2016

Assessing the Impact of Vertical Land Motion on Twentieth Century Global Mean Sea Level Estimates

B. D. Hamlington
Old Dominion University, bhamling@odu.edu

P. Thompson

W. C. Hammond

G. Blewitt

R. D. Ray

Original Publication Citation

Hamlington, B.D., Thompson, P., Hammond, W.C., Blewitt, G., & Ray, R.D. (2016). Assessing the impact of vertical land motion on twentieth century global mean sea level estimates. *Journal of Geophysical Research: Oceans, 121*(7), 4980-4993. doi: 10.1002/2016JC011747

AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Oceans

RESEARCH ARTICLE

10.1002/2016JC011747

Key Points:

- Tide gauges, on average, are experiencing uplift after removing the impact of GIA
- Removing non-GIA VLM from the tide gauges significantly impacts twentieth century GMSL trend estimates
- GPS VLM errors and the short GPS records do not appear to have a large impact on GMSL estimates

Correspondence to:
B. D. Hamlington,
bhamling@odu.edu

Citation:
Hamlington, B. D., P. Thompson, W. C. Hammond, G. Blewitt, and R. D. Ray (2016), Assessing the impact of vertical land motion on twentieth century global mean sea level estimates, *J. Geophys. Res. Oceans*, *121*, 4980–4993, doi:10.1002/2016JC011747.

Received 22 FEB 2016
Accepted 16 JUN 2016
Accepted article online 20 JUN 2016
Published online 22 JUL 2016

Assessing the impact of vertical land motion on twentieth century global mean sea level estimates

B. D. Hamlington[1], P. Thompson[2], W. C. Hammond[3], G. Blewitt[3], and R. D. Ray[4]

[1]Department of Ocean, Earth and Atmospheric Sciences, Old Dominion University, Norfolk, Virginia, USA, [2]Department of Oceanography, University of Hawai'i at Mānoa, Honolulu, Hawaii, USA, [3]Nevada Geodetic Laboratory, Nevada Bureau of Mines and Geology, University of Nevada, Reno, Nevada, USA, [4]NASA Goddard Space Flight Center, Greenbelt, Maryland, USA

Abstract Near-global and continuous measurements from satellite altimetry have provided accurate estimates of global mean sea level in the past two decades. Extending these estimates further into the past is a challenge using the historical tide gauge records. Not only is sampling nonuniform in both space and time, but tide gauges are also affected by vertical land motion (VLM) that creates a relative sea level change not representative of ocean variability. To allow for comparisons to the satellite altimetry estimated global mean sea level (GMSL), typically the tide gauges are corrected using glacial isostatic adjustment (GIA) models. This approach, however, does not correct other sources of VLM that remain in the tide gauge record. Here we compare Global Positioning System (GPS) VLM estimates at the tide gauge locations to VLM estimates from GIA models, and assess the influence of non-GIA-related VLM on GMSL estimates. We find that the tide gauges, on average, are experiencing positive VLM (i.e., uplift) after removing the known effect of GIA, resulting in an increase of 0.24 ± 0.08 mm yr^{-1} in GMSL trend estimates from 1900 to present when using GPS-based corrections. While this result is likely dependent on the subset of tide gauges used and the actual corrections used, it does suggest that non-GIA VLM plays a significant role in twentieth century estimates of GMSL. Given the relatively short GPS records used to obtain these VLM estimates, we also estimate the uncertainty in the GMSL trend that results from limited knowledge of non-GIA-related VLM.

1. Introduction

In the past two decades, estimates of global mean sea level (GMSL) are provided by continuous, near-global measurements of sea surface height from satellite altimeters. The satellite-derived estimate of the trend in GMSL from 1993 to present is ~3.3 mm yr^{-1} [*Nerem et al.*, 2010]. This relatively short record length is influenced by interannual to decadal-scale internal climate variability that can affect trend estimates of GMSL [e.g., *Cazenave et al.*, 2012; *Hamlington et al.*, 2013]. The portion of the 3.3 mm yr^{-1} associated with longer-term sea level rise that may be linked to anthropogenic effects is difficult to ascertain from the satellite record alone. For this reason, the historical sea level record has been heavily studied [e.g., *Gornitz*, 1982; *Douglas*, 1991, 1997; *Holgate*, 2007; *Jevrejeva et al.*, 2008; *Church et al.*, 2006, 2011; *Ray and Douglas*, 2011; *Meyssignac et al.*, 2012; *Hamlington et al.*, 2011, 2013; *Hay et al.*, 2015; *Thompson and Merrifield*, 2014; *Hamlington and Thompson*, 2015] to provide context for the sea level variability observed during the satellite altimeter era.

The primary source of sea level data prior to satellite altimetry is historical tide gauge records. This data set provides a significantly longer time series relative to that provided by satellite altimetry, with a few records extending back into the eighteenth century. There are several problems associated with the tide gauge records, however, that make estimating long-term sea level rise on both global and regional scales a challenge and comparisons to satellite altimetry difficult. First, the spatial coverage of the tide gauges is generally poor, with gauges clustered around heavily populated and developed coastlines and a distinct sampling bias toward the northern hemisphere particularly when considering the record prior to 1950. In addition to poor spatial coverage, the temporal sampling is not uniform with some gauges having large gaps within their records and many covering time periods of only a few years. As seen with the satellite altimetry record, trends over short records can differ significantly from the long-term rate, raising serious questions about how these gauges may affect estimates of the trend in GMSL.

Another challenge in working with the tide gauge data—that we address in this paper—is related to what signal the tide gauge actually measures. Tide gauges are necessarily located along continental and island coasts, providing measurements of sea level where the land and water meet. As such, tide gauges measure *relative* sea level, referring to the change in water level relative to land. When trying to estimate the sea level trend at a particular location, problems arise if the land itself experiences unknown vertical movement, biasing the estimate of sea level. Long-term studies of sea level relying on the tide gauges are subsequently limited by knowledge of the vertical land motion (VLM) of the tide gauge benchmarks (the point on land to which the tide gauge is referenced) in a geocentric reference frame. While the effect of VLM on specific tide gauge records may be known, it is less clear how VLM impacts estimates of long-term GMSL.

In studies of past sea level, typically VLM at the tide gauges is separated from GMSL using a glacial isostatic adjustment (GIA) model [e.g., *Church and White*, 2011; *Ray and Douglas*, 2011; *Hay et al*., 2015; *Hamlington and Thompson*, 2015]. This approach has two main limitations: (1) errors in the model due to poorly constrained parameters such as history of ice cover and viscosity structure of Earth's mantle can lead to uncertainty in VLM associated with GIA [*Argus and Peltier*, 2010] and (2) VLM arising from other processes is not taken into account and subsequently removed. Several processes can lead to non-GIA VLM including tectonic activity (coseismic, interseismic, and postseismic deformation from the earthquake cycle, particularly along near-coast subduction zones), groundwater withdrawal, plate flexure from sediment loading, among others [*Emery and Aubrey*, 1991]. An approach that potentially accounts for more of the processes leading to VLM is to compare tide gauge measurements to either the long-term GMSL trend [e.g., *Bouin and Wöppelmann*, 2010] or to the satellite altimetry [e.g., *Santamaría-Gómez et al*., 2014], with the difference in both cases representing the VLM at the TGs. These approaches, particularly the comparison to GMSL, assume that over a long enough time period differences between local and global/regional trends arise primarily from local VLM. Long-term estimates of GMSL from sea level reconstructions are generally made after correcting only for GIA-related VLM and unaccounted-for VLM could potentially affect the estimate of the long-term trend in GMSL itself. Additionally, there is spatial variability in the long-term rate of sea level rise, with the GMSL trend providing a poor representation of the long-term rate in many locations across the globe. Furthermore, there is little consensus regarding the GMSL time series in the twentieth century, with estimates of the trend in GMSL from 1900 to 1990 ranging from 1.2 to 1.9 mm yr^{-1}, with significant disagreement on decadal time scales [*Jevrejeva et al*., 2008; *Hay et al*., 2015].

To remedy some of these issues and to account for VLM at the tide gauges, colocated geodetic observations have been used [*Neilan et al*., 1998]. Some of the geodetic techniques used to account for VLM at or near tide gauges over the past several years include Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) [e.g., *Cazenave et al*., 1999], absolute gravity [e.g., *Williams et al*., 2001], and Global Positioning System (GPS) [e.g., *Sanli and Blewitt*, 2001]. In several recent studies, GPS data have been demonstrated to provide reasonable estimates of VLM at the tide gauge locations [e.g., *Wöppelmann et al*., 2007, 2009, 2014; *Wöppelmann and Marcos*, 2016; *Santamaría-Gómez et al*., 2012]. One important limitation of the GPS-based VLM corrections, however, is the relatively short time period that the GPS records cover. Most GPS time series are shorter than 10 years in length, and while it may be true that VLM estimates are accurate over the time period that the GPS covers, further information is needed about a particular location to ascertain how far into the past this level of VLM extends and if indeed it is constant over the full tide gauge record. A related problem is presented by the lack of collocated GPS measurements for many tide gauges around the world. To fully account for VLM in the study of sea level, either these gauges must be excluded for analysis, or additional analysis and filtering must be performed to extend available GPS data to the tide gauge locations, as will be discussed here.

The objective of this study is to understand the impact of non-GIA VLM at the tide gauge locations typically used for long-term sea level studies on estimates of GMSL. In doing so, we extend on the work of several previous studies [e.g., *Wöppelmann et al*., 2007, 2009, 2014; *Bouin and Wöppelmann*, 2010; *King et al*., 2012]. Additionally, in a recent paper, *Wöppelmann and Marcos* [2016] investigated, in depth, the role of VLM in understanding sea level change and variability, focusing largely on regional sea level with some discussion on global scales. Here we focus on the role of VLM in estimating GMSL, expanding on the discussion of *Wöppelmann and Marcos* [2016] and arriving at both similar and different conclusions, as will be detailed in the remainder of this paper. In particular, we compare corrections using GIA model-based VLM and those using GPS-based VLM corrections and quantify the uncertainty introduced in estimates of twentieth century GMSL by unknown past VLM. We also provide a technique for estimating VLM at gauges that do not have a collocated GPS station. The tide gauge selection process that is necessary in any study of twentieth century sea level rarely accounts for the availability of VLM corrections beyond those provided by GIA models. This results in many gauges with unknown levels of VLM being included in sea level reconstructions. Subsequently, it is difficult to assess the potential impact of VLM on the estimates derived from the sea level reconstructions. Finally, based on the results included here, guidance is provided regarding how VLM should be treated in the computation of long-term GMSL.

2. Data

2.1. Tide Gauge Data

We use historical sea level data from monthly tide gauge observations (1900–2014) from the Permanent Service for Mean Sea Level (PSMSL) Revised Local Reference (RLR) data set [*Holgate et al*., 2013]. This data set consists of 1420 tide gauges, providing irregular sampling in space and time. No correction is made by PSMSL for VLM, although tide gauges without known benchmarks are omitted from this data set by PSMSL prior to release. This benchmark continuity, however, does not preclude many gauges from having datum jumps within their records. Additionally, performing a global sea level analysis using all 1420 tide gauges is challenging given the lack of consistent sampling in time and the presence of very short records. Rather than work with the sea level data from the full RLR data set, typically sea level reconstruction studies use a subset of the RLR data set, with selection choices based on the quality of a given tide gauge. The quality of a given gauge is assessed in a variety of different ways, with each study employing a different set of editing criteria. In this study, we use the entire data set for analysis of the distribution of VLM, but focus attention on the subset of 89 gauges selected by *Ray and Douglas* [2011, hereinafter RD2011] when discussing the impact of VLM on GMSL estimates. In selecting and using these gauges, RD2011 focused on the longest records, which is useful for our purposes too because it allows more accurate determinations of sea level trends [e.g., *Douglas*, 1997]. In addition, RD2011 attempted to avoid stations with significant VLM unrelated to GIA. In fact, they devoted considerable discussion as to why certain long time series that nominally might be used should, in fact, not be used because of VLM issues. However, without direct VLM measurements their selections cannot have been perfect. Nonetheless, to the extent that RD2011 were successful in avoiding non-GIA VLM, our adoption of those 89 stations to study the potential impact of VLM is likely to provide a lower bound on such impact. Any sea level study based on a less stringent station selection is likely to lead to larger VLM-related errors, as will be discussed in more detail here.

2.2. Vertical Land Motion Corrections

2.2.1. Glacial Isostatic Adjustment

Glacial isostatic adjustment refers to a process where the earth adjusts from a state loaded by ice sheets to an equilibrium state. After the ice load is removed, the solid earth rebounds causing displacement at locations in the near and far fields. Near the loading centers, due to continued uplift of the crust, VLM resulting from GIA is positive (away from Earth center, a sign convention maintained throughout this paper), with near-field relative sea level falling. In the far-field surrounding these loading centers, the crust subsides as the forebulge collapses, VLM is negative, and relative sea level increases. Several models provide estimates of GIA-induced VLM. In this paper, we use the ICE-6G (VM5a) model [*Argus et al*., 2014; *Peltier et al*., 2015]. Model estimates at the PSMSL locations are publicly available (www.atmosp.physics.utoronto.ca/~peltier/data.php). For this study, we use estimates of both the VLM and the rate of relative sea level change from the model. The VLM corrections provide for a direct comparison to the GPS-measured vertical velocities (discussed more below), while the relative sea level trends also incorporate GIA-related changes to the sea surface.

2.2.2. Global Positioning System (GPS) VLM

VLM estimates at the GPS stations are obtained using the nonparametric MIDAS algorithm [*Blewitt et al*., 2016]. This method finds rates in a manner that is insensitive to steps, outliers, and annual or seasonal transient motions. From the set of global GPS stations (over 14,000 stations now processed at the Nevada Geodetic Laboratory), we consider only the stations with time series having five or more years duration, rate uncertainty less than 2 mm yr^{-1}, and completeness of over 25% (further details in *Blewitt et al*. [2016]).

Stations contributing vertical velocities are declustered, so that any group of stations that cooccupy a circle of radius 100 m are grouped together and given the median vertical rate in the cluster.

The vertical rates are passed through a preliminary spatial filtering that despeckles the field, removing outlier rates, especially those that may be owing to very local effects that are not apparent at other nearby stations or subject to GPS VLM errors, and may thus be unrepresentative of nearby VLM. It should be noted that this does not mean local VLM signals are necessarily removed; rather, stations that demonstrate significantly different VLM when compared to other nearby stations are filtered. As will be discussed more below, this is particularly important when there are several stations in the vicinity of a tide gauge, but no station collocated with a gauge, which is often the case. A Delaunay triangulation on a sphere is formed from the station locations and the value at every station is revised to be the weighted median of vertical rates at neighboring stations connected in the triangulation, additionally accounting for the velocity uncertainty at the stations. No predefined grid is used, only the distances to neighboring station locations contribute to the weights, so the estimation is isotropic in the sense that no directionality bias is introduced. The local station is required to have at least half the total weight, and the remaining connected stations receive weights proportional to one over their distance to the evaluation station, except that inside a radius of 1/100th of a degree the weight is leveled to prevent very near stations from getting very large weight. The distance is measured in degrees so the weight falls off rapidly within 1° and more slowly at greater distances. The resulting filtered rate field at the GPS stations is more representative of signals that affect multiple stations, and tend to be those associated with large-scale geodynamic effects such as glacial isostatic adjustment, tectonic uplift or subsidence, and seismic cycle effects such as elastic strain accumulation, or viscoelastic relaxation following large earthquakes.

To understand the global impact of applying the spatial filtering, we compare the MIDAS vertical rate to the filtered vertical rate and consider histograms of the rates and their differences. About 50% of the filtered rates are within 0.1 mm/yr of the MIDAS rate, while 94% are within 2 mm/yr. The filtered rates have less heavy tails in their distribution, and the distribution of the differences has a clear spike within 0.1 mm/yr. These suggest that filtering has an effect on about half the data, but is at a level below 2 mm/yr for the vast majority of those cases. The biggest values in the rate field that can skew estimates of VLM the most are removed by the filtering and are relatively infrequent after we apply the selection criteria to the GPS data described above.

To estimate the vertical rate at the tide gauges, a new Delaunay triangulation is formed with each tide gauge and GPS stations locations. The rate at the tide gauge is the weighted median of the vertical rates at stations that are connected to the gauge in the triangulation subject to the same distance weighting method used in the filtering step, except that the tide gauge location has zero weight because it has no VLM estimate. Because the resulting rate is supported by multiple stations, and is derived using medians, it is a more robust estimate than simply using the nearest station alone (often several kilometers away) or using a mean of nearby stations which can be sensitive to outliers. The method works well when VLM representative to the tide gauge is sampled by more than one GPS station, and always takes the nearest station to have the greatest weight. Furthermore, since the estimate is the median of connected stations if a more distant station has a noncorroborative rate it will be disregarded. The largest errors occur in cases where VLM local to a tide gauge is very different than at the nearest GPS station. In this case the GPS correction may not be effective, but we note that much of global VLM attributable to solid Earth processes is geographically correlated over tens to hundreds of kilometers, while GIA is correlated over 10^3 km. This regionally stable part of the VLM is the part of the total GPS signal it is detected by multiple stations and is more likely attributable to Earth processes that persist over longer periods of time and hence can be more reliably extrapolated over the tide gauge record. As a final point, it is difficult to know when or if this situation arises, specifically the case when the TG is experiencing very local VLM without a collocated or nearby GPS station. The filtering and interpolation provides a reasonable way to obtain an estimate of VLM at such stations, which then allows us to also include these gauges that are typically included in the study of long-term sea level in our analysis. It should be recognized, however, that the filtered GPS rates for such cases might introduce additional errors.

Indeed, many of the tide gauges in the PSMSL RLR data set are located far from a GPS station. As shown in Figure 1, many gauges are located more than 100 km from the nearest GPS station. Specifically, 678 gauges are located more than 20 km from the nearest GPS station, while 353 gauges are located more than 100 km

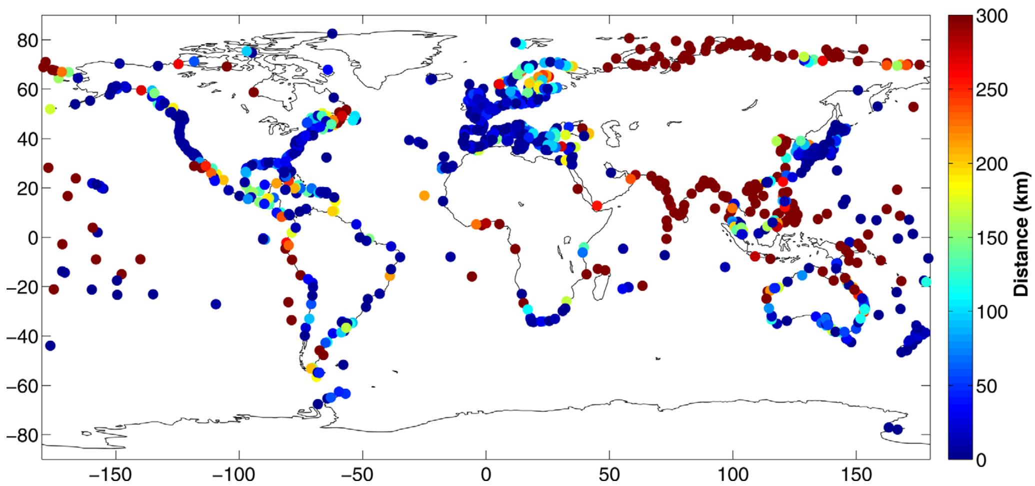

Figure 1. Distance (km) of each tide gauge in the PSMSL RLR data set from the nearest available GPS station.

from the nearest GPS station. Since our algorithm enhances the signal of the larger spatial-scale VLM, we have made the decision to still use the GPS corrections in many of these locations, albeit with the caveats discussed above. The only gauges that were removed based on distance to available GPS data were gauges where the distance to the nearest GPS station exceeded 300 km. Additionally, for the RD2011 subset, only 52 of the 89 gauges are located within 10 km of a GPS station. Furthermore, only 41 of the 89 gauges are located within 5 km of the nearest GPS station. As such, the case of a collocated GPS station is not common, and adds support for the filtering and interpolation discussed above when the goal is to assess the impact of VLM on tide gauge subsets that have been used for long-term sea level studies.

In this paper, we compare the filtered MIDAS GPS corrections (henceforth referred to simply as GPS VLM for simplicity) directly to modeled GIA VLM. The GPS VLM estimates include information regarding land motion resulting from all processes (within the boundaries of the filter) including GIA. The modeled GIA relative sea level trend estimates contain an additional factor not accounted for by the GPS, namely the impact of GIA on the sea surface. To analyze the impact on GMSL estimates using the GPS corrections in comparison to the GIA corrections in a consistent manner, the difference between the GIA relative sea level trend estimate and GIA VLM estimate is added into the GPS VLM correction before being applied to the tide gauge. While this corrects for the GIA component of the gravity redistribution and its resultant effect on sea level, we are not able to correct for a potential sea level signal associated with gravity redistribution associated with non-GIA VLM.

3. Results

3.1. GPS Versus GIA Correction

In past studies of twentieth century GMSL, typically the only correction for VLM applied to the tide gauge records comes from GIA models [e.g., *Church and White et al.*, 2011; *Ray and Douglas*, 2011; *Hamlington et al.*, 2011; *Hamlington and Thompson*, 2015]. As discussed above, however, this correction does not account for VLM resulting from other processes. As a first step in understanding the potential contribution of VLM to estimates of GMSL, we compare VLM from GPS and the ICE-6G GIA model (Figure 2). The 89 gauges in the RD2011 data set are shown in red. Based on this comparison of GPS and GIA VLM, two distinct regimes appear. The first is where the GPS and GIA corrections generally correspond with each other, particularly for strongly positive VLM. At these larger values (i.e., GPS ~6–8 mm yr^{-1}), however, the spread of GIA estimates relative to GPS suggests either that the GPS-based algorithm may be oversmoothing the GIA-related VLM, or the presence of errors in the GIA model. Some of the gauges included in this group have very long records, particularly those found in northern Europe and Scandinavia. While these long records provide valuable insight into long-term sea level trends, the lack of agreement between GPS and GIA VLM estimates potentially raises questions regarding their inclusion in global sea level reconstructions, especially when considering their influence on the early part of the GMSL reconstructions.

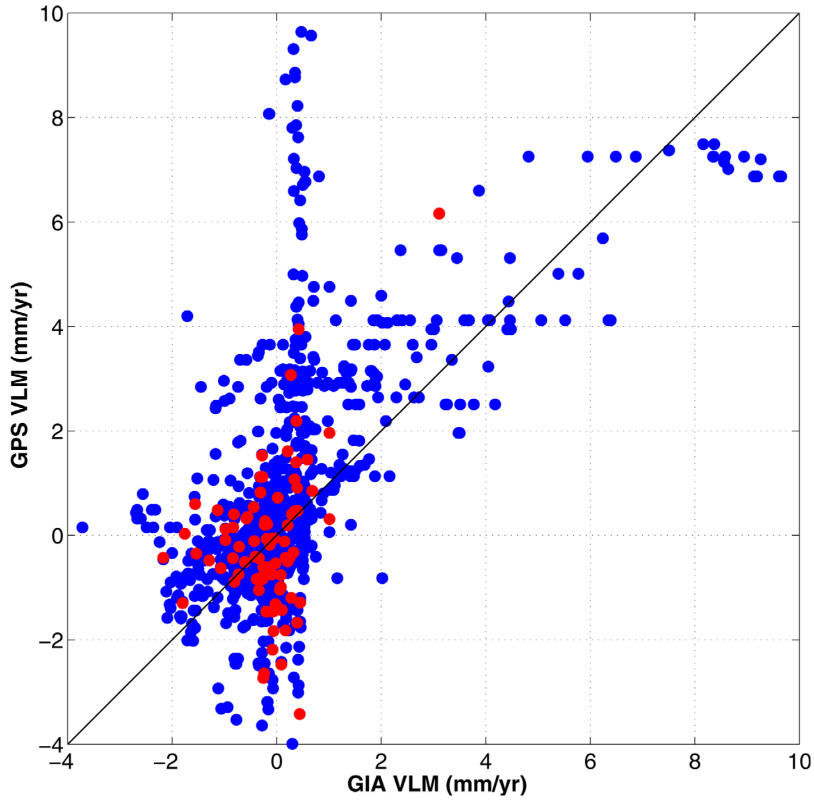

Figure 2. Comparison between GPS estimated vertical land motion (VLM) and modeled GIA VLM (ICE-6G) for the 1420 tide gauges in the PSMSL RLR data set. Tide gauges used in the RD2011 data set shown in red.

The other notable regime that is extracted is for gauges with small VLM values from the GIA model but a large spread in GPS-estimated VLM. It is for these gauges that using the GPS VLM estimates may provide the most benefit. For many of the tide gauge locations, particularly at low latitudes, the GIA-induced VLM is small. Figure 3 shows a map of the GPS VLM estimates minus the GIA model VLM estimates for the tide gauges in the RD2011 subset. These differences between the GPS and GIA model VLM estimates underscore the potential problems with only using a GIA model to correct for VLM at the tide gauges, reflecting conclusions in past studies [e.g., *Wöppelmann et al.*, 2007, 2009, 2014; *Bouin and Wöppelmann*, 2010; *King et al.*, 2012]. In particular, these differences show how interseismic tectonic and seismic cycle deformation,

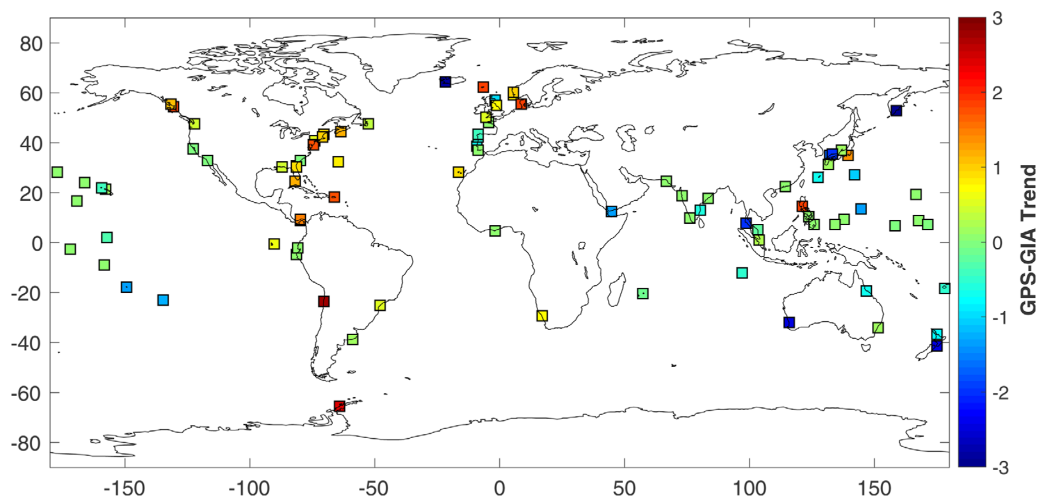

Figure 3. Difference (mm yr^{-1}) between the GPS VLM estimate and the GIA VLM estimate for the tide gauges in the RD2011 data set.

particularly at the major subduction zones of the Pacific Rim including those of Japan, Nazca, Alaska, and Cascadia, contribute to VLM at rates up to 4–6 mm yr^{-1} [e.g., *Aoki and Scholz*, 2003; *Larsen et al*., 2004; *Burgette et al*., 2009]. Other areas under influence from subsidence and large-scale flexural response from sediment loading are within the U.S. (e.g., Louisiana [*Ivins et al*., 2007]). Australia and New Zealand show significant subsidence—and thus relative sea level rise—attributable to non-GIA-related downward VLM. By looking at these differences, while still considering possible errors in GPS VLM and GIA VLM estimates, it may be possible to diagnose potential problems with individual tide gauges which could subsequently provide additional editing criteria for the tide gauge selection process in studies of long-term GMSL.

3.2. Distribution of VLM From GPS

As discussed above, VLM estimates are necessary for correcting individual gauges and identifying potentially problematic data that could lead to spurious sea level trends. The degree to which VLM can affect global trends, however, is an important issue for sea level reconstructions and associated estimates of long-term sea level rise. As a first step in assessing the impact of VLM at the tide gauges on GMSL, the distributions of GPS VLM estimates both for the full RLR data set (blue) and for the RD2011 subset (red) are shown in Figure 4a. For the full RLR data set, the average GPS-measured VLM is 0.63 ± 0.10 mm yr^{-1} with a median value of 0.14 ± 0.06 mm yr^{-1}, exhibiting a positive skew with a large positive tail. The RD2011 set of 89 gauges, on the other hand, has a mean of -0.14 ± 0.22 mm yr^{-1} and median value of -0.39 ± 0.20 mm yr^{-1}, exhibiting a shift toward general subsidence, albeit still with positive skew. Note that unless otherwise stated, error bars are representative of the 95% confidence interval throughout the paper.

By removing the GIA VLM estimate from the GPS VLM estimate at each gauge, it is possible to investigate how the non-GIA VLM that is unaccounted for by the GIA correction alone may impact estimates of GMSL. Figure 4b shows the distributions for the full RLR data set (blue) and the RD2011 data set (red) after removing the GIA VLM correction from the distributions shown in Figure 4a. In this case, the full RLR data set has a mean of 0.48 ± 0.09 mm yr^{-1} and a median of 0.21 ± 0.07 mm yr^{-1}, while the RD2011 set has a mean of 0.02 ± 0.19 mm yr^{-1} and a median of 0.05 ± 0.21 mm yr^{-1}. On a basic level, this suggests that GMSL estimates derived from the full data set will be lowered by tendency toward uplift if not corrected for non-GIA VLM, while the GMSL estimates from the RD2011 will be relatively unchanged with or without a correction of non-GIA VLM. It should be noted that no study has attempted to use the full set of PSMSL tide gauges to estimate GMSL, so we base few conclusions directly on this result. On the other hand, related to the results of the RD2011 data set presented here, *Wöppelmann and Marcos* [2016] arrived at a similar result, noting that non-GIA VLM will generally cancel out on global scales, as the distribution of the VLM is approximately symmetric with a zero mean. They also found a reduction in the mean VLM on the order of the 0.15 mm yr^{-1} when removing the GIA VLM. Due to the evolution of the tide gauge network, however, the problem is not that straightforward. The time period spanned by each tide gauge is generally different, and in many

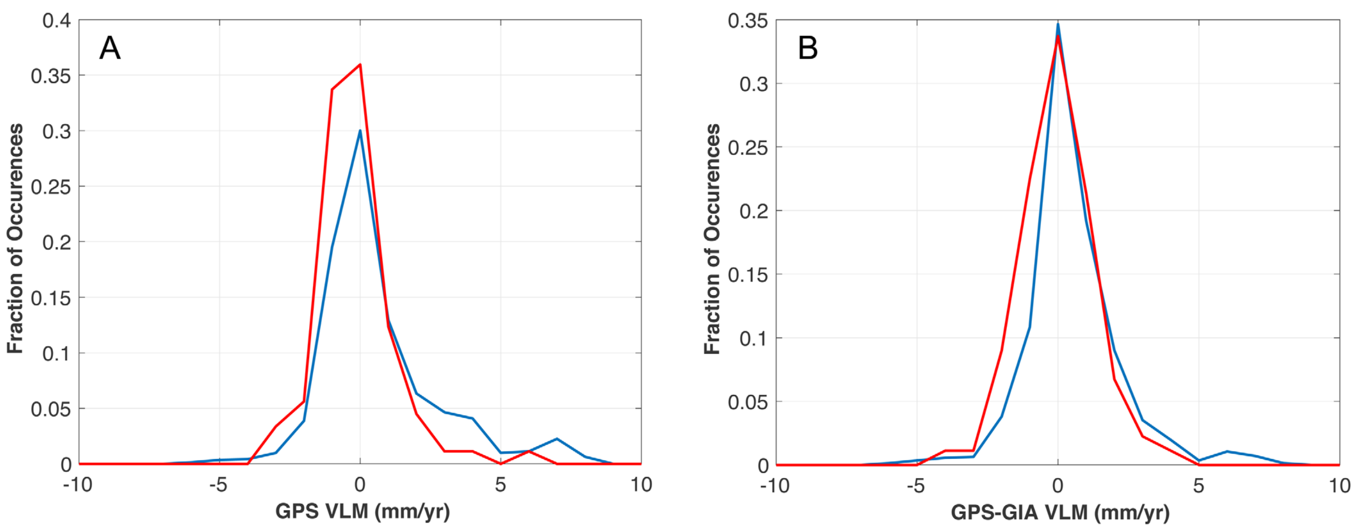

Figure 4. Distributions of the (a) GPS VLM and (b) GPS-GIA VLM for the tide gauges in the full RLR data set (blue) and the RD2011 data set (red).

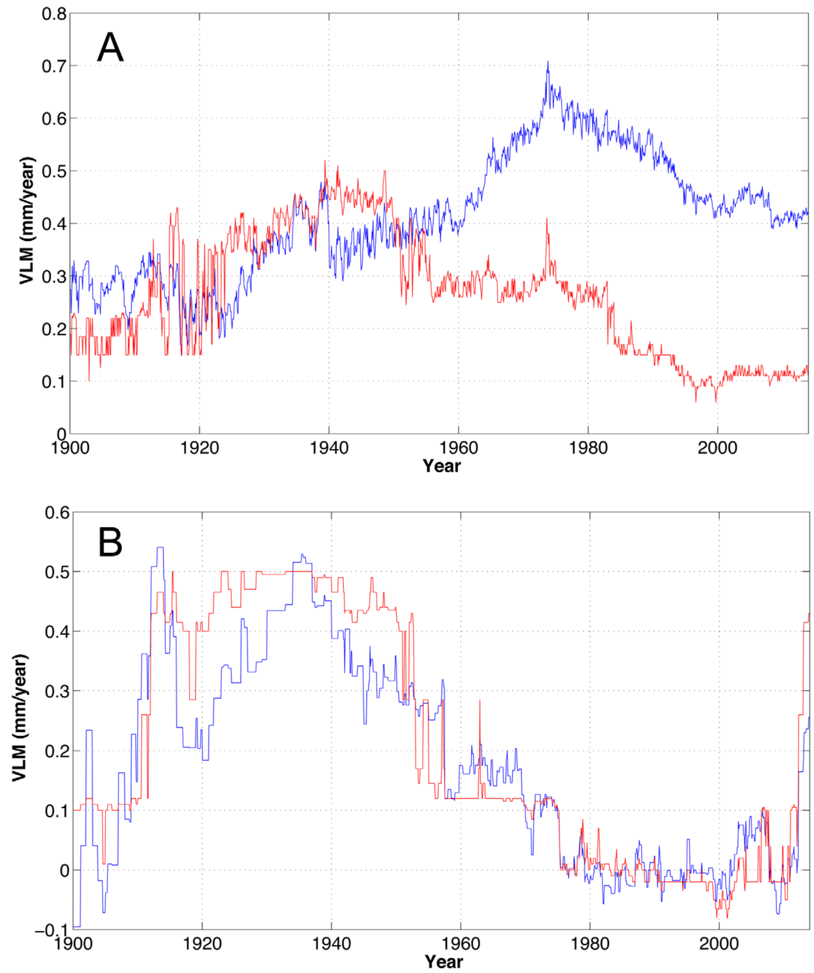

Figure 5. Mean (blue) and median (red) of the non-GIA VLM for the available tide gauges in (a) the full PSMSL data set and (b) RD2011 data set at each month in the record from 1900 to 2014.

cases, dramatically so. When assessing the impact of VLM on GMSL, understanding the distribution of non-GIA VLM throughout the record—and how it changes—is essential. While the 89 gauges in the RD2011 data set may have mean and median near zero, the same is not true at other times between 1900 and 2014 when only a subset of the 89 gauges are available. To study this in more detail, the mean and median of the non-GIA VLM of the available tide gauges at each month in the record is computed for both the full PSMSL data set (Figure 5a) and the RD2011 data set (Figure 5b). For the RD2011 data set, when most of the 89 tide gauges are available (1980–2000), the mean and the median of the non-GIA VLM are close to zero. For the rest of the record, however, the mean and median are both significantly higher, particularly from 1920 to 1960. This tendency toward uplift during this time period will lead to lower values in the GMSL time series if non-GIA VLM is not corrected for. The significantly different time series of the mean and median when using the full data set (Figure 5a) also suggests as more gauges are analyzed, this issue could be exacerbated or at least the time periods of general uplift could be shifted. Finally, the mean and median VLM contributions are considerably different in Figures 5a and 5b, highlighting the importance and potential impact of tide gauge selection choices.

3.3. Impact of VLM Correction on GMSL Estimates

Based on the analysis and results in section 3.2, VLM occurring at the tide gauges has a nonzero mean. The VLM also likely has a nonzero contribution to GMSL, although evolution of the tide gauge network through the record confuses the issue. To better ascertain the effect of VLM on GMSL, we have therefore recomputed the reconstruction of RD2011 with several new estimates of VLM at the tide gauges. No other facet of their original reconstruction has been changed here; we kept the same tide-gauge stations over the

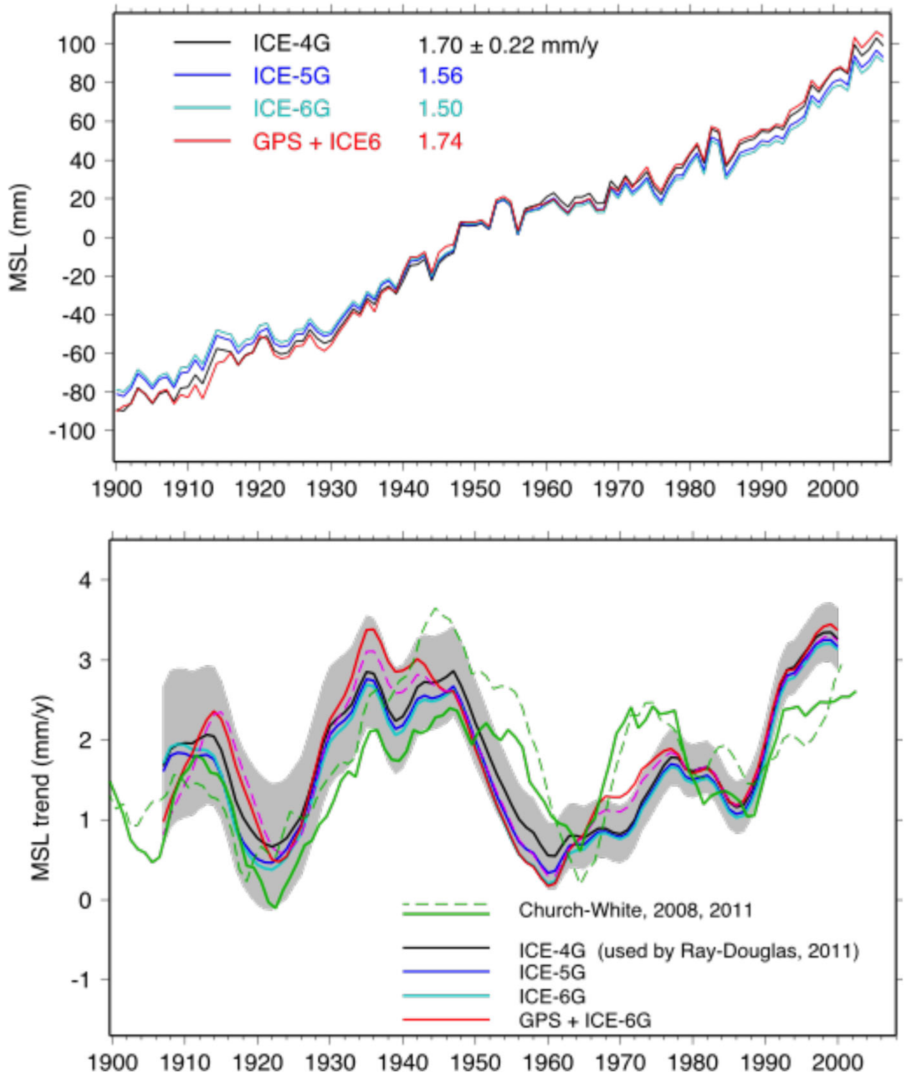

Figure 6. Reconstructed GMSL time series (a) using the technique and data from *Ray and Douglas* [2011] with varying VLM corrections. (b) Fifteen year trends for each time series shown in Figure 6a. Gray shading is the standard error on the 15 year trends from the GMSL time series in RD2011. The dashed green line corresponds to the older Church-White study. The two red lines are based on identical VLM adjustments from GPS; however, for the dashed line no GPS adjustment was applied if the distance between a tide gauge and the nearest GPS station exceeded 300 km. Thus, the very large GPS-based rate around 1935 must be arising, in part, from GPS adjustments interpolated over very long distances from certain tide gauges.

same time span, with all applied regularizations following the originally published approach. In their original reconstruction RD2011 applied GIA adjustments to all gauges based on the ICE-4G model. Here we show the reconstruction results based on four different estimates of GIA/VLM at the tide gauges: (1) ICE-4G, (2) ICE-5G, (3) ICE-6G [*Argus et al*., 2014; *Peltier et al*., 2015], and (4) GPS. As discussed above, the GPS VLM adjustment must be supplemented with a GIA model to account for the GIA-induced perturbation to the sea surface itself. Here we used ICE-6G for this purpose. Figure 6 (top) shows the resulting GMSL time series along with corresponding least squares linear trends. The uncertainty, 0.22 mm yr^{-1}, is roughly the same for all four cases, and is only listed for the first case. The method for computing this uncertainty is discussed in detail in RD2011. To summarize briefly, the uncertainty on the GMSL trend estimate is computed directly from the GMSL time series (and its error bars) by a Monte Carlo calculation. The linear residuals in the GMSL time series are fit to an autoregressive model of order 1 by solving the Yule-Walker equations (trivial for order 1), and this resulting model is used to generate Monte Carlo autocorrelated error realizations, scaled properly to reflect the time-varying error bar. Applying the GPS correction yields a higher estimate of the trend in GMSL, with a 0.24 ± 0.08 mm yr^{-1} increase relative to applying the ICE-6G GIA relative sea level correction. The uncertainty of 0.22 mm yr^{-1} shown in Figure 6a is largely a result of the decadal variability about the trend, and not the VLM itself. To isolate the significance of this increase in VLM and obtain the 0.08 mm yr^{-1} error bar, we have differenced the GMSL and computed the resultant 95% confidence interval. For comparison, the mean of the mean time series shown in Figure 5b is 0.23 mm yr^{-1}, further demonstrating that the temporal sampling of the tide gauges through the record plays an important role in the estimation of GMSL. It should also be noted that the trend difference is much smaller when comparing the GPS-corrected GMSL with the ICE-4G-corrected GMSL, for example. This also underscores the significant role that the choice of GIA model has on GMSL estimates, although we do not base any other conclusions on this result as the GPS corrections used in Figure 6 were supplemented with the ICE-6G GIA-induced perturbation to the sea surface itself.

Figure 6 (bottom) shows the variability in 15 year trends of the GMSL time series, and it depicts substantial differences over the course of the twentieth century. Note the gray shading represents the standard error of the 15 year trends and is simply reproduced from the original GMSL time series in RD2011. Similar to the discussion in section 3.2, it should be noted that these differences arise largely because of the different lengths of the tide gauge records used for the reconstruction. If each tide gauge spanned the full length of the record, the different 15 year trend time series would be offset by the average difference in the VLM corrections but would otherwise have the same variations through time. Demonstrating this and corresponding to the values in Figure 5b, the 15 year trends when correcting for non-GIA VLM are generally higher for the time period from 1920 to 1960, with an apparent net uplift signal at the available tide gauges being removed. Given that RD2011 focused on long records with small non-GIA VLM, the impact of VLM both in terms of long-term trends and decadal trend variability could be larger for studies using more tide gauges, many of which will necessarily have shorter records and potentially more impact on GMSL. As shown in Figures 4 and 5, VLM at the tide gauge data set as a whole has nonzero mean, and selecting more gauges from this set will likely lead to a shift in the computed trend if VLM is not appropriately accounted for.

3.4. Impact of VLM Uncertainty on GMSL Estimates

The GPS VLM estimates at each tide gauge are obtained from time series that are generally less than a decade in length. Additionally, the VLM estimates are made through a Delaunay triangulation, where the rate at the tide gauge is the weighted median of the vertical rates at stations that are connected to the tide gauge in the triangulation. As a result, there is uncertainty in the GPS VLM estimate associated with differences in the vertical rates for the stations connected to a particular tide gauge in the Delaunay triangulation, and also from the uncertainty in estimating the linear rate at a particular station associated with the length of time series, scatter in the time series, and deviation from linearity. It should also be noted that the information available regarding the formal uncertainty of the GPS velocities is an advantage over the VLM rates provided by GIA models. To obtain an idea of how these sources of uncertainty affect estimates of GMSL, we combine the two sources of uncertainty and perform a randomization test using the RD2011 tide gauge subset, selecting from an interval of $\pm$ the combined error for each gauge and subsequently estimating GMSL from 1900 to present. To obtain the estimates of GMSL, the VLM corrections are applied to differenced tide gauge data, which are then averaged together before being reintegrated to provide a GMSL time series from 1900 to 2014, following a procedure similar to that of *Hamlington and Thompson* [2015]. This process is completed 2000 times and a confidence interval on the GMSL trend associated with these two sources of uncertainty is obtained, as shown in Figure 7. The mean trend is found to be 1.91 mm yr^{-1}, with a 95% confidence interval between 1.74 and 2.07 mm yr^{-1}. For comparison, the trend obtained using the same procedure but relying only on the GIA relative sea level correction (ICE-6G) is 1.74 mm yr^{-1}. While these numbers are both higher than the results shown for the RD2011 reconstruction in Figure 6, the increased GMSL trend from the GIA correction to the GPS correction is consistent.

3.5. Impact of Nonlinear VLM on GMSL Estimates

Finally, while these corrections were applied to the full tide gauge records in the RD2011 reconstruction and the randomization test discussed above, without being able to attribute the VLM to a particular source, it is difficult to assess at what time within the tide gauge record that GPS-measured VLM began. As shown in Figure 6b, the length of each tide gauge record leads to differences in the 15 year trends when varying the VLM correction that is applied. Similarly, lack of knowledge regarding VLM prior to the

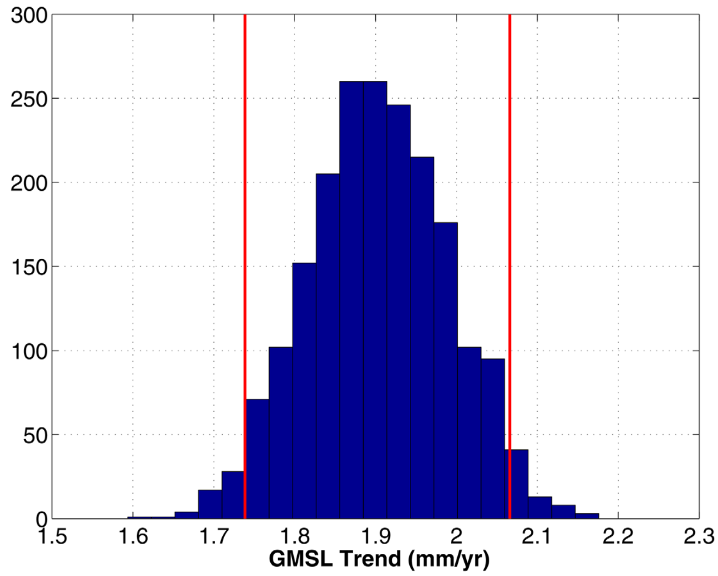

Figure 7. Randomization test results obtained by accounting for the error in the GPS VLM estimate at each tide gauge in the RD2011 data set. Error estimates are a combination of uncertainty associated with differences in the vertical rates for the stations connected to a particular tide gauge in the Delaunay triangulation, and also uncertainty in estimating the linear rate at a particular station associated with the length of time series, scatter in the time series, and deviation from linearity. Results for the 1900–2014 GMSL trends are shown. Solid red bars show the 95% confidence interval.

availability of GPS measurements may result in uncertainty in reconstructed GMSL trends. To estimate the uncertainty imparted by the unknown start-time of GPS-measured non-GIA VLM, a randomization test is performed. Initially, the GPS VLM is defined to be composed of two contributors: (1) GIA as estimated by the model and (2) non-GIA VLM, simply given as the difference of the GPS estimate and the GIA estimate of VLM. It is then assumed that the non-GIA VLM measured by the GPS began at some unknown time in the past. In reality, this would be representative of the case when human intervention resulted in a change in groundwater extraction, for example. In some cases, it is likely possible to identify gauges that have large trend changes in the record through visual inspection, which could subsequently allow for their removal from the analysis. This visual inspection is not performed, and as a result, the uncertainty estimated as a result of the test described here is likely approaching the upper bound of the impact of nonlinearity on GMSL estimates. The relative sea level correction provided by the GIA model (ICE-6G) is

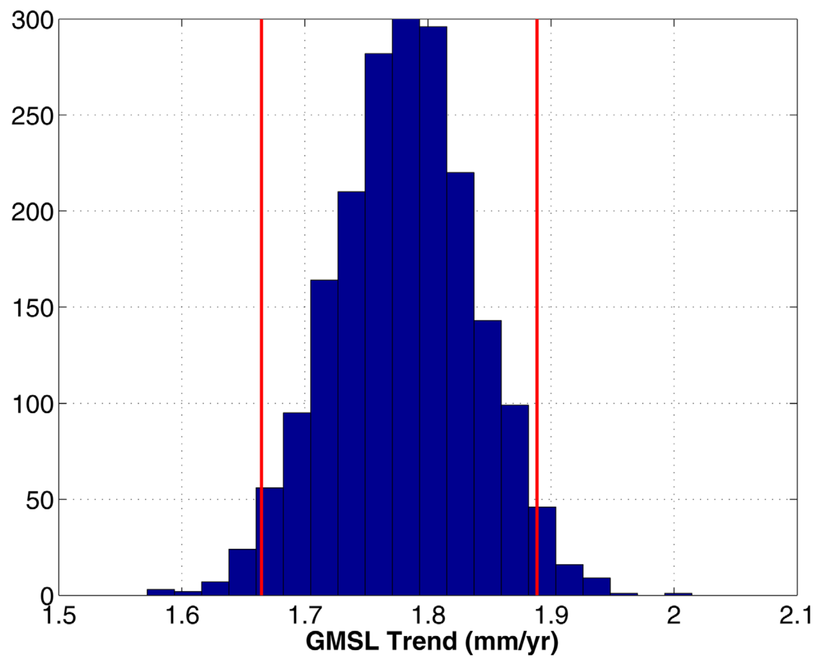

Figure 8. Randomization test results obtained by varying length of time period to which the GPS correction is applied, evaluating the impact of the unknown time of onset of the non-GIA VLM within each tide gauge record. Results for the 1900–2014 GMSL trends are shown. Solid red bars show the 95% confidence interval.

applied to the full tide gauge records in the data set defined by RD2011. Then the non-GIA VLM is applied to varying lengths of the record, from 5 years to the length of the full record, starting in 2014 and extending backward. This yields a set of tide gauge records affected by a possible time span of VLM both in terms of magnitude and timing from which a GMSL estimate can be obtained. This process is repeated 2000 times, with the timing of the VLM varied each time. The way this test is composed, shorter records will have the GPS correction applied to their full record more often than longer records, and gauges where the GPS VLM estimate is roughly equal to the GIA VLM estimate will not contribute significantly to the uncertainty in the GMSL estimate. The assumption is that the GPS minus GIA VLM occurs at a single time in the past and stays consistent for the rest of the record. It is possible that VLM is more nonlinear at some tide gauges and shifts in the level of VLM occur several times during the record. Finally, this test should be viewed as an extreme case when there is no additional knowledge about VLM at a particular location, and VLM varies on relatively short time scales. In reality, there is knowledge about the sources of VLM at many of the tide gauge locations (although not necessarily the magnitude of the VLM), and many sources of non-GIA VLM can be assumed to be constant over the time scales considered here and indeed over significantly longer time scales. The uncertainty in the GMSL trend provided here should serve as a first-order estimate of the impact of unknown VLM on GMSL, and more importantly, give an indication of how the short GPS records upon which the VLM estimates at the tide gauges are based can lead to uncertainty in the GMSL trend. The results of the randomization test are shown in Figure 8. The 95% confidence interval on the GMSL trend (solid line) is from 1.66 to 1.89 mm yr^{-1}. The mean trend of 1.77 mm yr^{-1} is again higher than the trend estimated directly from the RD2011 reconstruction but lower than if the GPS corrections were simply applied to the full tide gauge records. The relatively small uncertainty resulting from this test indicates that while the GPS VLM estimates at the tide gauges may be based on short time series, the associated uncertainty in the timing of the VLM does not contribute in a large way to uncertainty in the GMSL trend.

4. Summary and Discussion

The magnitude and frequency of future coastal flooding is closely linked to relative sea level rise. While the change in the height of the ocean will be a primary cause of sea level impacts felt at the coast, of similar importance is the movement of land relative to the ocean. As such, continuous monitoring of VLM with GPS is essential to understanding the magnitude of the potential sea level-related threats in the future. It is also possible to use GPS measurements to improve the analysis for the historical record, providing better context for recent sea level changes. Here, we have described the utility of GPS measurements in improving estimates of twentieth century GMSL. A significant limiting factor in this analysis is the availability of VLM measurements directly at the TG. As can be seen in Figure 1, most tide gauges do not have a collocated GPS station. In order to assess the impact of VLM on GMSL estimates, information from nearby GPS stations must be extended to the tide gauge locations (as described in section 2.2). In doing so, additional errors are introduced, but this does provide the opportunity to evaluate the tide gauges typically used for long-term sea level studies, as opposed to only the subset of gauges with a collocated GPS measurement. How useful the GPS-based VLM measurements are for correcting the historical record also depends on the physical source of VLM, which varies by location. A key distinction is whether the primary driver of VLM is steady in time, as is usually the case during interseismic tectonic deformation, or highly nonlinear, as is often the case in areas dominated by subsidence in aquifers subject to climatic and anthropogenic forcing. Similarly, an important topic of future research is the separation of the GPS-measured VLM into time-invariant and time-variable parts, perhaps by the consideration of global-scale tectonic models.

In this study, we seek to determine in what way non-GIA VLM affects estimates of long-term GMSL rise. To do this, comparisons have been made between GIA VLM estimates and GPS VLM estimates at the tide gauges around the world, leading to a number of important conclusions. First, in many locations around the world, the GPS estimate of VLM is dramatically different than the estimate accounting for GIA VLM alone. As seen in Figures 2 and 3, two regimes are visible when comparing the two different estimates. Tide gauges with much higher GPS rates when compared to the GIA rates are generally found in areas with significant tectonic activity, including around Japan, Nazca, Alaska, and Cascadia. The other regime arises for gauges in areas that are known to be impacted by GIA. The GPS and GIA VLM estimates generally track each other, although even at these locations, differences on the order of multiple mm yr^{-1} are observed.

This suggests possible errors in the GIA models, errors associated with the GPS estimates, or alternatively the presence of non-GIA VLM at gauges where a GIA-only VLM correction was generally thought sufficient.

A second important conclusion of this study is that both the GPS VLM estimates at the gauges in the full RLR data set and RD2011 data set have nonzero contributions to GMSL. More specifically, the gauges included in both of these sets have a general tendency toward uplift through the length of the record, suggesting estimates of GMSL in the twentieth century will be higher once the tide gauge records are corrected for non-GIA VLM (although the choice of GIA model and GPS-based correction may impact this result). This is particularly important for the RD2011 tide gauge data set that was specifically edited to remove gauges with known VLM issues, including those gauges located in areas experiencing tectonic activity. Despite this careful editing and tide gauge selection, the trend in GMSL from 1900 to present increased by 0.24 ± 0.08 mm yr^{-1} when using the GPS VLM correction. An important caveat to this is that this result is dependent on the subset of tide gauges and the actual corrections used in addition to the reconstruction technique that is applied. The 0.24 mm yr^{-1} should not be viewed as a "correction" to be applied to reconstructed GMSL trend estimates in general, as this value will certainly change with a change in tide gauges or reconstruction method. While it is indeed true that these results are not necessarily applicable to the tide gauge data sets in other reconstruction studies, the results shown here at least necessitate a careful examination of VLM at the tide gauges selected for use. This is in support of the conclusions of *Wöppelmann et al*. [2014] that first attempted to provide a new GPS-corrected GMSL value and found that a wide range of GMSL values could be obtained depending on tide gauge selection and weighting choices. Indeed, including more gauges than the 89 RD2011 used may lower the uncertainty in GMSL but can introduce greater bias coming from non-GIA VLM. It should also be emphasized that while the assumption of non-GIA VLM cancelling out in terms of impact on GMSL may be true for some periods of time in the time period of study, it is necessary to understand how the distribution of non-GIA VLM changes through time as tide gauges have varying record lengths. This underscores the importance of finding a way to correct for non-GIA VLM, as creating a tide gauge data set with a symmetric distribution about zero at every time during the past century is a difficult task.

Finally, the GPS VLM corrections provide a useful alternative to the GIA-only VLM corrections and allow for the identification of potentially problematic gauges that should be omitted from historical sea level studies. This approach can be used to supplement other efforts to identify gauges with anomalous measurements [e.g., *Santamaría-Gómez et al*., 2014]. The representativeness of the GPS VLM estimates over the longer time period, however, is unknown. As seen in the randomization test results in Figures 7 and 8, unknown past VLM can contribute uncertainty to estimates of GMSL. If GPS is relied on to correct for VLM over the full record of the tide gauges, error on the order of 0.1 mm yr^{-1} may be introduced to GMSL trend estimates as a result of potential past nonlinear VLM. On the other hand, as seen in both Figures 5 and 6, not accounting for the non-GIA VLM will lead to significantly lower estimates of the trend in GMSL. While GPS records are generally short, the uncertainty associated with extracting the long-term trend from the short time series (Figure 7) and the uncertainty associated with unknown past non-GIA VLM (Figure 8) are relatively small, and should be considered acceptable given the benefit of accounting for more of the VLM signal. To assume that non-GIA VLM is zero is likely a larger source of error, and ignores the advantages provided by the GPS measurements. In any case, careful consideration must be given to VLM at the tide gauge locations, requiring an approach combining GPS measurements, GIA models, and understanding of sources of VLM around the world that could be affecting the measurements made by tide gauges.

Acknowledgments
The tide gauge data are available from the Permanent Service for Mean Sea Level (http://www.psmsl.org/data/). The GIA corrections for the PSMSL stations are provided by Richard Peltier (http://www.psmsl.org/train_and_info/geo_signals/gia/peltier/). B.D.H, W.C.H, and G.B. acknowledge support from NASA Sea Level Change Team grant NNX14AJ98G. B.D.H also acknowledges support from NASA New Investigator Program NNX16AH56G. P.R.T acknowledges support from the NOAA Climate Program Office in support of the University of Hawaii Sea Level Center. W.C.H. and G.B. acknowledge support from NSF-EAR EarthScope project 1252210. We thank the great number of GPS network operators and data archivists who provided open access to GPS data used in this study. We thank the NASA Jet Propulsion Laboratory, Caltech, for providing the GIPSY OASIS II software used to generate GPS time series. We thank IGS and UNAVCO for providing the GPS data through their web portals http://www.igs.org and http://www.unavco.org. Time series used for this study were obtained through the Nevada Geodetic Laboratory web portal http://geodesy.unr.edu.

References

Aoki, Y., and C. H. Scholz (2009), Imaging interseismic locking at the Nankai subduction zone, Southwest Japan, in *Subduction Zone Geodynamics*, edited by S. Lallemand and F. Funiciello, pp. 159–171, Springer-Verlag, Berlin Heidelberg.

Argus, D. F., and W. R. Peltier (2010), Constraining models of postglacial rebound using space geodesy: A detailed assessment of model ICE-5G (VM2) and its relatives, *Geophys. J. Int.*, *181*, 697–723, doi:10.1111/j.1365-246X.2010.04562.x.

Argus, D. F., W. R. Peltier, R. Drummond, and A. W. Moore (2014), The Antarctica component of postglacial rebound model ICE-6G_C (VM5a) based upon GPS positioning, exposure age dating of ice thicknesses, and relative sea level histories, *Geophys. J. Int.*, *198*(1), 537–563, doi:10.1093/gji/ggu140.

Blewitt, G., C. Kreemer, W. C. Hammond, and J. Gazeaux (2016), MIDAS robust trend estimator for accurate GPS station velocities without step detection, *J. Geophys. Res. Solid Earth*, *121*, 2054–2068, doi:10.1002/2015JB012552.

Bouin, M.-N., and G. Wöppelmann (2010), Land motion estimates from GPS at tide gauges: A geophysical evaluation, *Geophys. J. Int.*, *180*, 193–209.

Burgette, R. J., R. J. Weldon II, and D. A. Schmidt (2009), Interseismic uplift rates for western Oregon and along-strike variation in locking on the Cascadia subduction zone, *J. Geophys. Res.*, *114*, B01408, doi:10.1029/2008JB005679.

Cazenave, A., K. Dominh, F. Ponchaut, L. Soudarin, J.-F. Cretaux, and C. Le Provost (1999), Sea level changes from Topex–Poseidon altimetry and tide gauges, and vertical crustal motions from DORIS, *Geophys. Res. Lett.*, *26*, 2077–2080, doi:10.1029/1999GL900472.

Cazenave, A., O. Henry, S. Munier, T. Delcroix, A. L. Gordon, B. Meyssignac, W. Llovel, H. Palanisamy, and M. Becker (2012), Estimating ENSO influence on the global mean sea level 1993–2010, *Mar. Geod.*, *35*, 82–97.

Church, J.A., and White, N. J. (2006), A 20th century acceleration in global sea level rise, *Geophys. Res. Lett.*, *36*, L040608, doi:10.1029/2005GL024826.

Church, J. A., and White, N. J. (2011), Sea-level rise from the late 19th to the early 21st century, *Surv. Geophys.*, *32–34*, 585–602.

Douglas, B. C. (1991), Global sea level rise, *J. Geophys. Res.*, *96*, 6981–6992.

Douglas, B. C. (1997), Global sea rise: A redetermination, *Surv. Geophys.*, *18*, 279–292.

Emery, K. O., and D. G. Aubrey (1991), *Sea Levels, Land Levels, and Tide Gauges*, Springer, N. Y.

Gornitz, V., S. Lebedeff, and J. Hansen (1982), Global sea level trend in the past century, *Science*, *215*, 1611–1614.

Hamlington, B. D., and P. R. Thompson (2015), Considerations for estimating the 20th century trend in global mean sea level, *Geophys. Res. Lett.*, *42*, 4102–4109, doi:10.1002/2015GL063306.

Hamlington, B. D., R. R. Leben, R. S. Nerem, W. Han, and K.-Y. Kim (2011), Reconstruction sea level using cyclostationary empirical orthogonal functions, *J. Geophys. Res.*, *116*, C12015, doi:10.1029/2011JC007529.

Hamlington, B. D., R. R. Leben, M. W. Strassburg, R. S. Nerem, and K.-Y. Kim (2013), Contribution of the Pacific Decadal Oscillation to global mean sea level trends, *Geophys. Res. Lett.*, *40*, 5171–5175, doi:10.1002/grl.50950.

Hay, C. H., E. Morrow, R. E. Kopp, and J. X. Mitrovica (2015), Probabilistic reanalysis of twentieth-century sea level rise, *Nature*, *517*, 481–484.

Holgate, S. J. (2007), On the decadal rates of sea level change during the twentieth century, *Geophys. Res. Lett.*, *34*, L01602, doi:10.1029/2006GL028492.

Holgate, S. J., et al. (2013), New data systems and products at the permanent service for mean sea level, *J. Coastal Res.*, *29*, 493–504.

Ivins, E. R., R. K. Dokka, and R. G. Blom (2007), Post-glacial sediment load and subsidence in coastal Louisiana, *Geophys. Res. Lett.*, *34*, L16303, doi:10.1029/2007GL030003.

Jevrejeva, S., J. C. Moore, A. Grinsted, and P. L. Woodworth (2008), Recent global sea level acceleration started over 200 years ago?, *Geophys. Res. Lett.*, *35*, L08715, doi:10.1029/2008GL033611.

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.

Larsen, C. F., R. J. Motyka, J. T. Freymueller, K. A. Echelmeyer, and E. R. Ivins (2004), Rapid uplift of southern Alaska caused by recent ice loss, *Geophys. J. Int.*, *158*, 1118–1133, doi:10.1111/j.1365-246X.2004.02356.x.

Meyssignac, B., M. Becker, W. Llovel, and A. Cazenave (2012), An assessment of two-dimensional past sea level reconstructions over 1950–2009 based on tide-gauge data and different input sea level grids, *Surv. Geophys.*, *33*, 945–972.

Neilan, R., P. A. Van Scoy, and P. L. Woodworth (Eds.) (1998), Proceedings of the Workshop on methods for monitoring sea level: GPS and tide gauge benchmark monitoring, GPS altimeter calibration Workshop organised by the IGS and PSMSL, Jet Propulsion Laboratory, 17–18 March 1997, 202 pp.

Nerem, R. S., D. Chambers, C. Choe, and G. T. Mitchum (2010), Estimating mean sea level change from the TOPEX and Jason Altimeter Missions, *Mar. Geod.*, *33*, 435–446.

Peltier, W. R., D. F. Argus, and R. Drummond (2015), Space geodesy constrains ice-age terminal deglaciation: The global ICE-6G_C (VM5a) model, *J. Geophys. Res. Solid Earth*, *120*, 450–487.

Ray, R., and B. Douglas (2011), Experiments in reconstructing twentieth-century sea levels, *Prog. Oceanogr.*, *91*, 496–515.

Sanli, D. U., and G. Blewitt (2001), Geocentric sea level trend using GPS and $>$100-year tide gauge record on a postglacial rebound nodal line, *J. Geophys. Res.*, *106*, 713–719, doi:10.1029/2000JB900348.

Santamaría-Gómez, A., M. Gravelle, X. Collilieux, M. Guichard, B. Martín Míguez, P. Tiphaneau, and G. Wöppelmann (2012), Mitigating the effects of vertical land motion in tide gauge records using state-of-the-art GPS velocity field, *Global Planet. Change*, *98–99*, 6–17.

Santamaría-Gómez, A., M. Gravelle, and G. Wöppelmann (2014), Long-term vertical land motion from double-differenced tide gauge and satellite altimetry data, *J. Geod.*, *88*, 207–222.

Thompson, P. R., and M. A. Merrifield (2014), A unique asymmetry in the pattern of recent sea level change, *Geophys. Res. Lett.*, *41*, 7675–7683, doi:10.1002/2014GL061263.

Williams, S. D. P., T. F. Baker, and G. Jeffries (2001), Absolute gravity measurements at UK tide gauges, *Geophys. Res. Lett.*, *28*, 2317–2320, doi:10.1029/2000GL012438.

Wöppelmann, G., and M. Marcos (2016), Vertical land motion as a key to understanding sea level change and variability, *Rev. Geophys.*, *54*, 64–92, doi:10.1002/2015RG000502.

Wöppelmann, G., B. Martín Míguez, M.-N. Bouin, and Z. Altamimi (2007), Geocentric sea-level trend estimates from GPS analyses at relevant tide gauges world-wide, *Global Planet. Change*, *57*, 396–406.

Wöppelmann, G., C. Letetrel, A. Santamaria, M.-N. Bouin, X. Collilieux, Z. Altamimi, S. D. P. Williams, and B. Martín Míguez (2009), Rates of sea-level change over the past century in a geocentric reference frame, *Geophys. Res. Lett.*, *36*, L12607, doi:10.1029/2009GL038720.

Wöppelmann, G., M. Marcos, A. Santamaría-Gómez, B. Martín-Míguez, M.-N. Bouin, and M. Gravelle (2014), Evidence for a differential sea level rise between hemispheres over the twentieth century, *Geophys. Res. Lett.*, *41*, 1639–1643, doi:10.1002/2013GL059039.