2005 reference frame, the subnet stations were globally distributed. Loosely constrained daily subnet solutions were produced using a priori site coordinates in the ITRF2005 reference frame; a priori orbits from the IGS; and a priori EOPs from the IERS Bulletin B. The daily subnet solutions (station coordinates with full co-variances) were combined and aligned to the ITRF2005 by means of minimum constraints using the CATREF Software [Altamimi et al., 2002, 2007]. The obtained global daily solutions were combined into weekly solutions in a second step. The weekly solutions were provided to the TIGA pilot project [Schöne

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et al., 2009]. The particular set of stations used to define the reference frame was chosen to provide optimal stability over the entire reanalysis period. More details on the GPS data processing strategy used in this study and implemented by the University of La Rochelle (ULR) analysis centre can be found in the electronic supplement (Text 01). An important feature to outline is the use of absolute antenna phase centre corrections for satellites and receivers [Schmid *et al.*, 2007].

2.2. Noise Characteristics and Velocity Error Estimates

[5] Previous works [e.g., Mao *et al.*, 1999; Williams *et al.*, 2004] demonstrated the presence of significant time-correlated noise in the de-trended GPS position time series residuals. An important consequence is that formal errors on the GPS-derived velocities are grossly underestimated by factors of 5 to 11 if correlations are not properly accounted for [e.g., Mao *et al.*, 1999]. To assign more realistic uncertainties on the GPS velocities, we carefully examined the noise content in our series by the maximum likelihood estimation (MLE) technique using CATS software [Williams, 2008]. These series were the non-linear post-fit residuals obtained from the combination of the whole GPS weekly station coordinates solutions over the 10-year period [Wöppelmann *et al.*, 2007, equation (1), p. 401]. They were previously inspected for outliers and offsets using an iterative approach described in the electronic supplement (Text S2).

[6] A combination of power-law plus white noise model turned out to provide the most likely stochastic description of our GPS position series. This finding was consistent with former results [e.g., Mao *et al.*, 1999; Williams *et al.*, 2004]. The estimated spectral indexes were close to -1 (flicker noise), whatever the positioning component. Furthermore, the noise levels were significantly reduced (30 to 40% in the vertical component) compared to previous global network solutions using similar data spans [e.g., Williams *et al.*, 2004]. The average noise levels were 2.6 ± 0.4 mm and 8.2 ± 1.0 mm/yr^{0.25} for the white- and power law noises, respectively. They support the results obtained by Feissel-Vernier *et al.* [2007] on a preliminary (shorter) version of our reprocessed GPS solutions with an independent noise analysis method (Allan variance). For completeness and further investigations, the electronic supplement provides the vertical GPS velocities in the ITRF2005 and their “CATS” error bars (Table S1). It includes details of the noise analysis for 180 out of the 227 stations that fulfilled the time series selection criteria of 3.5 years of minimum length with more than 70% of valid data in the time series [Blewitt and Lavallée, 2002].

2.3. From ITRF2000 to ITRF2005 Reference Frame

[7] Wöppelmann *et al.* [2007] expressed their long-term cumulative solution in the ITRF2000 [Altamimi *et al.*, 2002], the most recent and robust realization available at that time. In the meantime, three additional observation years were computed at ULR, and the ITRF2005 was released [Altamimi *et al.*, 2007]. Using the ITRF2005 datum and the ITRF2000 as a priori reference frames, starting from the GAMIT loosely constrained subnet solutions in our processing scheme (section 2), resulted in two different solutions over the 10-year period, hereafter ULR2 (using

ITRF2000) and ULR3 (using ITRF2005). The Wöppelmann *et al.* [2007] solution over the shorter 6.7-year period is called ULR1, hereafter. Figure S2 of the auxiliary material shows differences up to 2 mm/yr in the vertical velocities between the two ULR2 and ULR3 solutions (Figure S2, top). A 14-parameter transformation was estimated using the 227 stations in both GPS solutions, yielding a translation rate along the Z-axis of -1.7 ± 0.2 mm/yr and a drift in the scale of 0.13 ± 0.03 ppb/yr. These estimates are consistent with Altamimi *et al.* [2007]. The Z-translation rate between the two frames impacts the vertical velocity of any site at latitude ϕ by $1.7 \times \sin(\phi)$ mm/yr, whereas the scale rate results in a vertical velocity change of about 0.8 mm/yr. Applying these reference frame corrections to the ULR2 solution resulted in differences not statistically significant in the vertical velocities with respect to the ULR3 solution (Figure S2, bottom), thus they were only due to the use of two different reference frames. The transformation parameters between each weekly GPS solution and the combined one expressed in the ITRF2005 (translations and scale factor) showed that our processing scheme implemented the ITRF2005 reference frame at the 1–2 mm level accuracy on a weekly basis (Figure S3).

3. Rates of Sea-Level Change

3.1. Results

[8] The GPS vertical velocities were used to correct for the land motion affecting the tide gauge records to derive absolute (geocentric) changes in sea level (Figure 1). This exercise was carried out at coastal sites with tide gauge records fulfilling the Douglas [2001] selection criteria in determining a global rate of sea level rise. That is, tide gauge records were required to contain more than 85% of valid data over a time span of at least 60 years. The final number of records complying with the selection criteria was identical to the number of records used by Douglas [2001], as it was for the number of regions, respectively 27 and 10 (Figure 1), if the Fernandina record was discarded (see discussion). The tide gauge records and their analysis were presented by Wöppelmann *et al.* [2007]. The results are summarized in Table 1, and completed with the 3-year extended ULR solutions presented in section 3.2 (ULR2 and ULR3). The tide gauge and GPS error estimates were each of comparable size, supporting the exercise of applying the GPS vertical velocities for land motion corrections. The “CATS” error bars (section 2.2) are shown for the ‘best’ vertical GPS velocity field (ULR3).

[9] Although the above mentioned error estimates take into account the noise properties of the GPS position time series, they remain an intra-technique estimate. From herein, intra and inter-regional agreement of the sea level trends will be regarded as a most robust estimate of uncertainty.

3.2. Discussion

[10] In estimating absolute sea level trends, we assumed that land motion is essentially linear on the time span considered here (100 years). This assumption is supported by the very small scatter of the acceleration term in the tide gauge records longer than 50–60 years, suggesting that vertical land motion rates are nearly constant at most sites [Douglas, 2001, Figure 3.16, p. 61]. Observational evidence for acceleration was only detected in reconstructions of

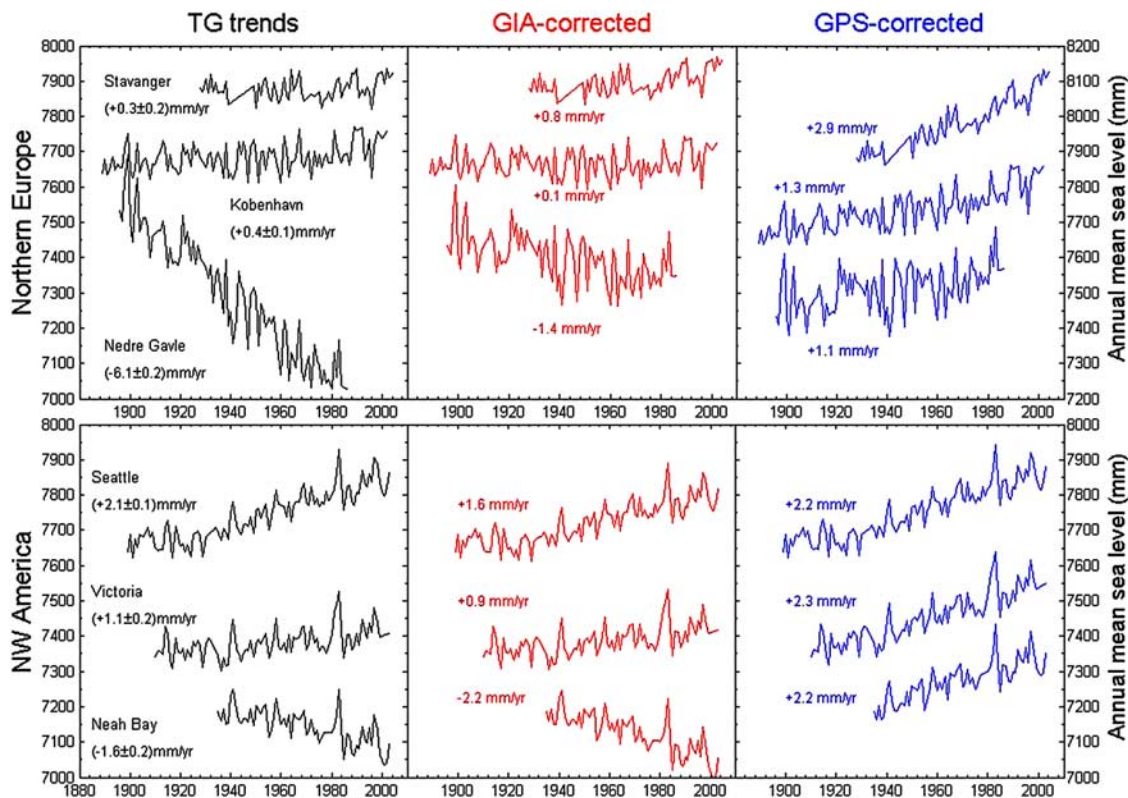


Figure 1. Time series of annual mean sea-level values from: (left) tide gauges; (middle) tide gauges corrected for GIA using *Peltier* [2004] ICE5G (VM2) model predictions; and (right) GPS-corrected tide gauge records in the ITRF2005 reference frame; in (top) Northern Europe and (bottom) North West America. The time series are displayed with arbitrary offsets for presentation purposes (units are in mm).

global sea level curves using large amounts of data [Church and White, 2006; Jevrejeva et al., 2008]. In addition, we assumed that the local vertical displacements of the relatively close observation points (tide gauges and GPS antennae) are under the sub-mm per year level. The validity of this second working hypothesis is raised, especially at Fernandina, where the land motion corrections failed to provide an agreement with the other stations in the South-East North America region. In absence of repeated high-precision levelling data between the GPS antenna and the tide gauge benchmarks, the hypothesis was necessitated in our exercise.

[11] Table 2 summarises the scatter of the individual-, and regional rates of sea level change as measured by the standard deviation statistic. It reveals a slight but steady progress in the land motion corrections performed by the successive ULR solutions. *Wöppelmann et al.* [2007] already noted that GPS corrections provided figures that were more in agreement within a region than GIA corrections from *Peltier* [2004] (e.g., Figure 1). However, the most striking improvement shown here is the significant reduction in the scatter of the regionally averaged sea level trends using ITRF2005 (ULR3 solution, Table 2). Progresses were definitely made in the reference frame realization when shifting to ITRF2005. In contrast, the 3-year data extension barely reduced this scatter using ITRF2000 (ULR1 to ULR2), suggesting that the limitation was more in the

analysis strategy (models, reference frame) than in the data span. This remark is consistent with the predicted standard errors that were obtained for the GPS vertical velocities as a function of the time span of the GPS data (Figure S4). For comparison, the predicted standard errors were also plotted assuming a pure white noise, or using the best noise characteristics observed by *Williams et al.* [2004] in previous global network solutions using similar data spans. GPS analyses have thus reached the maturity to provide useful information for separating land motion from sea level changes recorded by tide gauges, in particular the most underrated and difficult to model effects that are sediment compaction and land subsidence associated with coastal reclamation, development and withdrawal of underground water (Figure 1). Such effects are very site specific, but are sufficiently frequently associated with harbours and tide gauge sites to raise serious concerns on the validity of global averages obtained from uncorrected secular trends.

[12] There might be a limit in the reduction of the scatter of long term sea level trends, however. The issue is the subject of an extensive scientific debate. Sea level rise is expected to vary spatially as a result of the redistribution of melt-water within the Earth system [e.g., *Mitrovica et al.*, 2001]. These variations are long wavelength (>1000 km), and could explain that using ITRF2005 or ITRF2000 did not change significantly the scatter of the geocentric sea-level trends within a region. However, the GPS-corrected

Table 1. Relative and Absolute Sea Level Trends From Tide Gauge Records Using Different Vertical Velocity Fields Computed at ULR^a

Groups of Stations	Span (yr)	Tide Gauges (TG) Trend (mm/yr)	GPS/TG Dist. (m)	Span (yr)	ULR1 Trend (mm/yr)	TG+ULR1 Trend (mm/yr)	Span (yr)	ULR2 Trend (mm/yr)	TG+ULR2 Trend (mm/yr)	ULR3 Trend (mm/yr)	TG+ULR3 Trend (mm/yr)
<i>North Sea + English Channel</i>											
ABERDEEN I+II	103	0.58 ± 0.10	2	6.7	0.15	0.73	8.2	-0.10	0.48	0.67 ± 0.22	1.25
NEWLYN	87	1.69 ± 0.11	10	6.7	-1.04	0.65	8.1	-0.90	0.79	-0.21 ± 0.27	1.48
BREST	83	1.40 ± 0.05	350	6.7	-1.18	0.22	8.0	-1.18	0.22	-0.54 ± 0.77	0.86
<i>Atlantic</i>											
CASCAIS	97	1.22 ± 0.10	84	6.7	-0.58	0.64	8.1	-0.37	0.85	0.12 ± 0.19	1.34
LAGOS	61	1.35 ± 0.18	138	5.3	-0.32	1.03	6.6	-0.59	0.76	-0.10 ± 0.29	1.25
<i>Mediterranean</i>											
MARSEILLE	105	1.27 ± 0.09	5	6.7	-0.32	0.95	8.3	0.34	1.61	0.82 ± 0.37	2.09
GENOVA	78	1.20 ± 0.07	1000	6.6	-0.26	0.94	8.3	-0.61	0.59	-0.16 ± 0.85	1.04
<i>New Zealand</i>											
AUCKLAND II	85	1.30 ± 0.13	5	3.9	1.61	2.91	5.3	1.47	2.77	-0.87 ± 0.48	0.43
PORT LYTTTELTON	101	2.08 ^b ± 0.11	2	5.8	1.21	3.29	7.0	1.66	3.74	-0.59 ± 0.35	1.49
<i>Pacific</i>											
HONOLULU	99	1.46 ± 0.13	5	6.5	0.46	1.92	8.6	0.12	1.58	-0.15 ± 0.36	1.31
<i>SW North America</i>											
LA JOLLA	72	2.11 ± 0.16	700	6.7	-1.36	0.75	9.8	-0.75	1.36	-0.38 ± 0.62	1.73
LOS ANGELES	78	0.86 ± 0.15	2200	6.7	-0.64	0.22	7.9	-0.67	0.19	-0.30 ± 0.48	0.56
<i>SE North America</i>											
CHARLESTON I	82	3.23 ± 0.16	8200	4.8	-1.80	1.43	6.9	-1.76	1.47	-1.31 ± 0.44	1.92
FERNANDINA	83	2.00 ± 0.13	5500	6.7	-4.28	-2.28	9.4	-3.99	-1.99	-3.58 ± 0.30	-1.58
GALVESTON II	94	6.47 ± 0.17	4200	4.5	-6.85	-0.38	5.9	-6.30	0.17	-5.89 ± 0.61	0.58
MIAMI BEACH	45	2.29 ± 0.26	4800	5.2	0.92	3.21	6.7	0.08	2.37	0.46 ± 0.61	2.75
KEY WEST	90	2.23 ± 0.10	16000	6.7	-0.50	1.73	9.4	-0.97	1.26	-0.59 ± 0.38	1.64
<i>NE North America</i>											
EASTPORT	63	2.07 ± 0.16	800	6.2	1.39	3.46	8.1	1.48	3.55	2.07 ± 0.87	4.14
NEWPORT	70	2.48 ± 0.14	500	6.1	-0.18	2.3	7.3	-0.18	2.3	0.42 ± 0.37	2.9
HALIFAX	77	3.29 ± 0.11	3100	2.8	-1.57	1.72	3.9	-1.5	1.79	-0.72 ± 0.31	2.57
ANNAPOLIS	70	3.46 ± 0.17	100	6.7	-0.12	3.34	8.9	0.19	3.65	0.69 ± 0.94	4.15
SOLOMON'S ISL.	62	3.36 ± 0.19	200	6.7	-3.36	0.00	9.8	-2.92	0.44	-2.43 ± 0.69	0.93
<i>Northern Europe</i>											
STAVANGER	63	0.27 ± 0.17	16000	4.7	0.23	0.50	6.0	1.81	2.08	2.68 ± 0.82	2.95
KOBENHAVN	101	0.32 ± 0.12	7300	2.6	-0.08	0.24	3.9	0.25	0.57	0.97 ± 0.35	1.29
NEDRE GAVLE	90	-6.05 ± 0.23	11000	6.4	6.22	0.17	7.7	6.46	0.41	7.12 ± 0.19	1.07
<i>NW North America</i>											
VICTORIA	86	1.10 ± 0.15	12000	6.7	0.68	1.78	9.8	0.65	1.75	1.20 ± 0.23	2.30
NEAH BAY	65	-1.59 ± 0.22	7800	6.7	4.21	2.62	8.8	3.28	1.69	3.82 ± 0.69	2.23
SEATTLE	104	2.06 ± 0.11	5900	6.7	-0.57	1.49	8.8	-0.42	1.64	0.14 ± 0.31	2.20

^aThe sites are grouped into regions according to *Douglas* [2001]. The columns TG+ULR represent the GPS-corrected tide gauge trend with the different ULR solutions (see text for details).

^b[from *Hannah*, 2004].

trends were different in ITRF2005 or ITRF2000 due to the systematic differences between the frames (section 2.3); leading to different values of regionally averaged sea level trends, and scatter (Table 2).

[13] In contrast, *Douglas* [2008] found no conclusive evidence of glacial melting fingerprints in any of the long tide gauge records that were used by most authors in their determinations of global sea level rise. The assumption that

Table 2. Scatter of the Individual-, and Regional Rates of Sea-Level Change as Measured by the Standard Deviation Statistic Using Different Land Motion Corrections^a

Land Motion Correction at the Tide Gauges	No Correction	GIA-Corrected ICESG (VM2)	GPS-Corrected		
			ULR 1	ULR 2	ULR 3
Scatter of the individual rates of sea-level change	2.05 mm/yr	1.49 mm/yr	1.32 mm/yr (1.15)	1.23 mm/yr (1.06)	1.15 mm/yr (0.98)
Scatter of the regional rates of sea-level change	1.37 mm/yr	0.98 mm/yr	0.93 mm/yr (0.91)	0.87 mm/yr (0.83)	0.62 mm/yr (0.60)

^aSee text for details on the ULR solutions. The figures in parentheses correspond to the removal of Fernandina record from the statistics.

underlies the studies which aim at estimating a secular rate of global sea level rise is that the longer the period of sea level variation, the greater the spatial extent of that signal.

[14] Furthermore, Prandi *et al.* [2009] did not find any significant difference between coastal and global mean sea level rise, comparing tide gauges and satellite altimetry data over 1993–2007. Using Douglas [2001] approach and our best estimates of land motion from GPS (ULR3 corrections) yielded a global-average rate of geocentric sea-level rise for the past century which is in good agreement with the recent estimates (e.g., 1.7 mm/yr [Church and White, 2006; Holgate, 2007]). Including or discarding the anomalous Fernandina record resulted in an estimate of 1.55 ± 0.19 mm/yr or 1.61 ± 0.19 mm/yr, respectively. The approach is therefore robust (see also figures in parenthesis in Table 2), and gave further support to the Douglas [2001] morphological grouping of tide gauges, which was based on their correlation at low frequencies with their neighbours. Despite the different time spans, our estimate of global sea level rise appeared to be in good agreement with the sum of steric sea level and land ice contributions estimated by Leuliette and Miller [2009] over the recent period of 2003–2007 (1.5 mm/yr) using altimetry, Argo, and GRACE gravity observations.

4. Conclusions

[15] Although there might be a natural limit in the reduction of the scatter of long term sea level trends due to the variability of sea level rise, the geodetic approach is reducing this long-term spatial variability by taking into account the land motion at the tide gauges, whatever the origin of the land motion. The significantly improved results, shown in this paper, give further evidence for a reduction of technique errors and analysis artefacts thanks to the utilization of a fully consistent processing strategy throughout the entire 10-year GPS data span. Improving the analysis strategy proved to be more relevant than extending the data span. Many of our GPS vertical velocities were estimated with uncertainties several times smaller than the 1–3 mm/yr associated with global sea level change, taking into account the stochastic properties of the GPS position time series. Hence, they could be applied to correct the long tide gauge records for land motion, leading to an updated GPS-corrected estimate of global-scale sea level rise which is in agreement with previous ones [e.g., Church and White, 2006].

[16] Other studies may benefit from our new global GPS velocity field, for instance to compare with satellite altimetry data, which requires to monitor the tide gauges in the same geocentric reference frame. The uncertainty introduced by land motion in radar altimeter calibration using tide gauges is estimated to be about 0.4 mm/yr [Mitchum, 2000]. We are looking forward to seeing results from the application of our GPS velocity field in such investigations. These will certainly provide invaluable feedback to further assess the performance of our results, but are beyond the scope of this paper.

[17] Last but not least, improving our understanding of sea-level rise and variability, as well as reducing the associated uncertainties, depends critically on the availability of a stable global reference frame. The accuracy of its

origin and scale is the main factor limiting the determination of geocentric sea level trends today. Progressively improving the frame's accuracy is an important continued mission and effort of international services like the IGS.

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