Regional biases in absolute sea-level estimates from tide gauge data due to residual unmodeled vertical land movement

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Received 10 May 2012; revised 13 June 2012; accepted 13 June 2012; published 27 July 2012.

[1] The only vertical land movement signal routinely corrected for when estimating absolute sea-level change from tide gauge data is that due to glacial isostatic adjustment (GIA). We compare modeled GIA uplift (ICE-5G + VM2) with vertical land movement at ∼300 GPS stations located near to a global set of tide gauges, and find regionally coherent differences of commonly ±0.5–2 mm/yr. Reference frame differences and signal due to present-day mass trends cannot reconcile these differences. We examine sensitivity to the GIA Earth model by fitting to a subset of the GPS velocities and find substantial regional sensitivity, but no single Earth model is able to reduce the disagreement in all regions. We suggest errors in ice history and neglected lateral Earth structure dominate model-data differences, and urge caution in the use of modeled GIA uplift alone when interpreting regional- and global- scale absolute (geocentric) sea level from tide gauge data. **Citation:** King, M. A., M. Keshin, P. L. Whitehouse, I. D. Thomas, G. Milne, and R. E. M. Riva (2012), Regional biases in absolute sea-level estimates from tide gauge data due to residual unmodeled vertical land movement, *Geophys. Res. Lett.*, *39*, L14604, doi:10.1029/2012GL052348.

1. Introduction

[2] Relative sea-level (RSL) change estimates derived from tide gauges require correction for tide gauge (TG) vertical movement in order to determine regional and global patterns of absolute (geocentric) sea-level (ASL) change [e.g., *Church et al.*, 2004]. Assuming TGs are located on stable monuments (e.g., piers), this movement will be dominated by the signal due to vertical land movement (VLM). Since an accurate and spatially comprehensive map of total VLM is not yet available, corrections have been limited to the application of models of glacial isostatic adjustment (GIA) which, globally, is the dominant geophysical process affecting VLM. However, regardless of the accuracy of a given GIA model, other geophysical and anthropogenic processes are active over a range of spatial scales [*Woodworth*, 2006] which may bias subsequent interpretation of ASL change.

[3] Alternatively, observations of VLM from Global Positioning System (GPS) data have recently been applied to TG data [e.g., *Wöppelmann et al.*, 2009]. (We note that GPS-corrected TG data will also benefit from the removal of the spatial pattern of GIA-related ASL, which can only come from a GIA model; see Text S1 of the auxiliary material).[1] *Wöppelmann et al.* [2009] showed improved intra-regional sea level agreement using GPS-derived VLM corrections compared to those based on the ICE-5G(VM2) GIA model [*Peltier*, 2004] and interpreted this as being due to improved VLM accuracy. *Becker et al.* [2012] reported important differences between GPS and ICE-5G VLM in the Pacific while *Argus and Peltier* [2010] reported similar for North America. Several authors [e.g., *Wöppelmann and Marcos*, 2012] have derived VLM from a combination of satellite altimetry and TG data and showed that, compared to the modeled GIA signal, residual VLM errors can be regionally systematic. To date, the only globally complete and self-consistent study has been that of *Bouin and Wöppelmann* [2010] who examined VLM from 148 GPS sites located near to tide gauges. They found that about half of their sites were consistent (within 1σ) with ICE-5G predicted radial crustal displacement, hereafter referred to as "uplift", but with no evident spatial pattern. Differencing ∼100 globally sparse TG records with nearby altimetry records, *Mitchum et al.* [2010] identified substantial differences from ICE-4G (VM2), most notably at mid-to-high northern latitudes, with ICE-4G(VM2) predicting lower rate by up to 2–3 mm/yr.

[4] In this paper we consider vertical velocities from about 300 GPS sites located close to TGs; we report on regionally correlated differences at the mm/yr-level between them and modeled GIA uplift, and investigate the origin, and discuss the consequences of, these differences.

2. Data and Models

[5] We searched GPS data archives for GPS sites within 50 km of the combined set of tide gauges used in recent sea-level reconstructions [*Church et al.*, 2004; *Jevrejeva et al.*, 2008], totaling about 1500 TG records. We processed the raw GPS data on a point-wise basis using the same satellite orbits and clocks and analysis procedures as *Thomas et al.* [2011], producing GPS time series in the GPS realization of ITRF2005 ([*Altamimi et al.*, 2007] IGS05). We found 472 GPS records that satisfied this criterion and also had sufficient completeness (>75%) and data span (>1.5 years), likely monument stability, metadata completeness (especially antenna information), and time series linearity (as

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0094-8276/12/2012GL052348

[1]Auxiliary materials are available in the HTML. doi:10.1029/2012GL052348.

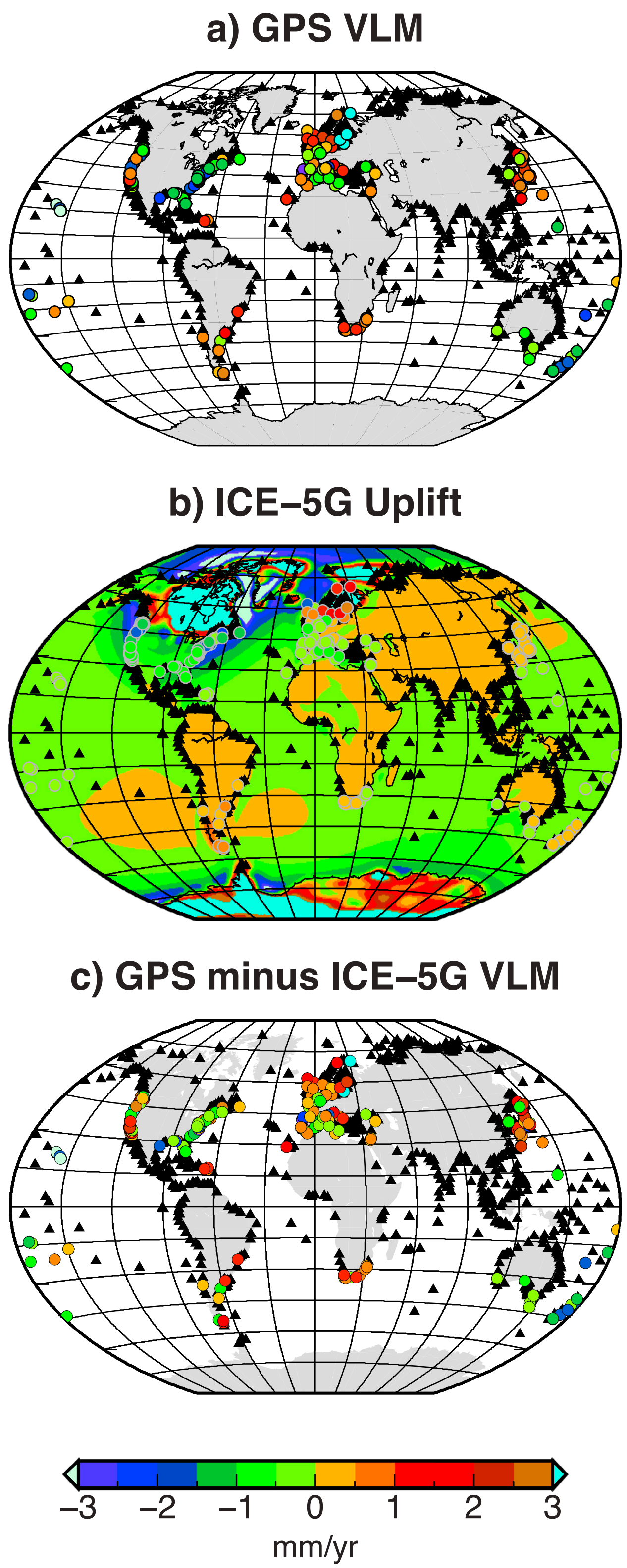

Figure 1. (a) Vertical land movement observed by GPS, (b) modeled GIA uplift (ICE-5G + VM2(v1.2)) with GPS locations and (c) the difference. Black triangles are tide gauge locations [*Church et al.*, 2004; *Jevrejeva et al.*, 2008] without GPS VLM, mainly due to a lack of GPS installations. The GPS sites with the greatest precision are plotted last. See Figure S1 of the auxiliary material for comparison to the formal uplift rates based on ICE-5G + VM2(v1.3a).

visually judged); these correspond to 542 unique TG records. We manually picked offset times in the time series and solved for velocities together with offset magnitude, annual and semiannual signals, and realistic formal errors [*Herring*, 2003].

[6] The resulting vertical velocities reflect a combination of large-scale geophysics, including GIA, plus very localized motions and error. Since our intention was to investigate VLM as related to regional sea-level patterns, we rejected sites dominated by highly localized effects or errors by filtering the site velocities using a block median filter (30° longitude × 10° latitude). Local motion between the GPS and TG, which is often not regularly or ever measured, is irrelevant to this study since we choose to focus on regional-scale effects. To ensure robust outlier detection we only considered sites in blocks with ≥3 sites, and rejected any site whose uncertainty was >1 mm/yr or whose absolute velocity was >2 mm/yr different to the median within that block. Short and incomplete time series will have larger velocity uncertainties than average and hence be more commonly filtered out. The 2 mm/yr threshold was chosen conservatively to consider the likely maximum range of GIA uplift within this window size at our sites (<3.7 mm/yr, and more commonly <1.6 mm/yr, range). We also rejected sites at high latitudes where large elastic rebound effects are present (e.g., Alaska, Greenland and Antarctica). This left us with 286 high quality site velocities with global distribution, as shown in Figure 1a; these correspond to 353 unique TG records.

[7] We compare the GPS vertical velocities to GIA uplift predictions, which were derived by using the ICE-5Gv1.2 deglacial history and the VM2 Earth model [*Peltier*, 2004] to solve the sea-level equation in terms of present-day uplift rates, considering rotational feedback [*Mitrovica et al.*, 2005] (see Text S1 of the auxiliary material for further details). The ICE-5G ice history is the foundation for GIA uplift rates used in a large number of recent studies on sea level, either in terms of its formal uplift rates at http://www.atmosp.physics.utoronto.ca/~peltier/data.php [e.g., *Bouin and Wöppelmann*, 2010] or as computed by others using their own GIA model code together with the ICE-5G ice history and the VM2, or some other, Earth model [e.g., *Tsimplis et al.*, 2011]. The use of a formal or other realization is often not specified. Some previous studies [e.g., *Wöppelmann et al.*, 2009] have used the negative of the modeled relative sea level change predictions from http://www.pol.ac.uk/psmsl/peltier/index.html rather than the uplift and compared them to independent VLM estimates; here we more rigorously use modeled uplift (see *Tamisiea and Mitrovica* [2011] and Text S1 of the auxiliary material for a description of the differences). Our computed ICE-5G + VM2(v1.2) uplift is shown in Figure 1b. We repeat our analysis using the formal ICE-5G + VM2(v1.3a) uplift rates in auxiliary material.

3. Results

[8] Considering all sites together, the overall level of correspondence is high (Figure 2). A χ^2 goodness-of-fit test suggests the differences between the GPS VLM and modeled GIA uplift are normally distributed with 1% significance [cf. *Houston and Dean*, 2012]. We note that we do not expect an exact match between GPS VLM and modeled GIA uplift due

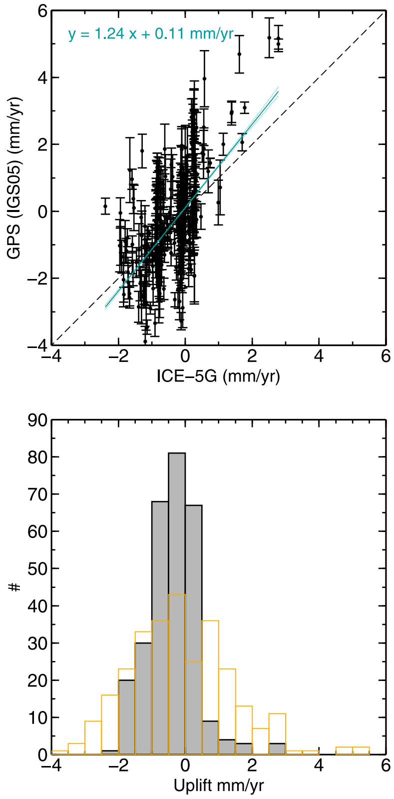

Figure 2. (top) Modeled GIA uplift versus observed GPS VLM with the best fitting line in cyan. Dotted lines are 95% confidence limits. (bottom) Histograms of GPS VLM (orange) and modeled GIA uplift (grey). See Figure S2 of the auxiliary material for comparison to the formal uplift rates based on ICE-5G + VM2v1.3a.

to non-GIA motions and errors in both the GPS velocities and the modeled uplift rates. Nevertheless, the regionally coherent differences between the observed GPS VLM and modeled GIA uplift that are evident in Figure 1c are striking.

[9] In the Southern Hemisphere, GPS sites in Australia show consistently lower VLM than the modeled GIA uplift, with the differences increasing to 1–2 mm/yr in New Zealand and the south Pacific. In South Africa and South America, GPS rates are higher than modeled GIA uplift by ∼1 mm/yr, while in the Northern Hemisphere, GPS rates on the US East Coast are ∼0.5–1 mm/yr lower than the modeled GIA. Differences along the US West Coast are highly variable in space, but GPS rates are higher on average by ∼0.5 mm/yr; this variability may suggest unfiltered localized effects along this coastline [see also *Brooks et al.*, 2007]. In Western Europe a very clear pattern is evident, with GPS rates higher by 1 mm/yr. Differences in Japan are 1–2 mm/yr with the GPS rates higher.

[10] The observed differences will be affected by site proximity to plate boundaries, e.g., in Japan, New Zealand and the western US, but the spatial pattern of the differences suggests these are not dominant at the majority of the sites in these regions. To further investigate the origin of the regional-scale differences between our observed VLM and modeled GIA uplift we consider: 1) reference frame errors; 2) uplift due to present-day surface mass trends; and 3) GIA model errors.

[11] Our GPS velocities are in a reference frame whose origin is defined to be at the centre of mass of the entire Earth system (CM); in ITRF2005, CM is established by observations over the period 1993–2006. The GIA uplift predictions are in a centre of mass of the solid Earth only reference frame (CE). The motion of our CE relative to our CM is due to present-day mass trends (PDMT) over 1993–2006 [see, e.g., *Métivier et al.*, 2010] and the difference between CE and CM within the GIA model computations, which also depends on Earth model parameters. We found the effect of the GIA model origin on present-day uplift rates to be <0.1 mm/yr in terms of geocenter motion [see also *Klemann and Martinec*, 2011] and <±0.2 mm/yr in terms of regional patterns for a wide range of Earth models, and hence negligible. The effects of origin translations due to PDMT alone cannot explain the complex spatial pattern of the GPS-model differences we observe (see also Text S1 of the auxiliary material).

[12] Secondly, we consider the spatial pattern of the solid Earth response to PDMT to examine if it is of sufficient magnitude to explain the differences we observe in Figure 1c. In Figure 3a we show predicted elastic uplift due to PDMT relative to CM based on an update of the work of *Riva et al.* [2010] (see Text S1 of the auxiliary material). The

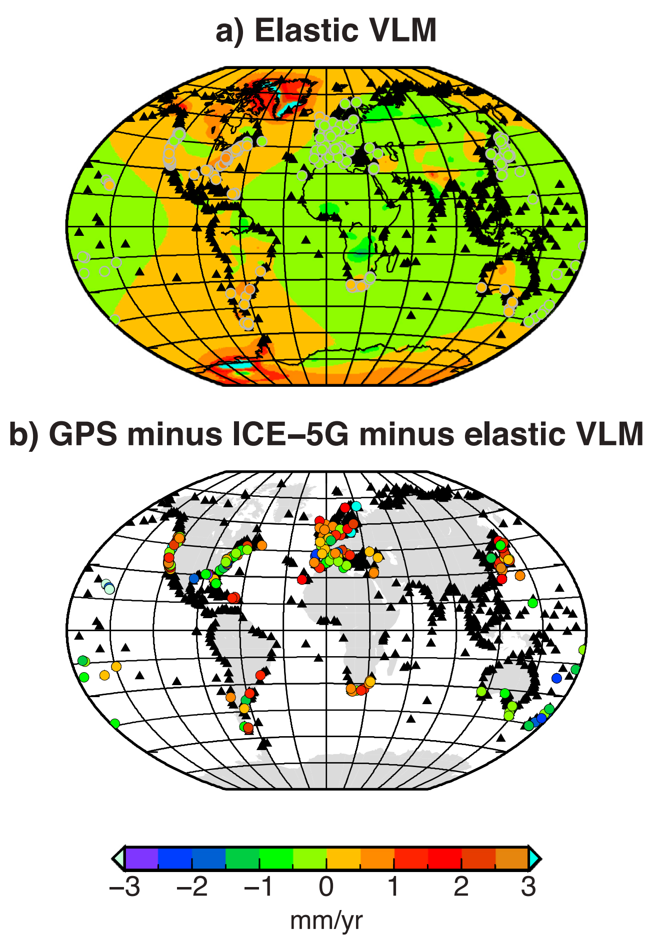

Figure 3. (a) Elastic uplift due to present-day ice mass change and (b) same as Figure 1c, but with elastic uplift and ICE-5 G + VM2(v1.2) subtracted from the GPS VLM.

signal magnitude does not exceed ±0.5 mm/yr over most of the global oceans. We subtracted the sum of the PDMT and ICE-5G uplifts from the GPS rates and show the results in Figure 3b, revealing that this estimate of PDMT uplift cannot explain the regionally coherent differences. The PDMT uplift predictions are sensitive to the PDMT assumptions of *Riva et al.* [2010], and in particular to the chosen GIA model, and the relatively low spatial resolution of their estimates of PDMT. However, the small PDMT uplift away from the large ice sheets suggests this error could not explain our differences even with very large changes in estimated PDMT.

[13] Finally, we consider GIA model errors which are believed to mainly stem from errors in the assumptions of Earth structure and rheology or incomplete knowledge of ice sheet history since the Last Glacial Maximum (LGM). To investigate Earth model error, we repeated the uplift predictions using a range of Earth models, sampling lithospheric thickness (LT; 71, 96 and 120 km) and upper (UM; 0.05, 0.08, 0.1, 0.2, 0.3, 0.5, 0.8, 1.0, 2.0 and 5.0 × 10^{21} Pa s) and lower (LM; 1, 5, 8, 10, 20, 50 × 10^{21} Pa s) mantle viscosities. Since potential GIA errors due to incorrect ice history will be largest near the large LGM ice sheets, we identified the model which minimized the difference between GIA predictions and GPS uplift rates at sites far from these ice sheets – namely South Africa, Australia and New Zealand. The tests preferred UM and LM viscosities of 1 × 10^{21} and 1 × 10^{22} Pa s, respectively, with no LT sensitivity. This significantly altered the misfit in specific regions, but did not systematically resolve all regional differences. We repeated the exercise using sites only in Western Europe but found no improvement over VM2. These results suggest that altering the 1-D Earth model alone, while resulting in important differences [see also *Mitrovica and Davis*, 1995], is not sufficient to explain the differences in GPS VLM and GIA uplift.

4. Discussion and Conclusions

[14] Our GPS observations of vertical land movement at nearly 300 sites show regionally coherent differences to modeled GIA uplift, at the level of ±0.5–2 mm/yr. Reference frame errors/differences and uplift related to present day surface mass trends are small at our chosen sites, plate boundary effects appear negligible, and reasonable changes to the 1-D Earth model are unable to substantially reduce the differences. The effects of lateral (3-D) variations in the Earth structure may also be contributing to the differences, with some preliminary results indicating these contribute a signal of order 1 mm/yr around the periphery of previously glaciated regions and 0.1 mm/yr in far-field regions [*Kendall et al.*, 2006]. Deficiencies in the ICE-5G ice history are the other most likely source of the discrepancies shown in Figure 1c (and Figure S1c of the auxiliary material). Indeed, recent studies have suggested limitations in the North American [*Argus and Peltier*, 2010; *Horton et al.*, 2009] and Antarctic [*Thomas et al.*, 2011] components of the ICE-5G reconstruction.

[15] Some of the most regionally coherent data-model discrepancies occur where the influence of True Polar Wander on VLM is the largest [*Milne and Mitrovica*, 1998]: east coast of the US, southern South America, southwest and northwest Pacific. Specifically, the discrepancy in these regions (Figure 1c) is compatible with an underestimation of this signal. In comparison, the results based on the formal ICE-5G realization (Figures S1b and S1c of the auxiliary material) indicate a consistently larger rotational feedback signal resulting in residuals that are either substantially reduced (e.g. northwest Pacific) or of opposite sign (US east coast). These results are compatible with a suggestion that the rotational feedback component in the formal ICE-5G realization is overestimated [*Chambers et al.*, 2010] and imply that the ICE-5G ice history reconstruction is biased to counteract this model error.

[16] Regardless of the origin of the residuals shown in Figure 1c, the consequence of our results for sea-level studies is that regional sea-level estimates based on tide gauge data, that only apply a modeled GIA uplift correction, will commonly be biased by up to ±1–2 mm/yr. Unmodeled localized effects would add further TG-specific bias. There are some prominent studies that have used GIA uplift values other than those based on ICE-5G; *Church et al.* [2004] used GIA uplift rates based mainly on ICE-3G ice history and *Jevrejeva et al.* [2008] used those based on the formal ICE-4G + VM2 uplift rates (S. Jevrejeva, personal communication, 2011). The spatial pattern of GIA uplift from those models will differ from that considered here and, consequently, so will the magnitude and pattern of regional biases, but we do not expect the effect to be substantially smaller on average than shown here with ICE-5G. It is important to note, though, that that regional sea level trends, especially over shorter-periods, are often larger than the biases we observe here.

[17] The mean bias between our GPS VLM and modeled GIA uplift (Figure 2) suggests that the application of GPS VLM to TG rates of sea-level change would produce a systematically different estimate of global-mean ASL change. A simple mean across all our sites suggests that using a GPS correction would produce an ASL rate estimate 0.18 mm/yr higher than if we used our realization of ICE-5G + VM2(v1.2), or 0.37 mm/yr higher than if we used the formal ICE-5G + VM2(v1.3a) rates. However, these values depend significantly on the spatial distribution of sites, and mean differences of opposite sign are possible.

[18] To illustrate this, we reconsidered the RSL rates from *Douglas* [1997], limiting ourselves to 22 of the 24 sites where we have GPS velocities. The reported 1.8 mm/yr regional median ASL rate, derived using ICE-3G, is unaltered with this subset. We correct the original RSL rates for VLM and the ASL effect of GIA, first using our realization of ICE-5G + VM2 and then the formal ICE-5G. We find that this 1.8 mm/yr value drops to 1.6 mm/yr when the RSL rates are corrected using our realization of ICE-5G (formal ICE-5G: 1.4 mm/yr). Using instead our 30° × 10° median GPS VLM, and accounting for the fall in ASL due GIA at each site using our realization of ICE-5G (see Text S1 of the auxiliary material), the regional median value of 1.4 mm/yr is obtained. Removing one region from the GPS-derived median computation increases the value to 1.7 mm/yr highlighting the benefits of studies with larger TG sets.

[19] However, a routine application of GPS VLM to a large set of TG records [e.g., *Church et al.*, 2004] is presently hampered by the fact that only 1/3 of the tide gauges

used in the most widely cited sea-level reconstructions presently have a GPS located within a tolerable distance, and only about 2/3 of those have time series of sufficient quality. This must be urgently addressed by TG observation agencies and the Global Sea Level Observing System (GLOSS) program by deploying GPS receivers at all high-quality TG sites. The regions of greatest need can be identified in Figure 1a (black triangles show TG sites with no GPS).

[20] Our finding (Figure 3a) of the relatively small effect of PDMT on uplift rates addresses an uncertainty in the conclusions of *Métivier et al.* [2012] who compared degree-2 spherical harmonics derived from GIA model rates and GPS VLM. In the case of an unspecified version of the formal ICE-5G(VM2), they found large differences in the degree 2, order 1 terms but were unsure if this suggested a GIA modeling error, related to rotational feedback, or was due to a signal of equal but opposite sign from PDMT. Our Figure 3a shows that PDMT-related elastic uplift, which includes the effects of rotational feedback, does not have a large degree 2 order 1 component. This result and the differences between Figures 1b and S1b and Figure 1c and S1c support the conclusion that this difference in the degree 2, order 1 terms is dominated by a modeling error related to rotational feedback [*Chambers et al.*, 2010].

[21] Finally, while the GPS stations used in this study were chosen to be in close proximity to tide gauges used in sea-level reconstructions, our conclusions equally apply to paleo sea level studies that use only a GIA uplift correction to isolate changes in sea surface height: we also urge caution in such studies.

[22] **Acknowledgments.** This work was supported by NERC and COST action ES0701. M.A.K. was also funded by a RCUK academic fellowship. We thank Neil White and Svetlana Jevrejeva for supplying their tide gauge locations and W. Richard Peltier for making ICE-5G available. GPS data were kindly provided by archives of the IGS, TIGA, BIGF, SOPAC, CDDIS, amongst others, and we especially thank GPS station operators for making their data available to these archives. We thank Neil White and an anonymous reviewer for their helpful comments.

[23] The Editor thanks Neil White and an anonymous reviewer for their assistance in evaluating this paper.

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