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Considerations for Estimating the 20th Century Trend in Global Mean Sea Level

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Key Points:

- Recent studies have provided differing estimates of the trend in GMSL
- These differences are due, in part, to tide gauge selection choices
- Only gauges representative of the trend should be used when estimating GMSL

Supporting Information:

- Text S1

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Considerations for estimating the 20th century trend in global mean sea level

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Abstract Recent efforts in reconstructing historical sea level change have led to a range of published estimates for the global mean sea level trend over the last century. Disagreement in these estimates can be attributed to two factors: (1) differences in analysis and/or reconstruction techniques and (2) differences in tide gauge selection and quality control of the data. Here the impact of tide gauge selection is explored by calculating global mean trends using three different tide gauge data sets that have been utilized in recent reconstruction studies. The inclusion of tide gauge records that are affected by unresolved internal variability and/or unaccounted for vertical land motion are found to significantly impact the estimates of the long-term trend in global mean sea level. In conclusion, several guidelines are presented regarding the selection of tide gauges for use in historical reconstructions focused on estimating the 20th century global mean sea level trend.

1. Introduction

Estimates of global mean sea level (GMSL) rise are well constrained since the early 1990s due to the advent of satellite altimetry, which provides continuous, near-global measurements of sea surface height. The satellite-derived estimate of GMSL rise during this period is ~3.2 mm/yr (1993 to present), but due to the short record length, it is difficult to separate the effect of interannual to decadal scale internal climate variability on GMSL [e.g., *Cazenave et al.*, 2012; *Hamlington et al.*, 2013] from the long-term secular trend.

Prior to satellite altimetry, the primary source of sea level data is historical tide gauge records. This data set, while providing longer time series, presents a variety of challenges when attempting to calculate GMSL. First, the tide gauge data set is composed of discrete spatial samples that are necessarily located along continental and island coasts. This is problematic, because the ocean interior is poorly sampled, and local oceanographic and geodetic processes dominate the variability. Second, sampling by tide gauges is far from uniform in space and time. The network of gauges is sparse until the latter half of the 20th century, and there is significant clustering of gauges around heavily populated areas—particularly in the Northern Hemisphere. Third, individual records can be short, spanning only a few years, and trends estimated directly from these gauges are significantly impacted by the influence of regional and local variability. Trends over short records often differ substantially from the global mean rate and are not likely to be related to changes in GMSL. The constant evolution of the tide gauge network and the resulting nonuniform spatial and temporal sampling of oceanographic and geodetic processes is the greatest source of uncertainty when calculating GMSL from tide gauges. The result is large, time-dependent uncertainties in GMSL that generally decrease in time as sampling by the tide gauge network improves.

The most common method for overcoming the limitations of the tide gauge data set is to "reconstruct" historical sea level fields by combining information about the spatial covariance of sea level from satellite altimetry (and sometimes models) with the longer time series provided by tide gauges [*Chambers et al.*, 2002; *Church et al.*, 2004; *Church and White*, 2006, 2011; *Ray and Douglas*, 2011; *Hamlington et al.*, 2011; *Meyssignac et al.*, 2012; *Hay et al.*, 2015]. These reconstructions provide estimates of global sea level fields prior to the satellite era, and while they have been used to investigate regional variability, they are most widely cited for the resulting estimates of GMSL over the past century [e.g., *Vermeer and Rahmstorf*, 2009; *Rahmstorf et al.*, 2011; *Church et al.*, 2013]. Reconstructions are generally regarded as an improvement over estimates of GMSL calculated from the tide gauges only [e.g., *Douglas*, 1991, 1997; *Holgate*, 2007; *Jevrejeva et al.*, 2008; *Merrifield et al.*, 2009], because reconstructions attempt to account for the local variability at individual gauges, which may allow more data (i.e., shorter records) to be utilized.

In a broad sense, all the investigations cited above are motivated by the need for robust estimates of a common quantity: the long-term trend in GMSL. While these studies use different analysis and reconstruction techniques, the historical tide gauge data set available to each investigation is the same. The resulting estimates, however, differ significantly in terms of the decadal variability captured in the GMSL time series [*Church et al*., 2013] and different estimates of the rate of 20th century GMSL rise [*Hay et al*., 2015]. It is tempting to attribute differences between the various estimates to differences in methodology, but there is a second fundamental reason for these disagreements: differences in tide gauge selection and quality control of the data.

The nature of the trend captured by any given tide gauge is affected by the length of the record [*Douglas*, 1991, 1997]. Trends over short records (i.e., fewer than 30 years) tend to have larger amplitudes (both positive and negative) and are likely to be heavily influenced by ocean dynamics and internal climate variability. In contrast, trends over longer records (i.e., greater than 60 years) are more likely to reflect changes in the density and mass of the global ocean. Even among the longest records, there is significant variation in long-term trends due to vertical land motion and the gravitational fingerprints of ice melt. Away from tectonically active regions and far from melt sources, however, trends over the longest records do tend to converge toward the rate of GMSL rise [e.g., *Douglas*, 1997; *Holgate*, 2007].

In theory, including more data should improve estimates of 20th century GMSL rise. In practice, including more data generally involves including progressively shorter records with trends that are increasingly less representative of GMSL. Reconstruction techniques were developed, in part, to make it possible to include shorter tide gauge records by accounting for the contribution of nonglobal variability at any given location. There are multiple studies, however, that suggest that a simple arithmetic mean over a given subset of tide gauge records provides a similar estimate of the long-term GMSL trend to that obtained from more sophisticated reconstruction methodologies applied to the same set [e.g., *Douglas*, 1991, 1997; *Holgate*, 2007; *Ray and Douglas*, 2011; *Christiansen et al*., 2010; *Calafat et al*., 2014]. This implies that while reconstructions may provide improved estimates of spatial variability in historical sea level change, the impact of reconstruction techniques on estimates of the long-term GMSL trend is generally low. Thus, differences between the subsets of available tide gauge data used in various sea level reconstructions likely contribute substantially to differences in calculations of long-term GMSL trends.

In this paper, we highlight the effect that tide gauge selection can have on estimates of 20th century GMSL rise and offer basic guidelines for choosing an optimal set of gauges in such calculations. While some of the conclusions presented here were originally set forth by *Douglas* [1991, 1997] and reinforced by *Ray and Douglas* [2011], recent studies dictate both a review and continued analysis of the topic.

2. Tide Gauge Data

We analyze monthly tide gauge sea level data (1900–2013) from three different sets of gauges used in recent sea level reconstructions: *Ray and Douglas* [2011] (RD2011 hereafter), *Church and White* [2011] (CW2011 hereafter), and *Hay et al*. [2015] (H2015 hereafter). All three studies begin with tide gauge data from the Permanent Service for Mean Sea Level (PSMSL) Revised Local Reference (RLR) data set [*Holgate et al*., 2013], but each implements very different gauge selection choices and quality control criteria when forming the historical tide gauge data set used in their reconstructions. The three sets of tide gauges are subsets of the monthly PSMSL RLR database, including 89 gauges for RD2011, 491 gauges for CW2011, and 622 gauges for H2015. Rates of relative sea level change due to glacial isostatic adjustment (GIA) from ICE-5G v1.3 [*Peltier*, 2004] were subtracted from all of the tide gauge records. No other correction for vertical land motion was made.

Differences between the three sets are readily apparent when comparing the locations of all gauges included in each reconstruction (Figure 1a), and there are time-dependent differences between and within each set as well (Figures 1b–1d). The set of available gauges is most consistent in time for RD2011, while the set of gauges differs significantly during the 20th century for the CW2011 and H2015 data sets. The differences between the sets are largely accounted for by the selection philosophy employed in each case. RD2011 focused on fewer gauges with the longest records, while CW2011 and H2015 included a wider range of gauges with the intent of capturing more of the regional variability. In particular, the inclusion of high-

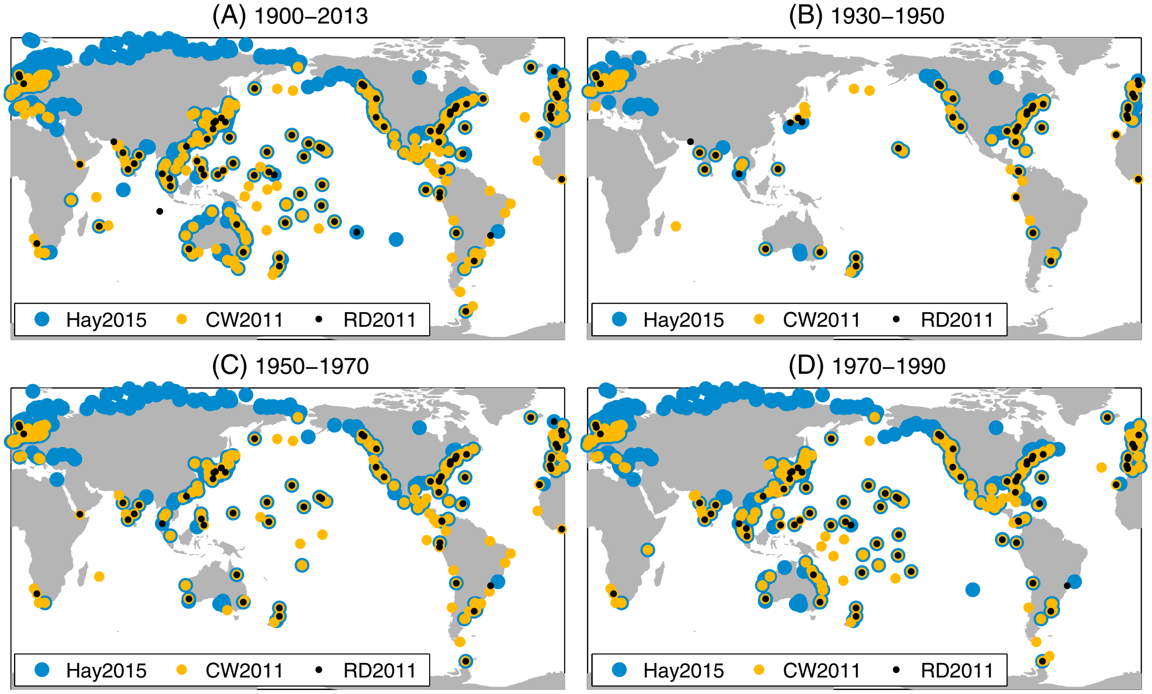

Figure 1. The tide gauges included in the studies of *Ray and Douglas* [2011] (black), *Church and White* [2011] (gold), and *Hay et al.* [2015] (blue). Tide gauges are shown if the record contains at least 60 monthly values during (a) 1900–2013, (b) 1930–1950, (c) 1950–1970, and (d) 1970–1990.

latitude tide gauges in the H2015 data set is a methodological necessity, as one of the goals of H2015 is to capture the sea level fingerprints associated with changes in the cryosphere.

3. Global Mean Sea Level

To diagnose the effect of tide gauge selection on estimates of the 20th century trend in GMSL, we apply an identical automated quality control procedure to each set and then calculate GMSL using a simple arithmetic mean over each set of gauges (see the supporting information for a complete description of the methodology, including a discussion on the error estimates provided in this paper). This method is not useful for reconstructing regional variability, but that is not the objective of this analysis. A simple mean has been shown to be an adequate method for computing long-term global trends (see above) and has the added advantage of being linear and transparent. This allows us to diagnose the effect of particular gauge selection choices on the estimated trends.

The three GMSL time series calculated using this simple methodology are shown in Figure 2. The RD2011 time series shows reduced variability about the trend when compared to the other two time series, which is particularly evident toward the beginning of the record. This results largely from the gauge selection choices made in RD2011, which focused on long, high-quality records and sacrificed spatial coverage to obtain a set of gauges representative of long-term sea level change. After 1960, the three GMSL time series agree very well, exhibiting similar trends and similar levels of variability about those trends.

The 20th century trends published by RD2011 (1.70 ± 0.26 mm/yr for 1900–2009) and CW2011 (1.7 ± 0.2 mm/yr for 1900–2009) are significantly greater than the global trend published by H2015 (1.2 ± 0.2 mm/yr for 1901–1990—provided in article text; 1.33 mm/yr for 1900–2009—calculated as a linear least squares trend from the annual GMSL time series provided with the online version of H2015). When we calculate linear least squares trends over the 1900–2013 period from the three GMSL time series in Figure 2, the differences between the rates are comparable: 1.82 ± 0.13 mm/yr for the RD2011 set, 1.95 ± 0.24 mm/yr for CW2011, and 1.34 ± 0.25 mm/yr for H2015 (see the supporting information for discussion of confidence intervals). Thus, when the three tide gauge sets are input into a consistent methodology, the H2015 set results in a substantially lower long-term rate that is independent of methodological

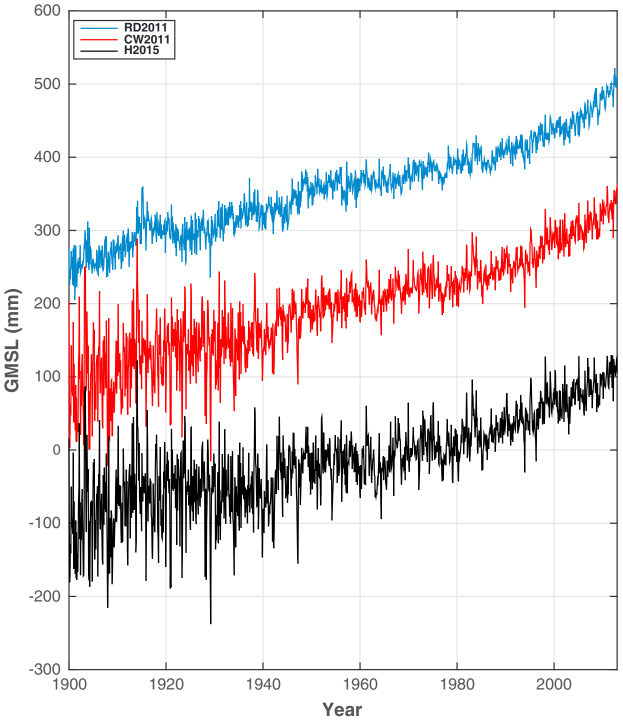

Figure 2. Global mean sea level time series (mm) from 1900 to 2013 estimated by a simple average of the tide gauge data sets from RD2011 (blue), CW2011 (red), and H2015 (black). Constant offsets are added to each curve for clarity.

differences. This suggests that the different 20th century trends obtained from the three reconstructions may be at least partially accounted for by differences in the tide gauge data set used in each case.

Differences in the 20th century trends from each set can be connected to particular time periods by comparing short-term trends calculated in running 20 year windows (Figure 3a). All three of the studies highlighted here (RD2011, CW2011, and H2015) quantify decadal GMSL variability using 15 year windows. We opt for a longer window, because our simple methodology produces GMSL time series that are inherently noisier than those obtained from the comparatively sophisticated reconstruction methods. The longer window increases the signal-to-noise ratio in the decadal trend time series (Figure 3). Phasing between the three trend time series is generally consistent throughout the 20th century. The magnitude of the trends from the RD2011 and CW2011 sets agree very well from 1940 onward, but the 20 year trends estimated from the H2015 set differ substantially over this time period. The largest disagreement occurs from 1940 to 1960 when rates from the H2015 set fall well below the other two curves, descending to almost −1 mm/yr while trends from the RD2011 and CW2011 sets remain positive. This is also apparent in the GMSL curves themselves (Figure 2), where the H2015 curve is noticeably flatter from 1940 to 1960 than in the other two sets. Notably, the H2015 set has a trend over the most recent 20 years (1994–2013) that corresponds more closely to the trend measured by satellite altimetry when compared to the other two studies.

4. The Effect of Tide Gauge Selection Choices

Trends calculated over the record length of individual tide gauges vary widely over the global ocean (Figure 4a). This illustrates the difficulty in extracting 20th century GMSL trends from this data set, but long-term absolute sea level change is much more coherent than suggested by the individual trend values. The dominant cause of the trend variation in Figure 4a is the wide range of temporal windows captured by each record that begin and end at various points during the 20th and 21st centuries. Trends over shorter records tend to have the largest amplitudes and primarily reflect regional variability associated with internal climate modes. Some long records are affected by tectonic vertical land motion that contributes to spatial differences in the GIA-corrected rates. Given the substantial trend variability in individual records, it is reasonable to expect that calculations of the long-term global trend are dependent on the particular set of gauges employed.

One of the primary differences between the three data sets is the inclusion of a substantial number of high-latitude tide gauges by H2015 (Figure 1a). To test the potential effect of these gauges on the global trend, we exclude gauges north of 65°N in the H2015 set and recalculate both the 1900–2013 trend and the running 20 year trends. The choice of the 65°N parallel is not arbitrary, as it corresponds closely to the orbital inclination of the TOPEX/Poseidan/Jason altimeters (66°). The RD2011 and CW2011 reconstructions utilize basis functions calculated from satellite-derived sea surface height fields, and as result, they do not include any gauges north of 65°N. Excluding the high-latitude gauges from the H2015 set results in

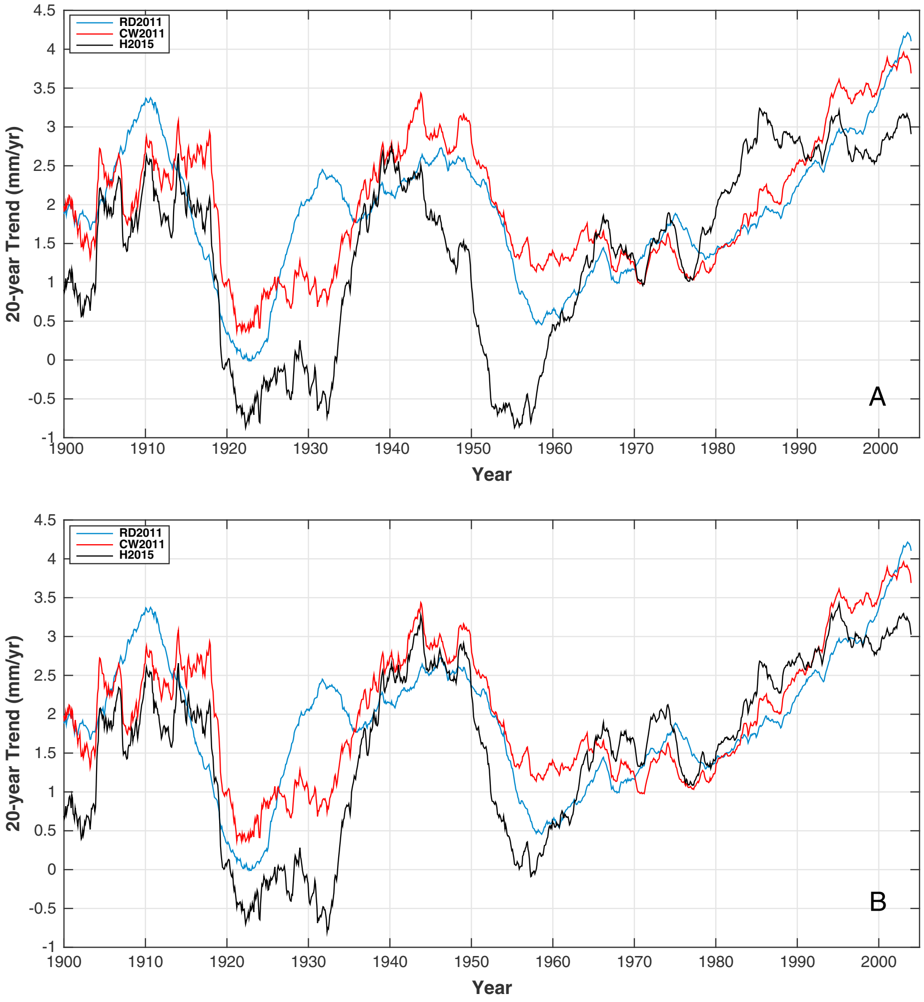

Figure 3. Twenty-year trends in global mean sea level (mm/yr) from 1900 to 2013 estimated the tide gauge data sets from RD2011 (blue), CW2011 (red), and H2015 (black). (a) The trends using all of the available gauges. (b) The trends after removing the tide gauges at latitudes higher than 65°. This results in curves for RD2011 and CW2011 that are the same in both Figures 3a and 3b.

an increase of the 1900–2013 trend to 1.57 ± 0.24 mm/yr, while the 20 year trends after 1940 converge toward the other two sets (Figure 3b). Prior to 1940, the removal of the high-latitude gauges has little effect on the 20 year trends in GMSL, because the Arctic records begin around the middle of the century (Figures 1b and 1c). The effect of removing the high-latitude gauges on GMSL calculated from H2015 is consistent with the 20 year trends in the individual Arctic gauges. These gauges contribute strongly negative trends from 1950 to 1970 (Figure 4b) before changing sign and contributing strongly positive trends from 1970 to 1990 (Figure 4c) [*Henry et al.*, 2012]. This is consistent with increased (decreased) 20 year global trends during 1950–1970 (1970–1990) when the Arctic gauges are excluded from the global mean calculation (Figure 3b).

There are a variety of additional gauge selection choices that may contribute to differences in the long-term trend between the three sets. CW2011 incorporated many more Southern Hemisphere tide gauges than the other two studies (e.g., Figure 1a), many of which became available only during the second half of the 20th century (a possible reason for their exclusion by RD2011). The H2015 set includes gauges exhibiting high trend variability around the Black Sea, while both the CW2011 and H2015 sets include many gauges around Japan that are excluded by RD2011 due to tectonic activity [*Ray and Douglas*, 2011]. The CW2011 and H2015 sets include many tide gauges around Scandinavia and the western coasts of Canada and Alaska that exhibit strongly negative trends over their entire records—even after being corrected for GIA

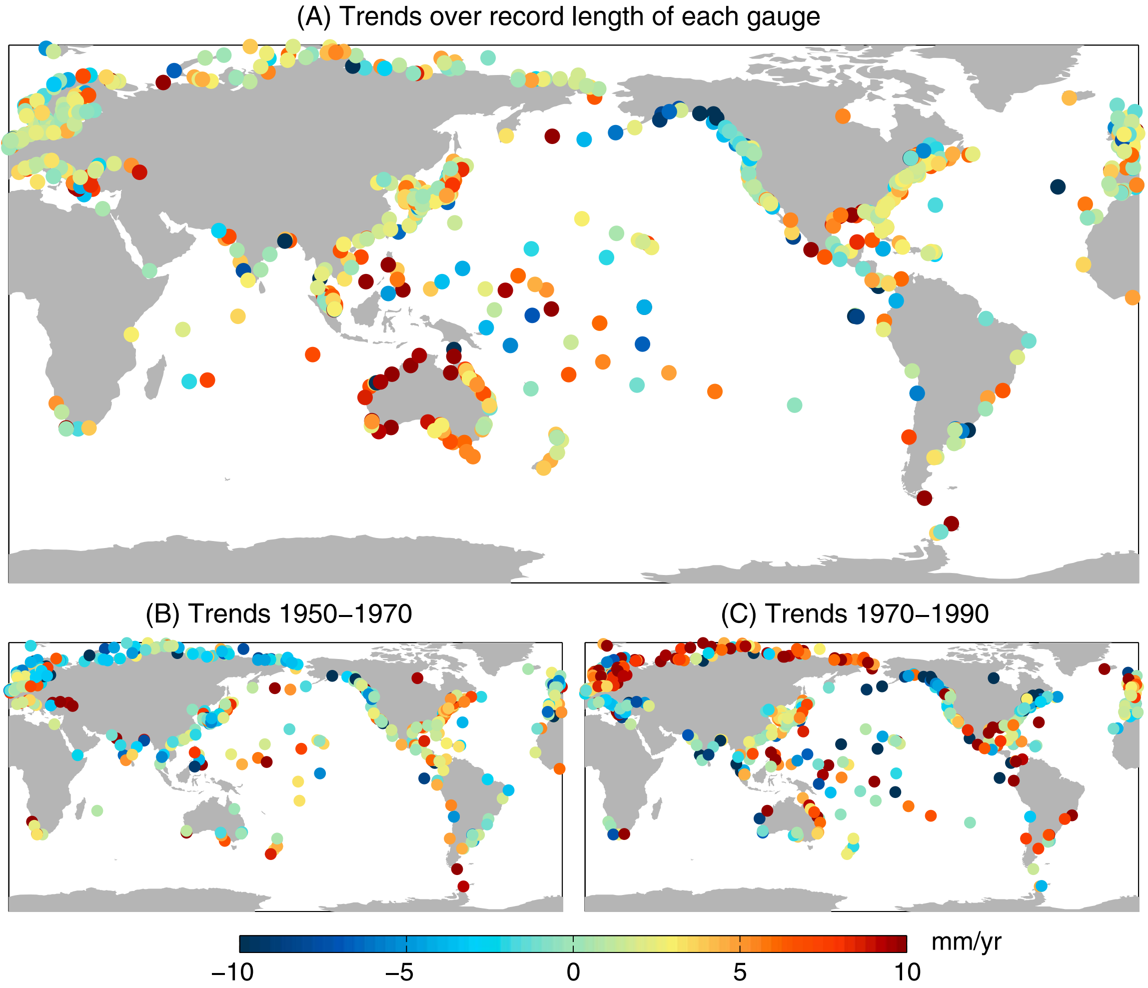

Figure 4. Sea level trends (mm/yr) corrected for GIA at tide gauges used in RD2011, CW2011, and H2015 computed for the (a) entire record, (b) 1950–1970, and (c) 1970–1990. Information regarding tide gauges specific to each set can be found in Figure 1.

(Figure 4a). The Scandinavian gauges also exhibit large variations in the 20 year trends—flipping sign from negative in 1950–1970 to positive in 1970–1990 (Figures 4b and 4c).

As a final test, we recomputed the long-term trends after again excluding the high-latitude gauges in H2015 but also excluding Scandinavian gauges and gauges off the western coast of Canada and Alaska for all three sets. The resulting trends from 1900 to 2013 converge to similar values: 2.01 ± 0.12 mm/yr for RD2011, 2.12 ± 0.18 mm/yr for CW2011, and 2.13 ± 0.19 mm/yr for H2015. This exercise is not intended to be a robust estimate of GMSL rise, but it does strongly suggest that the *differences* between estimates of 20th century GMSL trends achieved by each of these investigations are not entirely due to methodological differences but at least partially due to the choice of whether or not to include gauges in these regions.

5. Considerations for Reconstructing GMSL

The analysis conducted here represents a simplification of the actual reconstruction techniques used by RD2011, CW2011, and H2015 for estimating GMSL over the past century. The simple methodology, however, allows us to highlight the potential impact of tide gauge selection on estimates of 20th century global trends. To reiterate a point made by RD2011, reconstruction techniques cannot create new information and are fundamentally limited by the tide gauge data and basis functions available to them. Any variability captured by the tide gauges and not accounted for by the nonuniform basis functions will necessarily affect the estimate of the global mean in the reconstruction. While errors due to small-scale, local variability will tend to be normally distributed and cancel in a global average over many gauges, large-scale and spatially coherent variability manifesting in many tide gauges has the potential to degrade estimates of GMSL.

Decadal modes of internal climate variability result in large-scale, quasi-oscillatory regional sea level variability in tide gauge records that impact trend calculations. The presence of these modes dictates that the records most suitable for estimating long-term GMSL trends are long enough that the effect of decadal fluctuations is minimized [*Douglas*, 1997]. Alternatively, multiple gauges affected by the same mode but with opposing sign (e.g., the effect of El Niño–Southern Oscillation in the western versus eastern Pacific) can be averaged in a way such that the internal variability cancels [e.g., *Thompson and Merrifield*, 2014]. Selecting gauges for reconstructions of 20th century GMSL should be considered an analytical component of the methodology that is based on these ideas. It is not sufficient to assume that including more tide gauge data is better nor is it sufficient to assume that including more basis functions encompassing more processes is a methodological improvement. The core of any tide gauge set employed in reconstructions focused on estimating 20th century trends in GMSL should consist of long records that are chosen based on their likelihood of representing the global mean. Additional tide gauges with shorter records can (and should) be included only if the basis functions available to the reconstruction can be shown, a priori, to be adept at capturing the variability in these records that is inconsistent with variability in GMSL.

Determining if a particular set of tide gauges is appropriate for calculating long-term trends in GMSL is not the same as estimating the spatial sampling error associated with the set. Spatial sampling error is often estimated by repeatedly selecting a random subset of locations and recomputing GMSL [*Christiansen et al*., 2010; *Hay et al*., 2015], but this method does not capture the effect of large-scale, coherent variability. For example, consider the Arctic records discussed above that show spatially coherent multidecadal trends (Figures 4c and 4d) and make up a significant fraction of the total number of gauges in the H2015 set. If locations are randomly selected, the relative proportion of gauges that include the spatially coherent Arctic variability will remain consistent and the global mean trend is likely to appear robust to the set of gauges used. A better test is to exclude regions with spatially coherent variability (such as the Arctic) and recalculate GMSL [e.g., *Church et al*., 2004]. If the resulting estimate of the long-term trend is reasonably invariant to excluding particular regions, then it is safe to conclude that the set of gauges is appropriate and the set of basis functions used to capture nonuniform variability is largely complete.

We stress that while the above discussion focuses on the high-latitude gauges included by H2015, similar arguments can be made about any records that are either too short or heavily affected by vertical land motion. This includes many gauges around Japan, Canada, and Alaska. A particular example is the relatively long records along the convergent plate boundary near the coast of British Columbia. These gauges are known to be affected by tectonic activity [*Thomson et al*., 2008], and data from these locations exhibit long-term negative trends that are not accounted for by GIA (Figure 4a). The 20th century GMSL trend is invariably estimated using a variety of methods and sets of gauges to be between 1 and 2 mm/yr. The trends in this region are clearly not representative of GMSL, and the choice to include these gauges in GMSL reconstructions should be critically assessed. It may be possible to account for such strongly negative trends by including geodetic processes in the reconstruction, but this should be demonstrated explicitly when reconstructing century-scale rates of GMSL change.

6. Summary

When reconstructing historical sea level variability, there is a trade-off that must be negotiated. If the focus is on estimating the 20th century trend in GMSL, the set of tide gauges employed should largely consist of long records that are relatively unaffected by (or that can be reliably corrected for) vertical land motion. This choice, however, will lead to sparse spatial coverage and deficient estimates of regional variability in the resulting reconstruction. On the other hand, if the focus is on capturing and representing regional trends and variability, a greater number of gauges covering more of the ocean should be used. Caution should be taken, however, when interpreting the resulting trends in GMSL without first quantifying the impact of using short records or records from areas known to be affected by vertical land motion. These conclusions have been discussed or alluded to in several studies over the past two decades [e.g., *Douglas*, 1997; *Ray* *and Douglas*, 2011]. Ongoing discussions regarding the trend in GMSL over the past century necessitates that these considerations be restated explicitly to provide context for sea level reconstruction efforts in the recent past and in the future.

Acknowledgments
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