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Key Points:
- Detection of a spatial pattern between hemispheres in secular sea level rates
- Use of most advanced methods and data for studying secular trends in sea level
- Vertical land motion: An obstacle to detecting fingerprints in sea level change

Supporting Information:
- Readme
- Figure S1
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Evidence for a differential sea level rise between hemispheres over the twentieth century

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Abstract Tide gauge records are the primary source of sea level information over multidecadal to century timescales. A critical issue in using this type of data to determine global climate-related contributions to sea level change concerns the vertical motion of the land upon which the gauges are grounded. Here we use observations from the Global Positioning System for the correction of this vertical land motion. As a result, the spatial coherence in the rates of sea level change during the twentieth century is highlighted at the local and the regional scales, ultimately revealing a clearly distinct behavior between the Northern and the Southern Hemispheres with values of 2.0 mm/yr and 1.1 mm/yr, respectively. Our findings challenge the widely accepted value of global sea level rise for the twentieth century.

1. Context

The observed rates of twentieth century global sea level rise are overall the same as the value of 1.7 mm/yr given in the last Intergovernmental Panel on Climate Change (IPCC) report [*Church et al.*, 2013]. This is in spite of the different approaches developed to build global sea level curves, either based on the spatial variability observed in satellite altimetry data [*Church and White*, 2011] or on the so-called "virtual station" technique [*Jevrejeva et al.*, 2006]. The estimates are mostly identical to that obtained from the simplest approach of averaging linear trends from a high-quality set of over 60 year long tide gauge records [*Douglas*, 2001]. In this context, it is interesting to note that whichever data analysis strategy is employed, the evidence for sea level rise primarily comes from the information provided by long tide gauge records. These gauges are mainly located along the coasts of northeast America or western Europe, and given this uneven distribution, the information on long-term spatial variability is limited [*Woodworth*, 2006]. Furthermore, in the majority of studies the tide gauge records have only been corrected for the vertical land motion associated with the glacial isostatic adjustment (GIA) [*Peltier*, 2004]. Regardless of the accuracy of the GIA models [*Bouin and Wöppelmann*, 2010; *King et al.*, 2012; *Spada and Galassi*, 2012], other geophysical processes can cause vertical displacements of the land upon which the tide gauges are grounded. For instance, delta regions are prone to subsidence processes, which are often caused by sediment compaction and removal of underground water [*Kolker et al.*, 2011; *Wöppelmann et al.*, 2013], while tectonically active areas are likely to display abrupt vertical land movements [*Ballu et al.*, 2011].

2. The Use of Global Positioning System

The use of Global Positioning System (GPS) offers an alternate approach to measuring vertical displacements at tide gauges [*Blewitt et al.*, 2010], whatever their origin. In this study, GPS vertical velocities produced by the University of La Rochelle consortium [*Santamaría-Gómez et al.*, 2012] were used to correct the vertical land motion of a set of referenced and quality-controlled tide gauge records from the Permanent Service for Mean Sea Level (PSMSL) data repository [*Holgate et al.*, 2013]. Tide gauge data prior to 1900 were discarded as few records were available and the goal was focused on twentieth century sea level rise. Both the GPS and the tide gauge data sets were subject to stringent selection criteria that resulted in a set of 76 stations (Table S1). Once corrected for GPS vertical velocities, the tide gauge records were further corrected with the geoid rate of change component of the GIA [*Peltier*, 2004] but not for its radial crustal component. What remains should be coincident with the rate of sea level rise in a conventional geocenter reference frame. These (corrected) records were then grouped into 17 regions, 4 of which were constituted by a single station (Table 1

Table 1. Regional Rates of Sea Level Change (SLC)[a]

Region (Id. Number)	Noncorrected SLC (mm/yr)	GIA-Corrected SLC (mm/yr)	GPS-Corrected SLC (mm/yr)
Mediterranean Sea (MS)	1.6 ± 0.1	1.6 ± 0.1	1.7 ± 0.1
Western Europe (WE)	1.8 ± 0.1	1.8 ± 0.1	2.2 ± 0.1
North Sea (NS)	1.6 ± 0.1	1.8 ± 0.1	2.2 ± 0.1
Baltic Sea (BS)	−1.6 ± 0.2	1.2 ± 0.2	2.4 ± 0.2
N. Indian Ocean (NIO)	1.2 ± 0.2	1.5 ± 0.2	1.2 ± 0.2
Japan (J)	0.3 ± 0.2	0.7 ± 0.2	2.3 ± 0.2
New Zealand (NZ)	1.5 ± 0.1	1.8 ± 0.1	1.0 ± 0.1
Hawaii (H)	1.7 ± 0.1	1.9 ± 0.1	1.6 ± 0.1
NW America (NWA)	1.4 ± 0.1	0.9 ± 0.1	1.6 ± 0.1
Gulf of Mexico (GM)	4.8 ± 0.1	4.5 ± 0.1	1.9 ± 0.1
Tropical E. America (T)	2.5 ± 0.1	2.1 ± 0.2	1.7 ± 0.1
NE America (NEA)	2.9 ± 0.1	2.4 ± 0.1	2.1 ± 0.1
SE America (SEA)	1.5 ± 0.2	2.0 ± 0.2	1.0 ± 0.2
Bermuda (B)	2.1 ± 0.3	1.4 ± 0.3	1.5 ± 0.3
Kwajalein (KW)	2.1 ± 0.2	2.2 ± 0.2	1.2 ± 0.2
Kanmen (K)	1.8 ± 0.3	2.2 ± 0.3	2.1 ± 0.3
Tiksi (T)	1.2 ± 0.5	1.5 ± 0.5	2.3 ± 0.5

[a]Abbreviations in parenthesis identify the regions displayed in Figure S1. The four last rows correspond to "regions" with only one station. The regional rates of SLC are either noncorrected (column 2), corrected with GIA predictions [*Peltier*, 2004] (Column 3), or with GPS vertical velocities [*Santamaría-Gómez et al.*, 2012] (Column 4). The latter two sets of values are given with the geoid rate of change component of the GIA [*Peltier*, 2004]. The error bars represent the 95% confidence interval obtained from the least squares fit.

and Figure S1). It is noteworthy that our results are identical within the error bars, whether these four regions are included or not. Details on the materials and methods are provided in the supporting information. Nonetheless, it is worth underscoring here the hypothesis that the linear vertical land movement estimated from the GPS data is assumed to be consistent over the multidecadal to century timescale of the tide gauge record. This is a necessary working hypothesis when using GPS data to correct vertical land movements in tide gauge records, which has been discussed extensively in the literature [e.g., *Bevis et al.*, 2002; *Santamaría-Gómez et al.*, 2012].

The importance of correcting vertical displacements at tide gauges with GPS velocities was demonstrated in previous studies [*Wöppelmann et al.*, 2009]. Here its importance is further stressed at the regional scale (Table 1): the spread (standard deviation) in the rates of regional sea level change was substantially reduced from 1.4 mm/yr (no correction) to 0.5 mm/yr (GPS corrected). Notably, if GIA corrections were applied, the spread became 0.9 mm/yr. The value of 0.5 mm/yr is in agreement with what can be expected from the spatial variability of the climate signals [*Milne et al.*, 2009]. Within the regions, the spread of the individual (station) rates is also reduced when correcting with GPS velocities, by 34% on average (maximum is a reduction of 93%, minimum is no reduction at all). The different levels of spread are indicative of the presence of nonclimatic signals, more specifically of the vertical land movements. Certainly, a GIA model is not expected to correct for tectonic effects or for other vertical land movements than the GIA radial crustal displacement.

3. Mapping the Rates of Sea Level Change

Mapping the rates of individual (Figure 1) and regional (Figure 2) sea level change obtained in this study reveals a clear geographical pattern. Higher rates of sea level change are concentrated in the Northern Hemisphere, whereas lower individual and regional rates of sea level rise are observed at the southernmost locations, comprising the Southern Hemisphere and the equatorial Indian and western Pacific Oceans. By contrast, when vertical land movements at tide gauges are corrected using only GIA (Figure S2), this coherent spatial pattern is masked. The spread among regions within the two areas delineated above (coinciding roughly with—and therefore hereinafter referred to—the hemispheres) is 0.3 and 0.2 mm/yr, respectively. These values indicate an increased spatial coherence compared to that obtained when regions from the two hemispheres are gathered, for instance globally (0.5 mm/yr).

Figure 2 also displays the trends estimated at additional stations [*Hunter et al.*, 2003; *Marcos et al.*, 2013; *Testut et al.*, 2006; *Woodworth et al.*, 2010] that were not retained in our selection because they did not meet our

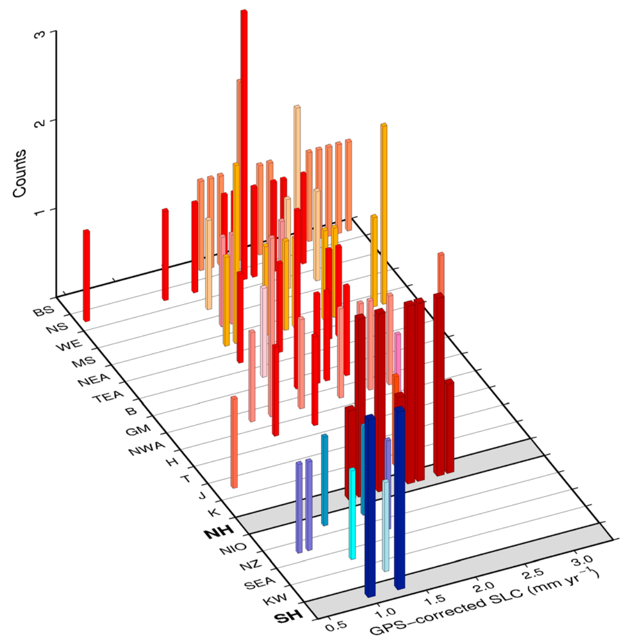

Figure 1. Histograms of the sea level changes (SLC) from the GPS-corrected tide gauge stations within regions (BS = Baltic Sea; NS = North Sea; WE = Western Europe; MS = Mediterranean Sea; NEA = northeast America; TEA = Tropical East America; B = Bermuda; GM = Gulf of Mexico; NWA = northwest America; H = Hawaii; T = Tiksi; J = Japan; K = Kanmen; NIO = North Indian Ocean; NZ = New Zealand; SEA = southeast America; and KW = Kwajalein) and of the regions derived from the virtual station technique [*Jevrejeva et al.*, 2006] in the "Northern Hemisphere" (NH) and in the "Southern Hemisphere" (SH). Yellow to red colors correspond to NH stations, blue colors to SH stations.

stringent criteria (triangles); for instance, the time series was not complete or GPS data were lacking. Vertical displacements were estimated from geological evidence in these studies. The published sea level trends are provided only for information and do not exactly match the twentieth century; they were thus not used in our calculations. The limited number of these supplementary stations is constrained by the availability of century-long individual sea level records for which some robust information on vertical land motion has been provided.

The spatial coherence observed between the two hemispheres led to a natural division of the regional rates of sea level change resulting in 2.0 ± 0.2 mm/yr for the Northern Hemisphere and 1.1 ± 0.2 mm/yr for the Southern Hemisphere. This discrepancy is significant at the 99% confidence level. Using all the regions, the rate of global sea level change corresponds to 1.8 ± 0.5 mm/yr, which is the same value as the most recent and quoted estimates over the same time period [*Church and White*, 2011; *Jevrejeva et al.*, 2006; *Douglas*, 2001]. The difference between this global value and that of the Southern Hemisphere was also significant at the 99% level, although this was not the case for the Northern Hemisphere value. (The supporting information describes how the uncertainties were computed and the procedure to test the differences.) The coincidence between the rate of sea level change for the Northern Hemisphere with the global estimates reported by the IPCC suggests a possible influence of the more numerous tide gauge records [*Holgate et al.*, 2013] in the Northern Hemisphere, potentially biasing the estimation of global sea level rise if a proper area-weighting scheme is not applied [*Woodworth*, 2006].

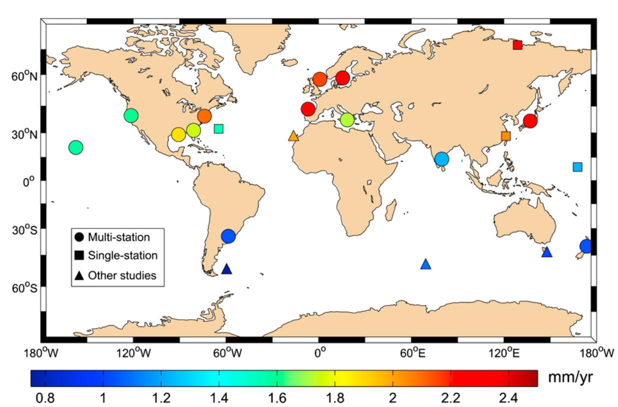

Figure 2. Regional sea level trends derived from the 76 tide gauges selected in this study and corrected with GPS velocities from *Santamaría-Gómez et al.* [2012] and GIA-geoid predictions from *Peltier* [2004]. The triangle estimates come from recently published studies.

4. Discussion

A question naturally arises about the impact of the uneven geographical tide gauge coverage on global and hemispheric mean sea level rise rates. Indeed, during the altimetry era (since 1993), satellite observations suggest that mean sea level has been rising faster over the Southern than over the Northern Hemisphere [*Cazenave and Llovel*, 2010]. This apparent inconsistency with the above results and the representativeness of regional sea level trends obtained from the tide gauge distribution was explored using a 138 year long global ocean model simulation [*Carton and Giese*, 2013]. First, regional

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mean sea level curves were built following the same strategy as for the observations [*Jevrejeva et al*., 2006] after selecting the model time series representative of the tide gauge sites. Second, global and area-weighted hemispheric mean sea level averages were computed from the model output. The comparison of both sets of curves demonstrates that at secular timescales, linear trends differ at most 0.15 mm/yr over the Northern Hemisphere and are indistinguishable over the Southern Hemisphere (Figure S3). Therefore, only about 17% of the difference in secular rates can be attributed to the tide gauge distribution. By contrast, if 20 year periods are considered (i.e., the satellite altimetry record length), differences in excess of 1 mm/yr are likely (Figure S3). The same procedure applied to other long ocean simulations led to the same conclusions (details in the supporting information).

A latitudinal artifact associated with the use of the GPS vertical velocities to correct the tide gauge records was also explored as another source of geographical differential pattern. The GPS vertical velocities are provided in the last realization of the International Terrestrial Reference Frame (ITRF) [*Altamimi et al*., 2011]. To explain the 0.9 mm/yr difference between both hemispheres (Figure 2), the geocenter definition of the ITRF should have a drift toward the North Pole of ~0.9 mm/yr with respect to the true geocenter. Such a drift is unlikely in view of the uncertainty associated with the geocenter definition of the ITRF. Indeed, the possible error in the geocenter drift has been estimated at ±0.5 mm/yr [*Altamimi et al*., 2011]. Consistently, assuming the worst-case scenario, our estimate of the geocenter drift error is ±0.4 mm/yr (95% confidence). Therefore, it would not be enough to explain the observed difference between hemispheres (details in the supporting information).

Possible physical mechanisms that could explain the reason for the difference in secular trends between hemispheres were explored, once technical limitations were discarded. For a long time it has been well known that there is a differential surface air temperature between hemispheres [*von Humboldt*, 1817], confirmed by meteorological observations since the nineteenth century. *Feulner et al*. [2013] pointed at the meridional heat transport by the ocean as the underlying cause and suggested that the difference would increase with higher greenhouse gas emissions. Whether this atmospheric effect has an oceanic counterpart in terms of a differential warming in the ocean remains uncertain. Indeed, *Johnson and Wijffels* [2011] suggested a differential warming of the upper and intermediate ocean layers, more pronounced in the Northern Hemisphere, but this was only for the last four decades, and their conclusions were limited by the heterogeneous hydrographic data distribution. On the other hand, changes in large-scale wind regimes affect coastal sea level up to decadal timescales [*Sturges and Douglas*, 2011] but act differently on islands, eastern and western boundaries.

Finally, the spatial patterns of long-term sea level change predicted for current-day melting of the continental ice sheets [*Milne et al*., 2009] do not match with the hemispheric pattern observed here, unless the Greenland ice sheet was stable and the Antarctic ice sheets were melting. There is, however, a lack of evidence to support that scenario over the past hundred years. Little observations are available on the ice sheets behavior over most of the twentieth century. The preceding discussion indicates that further research in the various areas of sea level science is still required, including the realization of the terrestrial reference frame.

5. Conclusions

Our results provide an observational evidence of a striking difference in secular trends of sea levels between hemispheres during the twentieth century. The different rates for the Northern and Southern Hemispheres mean sea level changes are robust in the current state of the art and suggest that a shift in the spatial scope from the global to the hemisphere basin scale (or smaller) is needed to confidently understand the secular trend budgets. In this context, the value of 1.8 mm/yr reported above from the here-adapted virtual station technique should not be regarded as a refined new estimate of global sea level rise over the past century. Given the coherent spatial patterns observed, a value of 1.5 ± 0.5 mm/yr is inferred from a weighted average of the hemispheric trends according to the area they represent. In this line of reasoning, the range of published estimates between 1 and 2 mm/yr [*Spada and Galassi*, 2012] can easily be explained from the analysis choices and the poorly sampled hemispheric patterns. What is more, some authors [e.g., *Pirazzoli*, 1986; *Emery and Aubrey*, 1991] have pointed out that the significance of a global sea level mean is doubtful and its rate indeterminable at the level of a few tenths of millimeter per year. The use of GPS effectively enables the detection of an important spatial pattern in secular sea level trends that is otherwise masked by vertical land movements. Our results confirm that the improvement in observations of sea level by tide gauges using GPS as supplemental data is an important priority [*Intergovernmental Oceanographic Commission*, 2012] and will likely be central to achieve confidence in sea level projections.

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