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The Twentieth-Century Sea Level Budget: Recent Progress and Challenges

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Abstract For coastal areas, given the large and growing concentration of population and economic activity, as well as the importance of coastal ecosystems, sea level rise is one of the most damaging aspects of the warming climate. Huge progress in quantifying the cause of sea level rise and closure of sea level budget for the period since the 1990s has been made mainly due to the development of the global observing system for sea level components and total sea levels. We suggest that a large spread (1.2 ± 0.2–1.9 ± 0.3 mm year^{-1}) in estimates of sea level rise during the twentieth century from several reconstructions demonstrates the need for and importance of the rescue of historical observations from tide gauges, with a focus on the beginning of the twentieth century. Understanding the physical mechanisms contributing to sea level rise and controlling the variability of sea level over the past few 100 years are a challenging task. In this study, we provide an overview of the progress in understanding the cause of sea level rise during the twentieth century and highlight the main challenges facing the interdisciplinary sea level community in understanding the complex nature of sea level changes.

Keywords Sea level rise · Sea level budget · Observing system · Data archeology

1 Introduction

For delicate coastal ecosystems, small islands and fast-growing coastal cities (Hallegate et al. 2013; Jevrejeva et al. 2014), sea level rise is one of the most dangerous aspects of climate change (IPCC 2013). Global sea level rise is an integral measure of warming

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climate (Munk 2002; Church et al. 2013; Jevrejeva et al. 2010), reflecting alterations in the dynamics and thermodynamics of the atmosphere, ocean and cryosphere as a response to changes in radiative forcing. Understanding the physical mechanisms contributing to sea level rise and controlling the variability of sea level over the past few 100 years are a challenging task (Munk 2002; Church et al. 2013). The primary climate-related contributors to twentieth-century sea level rise are ice loss of land-based glaciers and ice sheets in Greenland and Antarctica, and thermal expansion of the oceans (Church et al. 2013). In addition, there is a non-climatic contributor—changes in water storage on land due to groundwater mining and the construction of reservoirs (Church et al. 2013). However, the relative contributions from these components to twentieth-century sea level rise are still not well understood, and the closure of sea level budget is a subject of debate (Bindoff et al. 2007; Church et al. 2013; Gregory et al. 2013; Moore et al. 2011; Jevrejeva et al. 2008, 2012).

There are two main methods of estimating global-mean sea level rise. Firstly, an estimate can be obtained by adding together the cumulative effect of the main contributors to sea level rise: melting of ice in glaciers, ice loss from the Greenland and the Antarctic ice sheets, thermal expansion and changes in land water storage. Secondly, global sea level rise can be estimated using observations from tide gauges, complemented since 1993 with satellite altimeter measurements. If these two estimates agree (within an uncertainty range), then we call the sea level budget closed.

The main motivation to improve our understanding of the twentieth-century sea level budget is described by Munk (2002), suggesting that "…Sea level is important as a metric for climate change as well as in its own right. We are in the uncomfortable position of extrapolating into the next century without understanding the past." Quantifying the cause of past sea level rise is important for future sea level rise projections as the conventional approach to project sea level rise is based on simulation of individual sea level components, such as ocean thermal expansion and ice mass loss from glaciers and the ice sheets, and then sum them up (Meehl et al. 2007; Church et al. 2013).

Over the past 10–20 years, the sea level community has made huge progress in understanding present-day sea level rise, mainly due to unique information about changes in global and regional sea levels from space missions (Cazenave and Nerem 2004; Cazenave et al. 2009; Leuliette and Scharroo 2010; Cazenave and Llovel 2010; Cazenave et al. 2014). Since 1992, satellite altimetry measurements have provided a continuous and near-global record of modern-day sea level change, suggesting the rate of 3.2 ± 0.4 mm year^{-1} global sea level rise for the period 1993–2012 (Cazenave et al. 2012; Boening et al. 2012), which notably exceeds the estimate of 1.7 [1.5 1.9] mm year^{-1} sea level rise for the twentieth century (Church et al. 2013). In 2002, a pair of satellites, called the Gravity Recovery and Climate Experiment (GRACE), were launched to make monthly observations of changes in Earth's gravity field, providing estimates of mass loss from ice sheets in Greenland, Antarctica, and glaciers (Shepherd et al. 2012; Jacob et al. 2012) and tracking water mass movements at unique spatial scales (Leuliette and Willis 2011; Church et al. 2013). Data from ICESat (Ice, Cloud, and land Elevation Satellite), a satellite mission for measuring glaciers and ice sheet mass balance during the period 2003–2009, contributed to our understanding of ice mass changes from the cryosphere and its contribution to sea level rise (Schutz et al. 2005; Neckel et al. 2014). In addition, the development in the ARGO network (a series of autonomous floats that sink and ascend, monitoring temperature and salinity in the top 1000–2000 m of the ocean, with more than 3000 floats since 2000) has contributed to improved understanding of the ocean role in sea level rise (von Schuckmann and Le Traon 2011). These simultaneous measurements from satellite altimetry, GRACE and ARGO provide observational constraints on closure of the sea level budget for the period since 2003 (Dieng et al. 2015; Cazenave et al. 2014; Boening et al. 2012). In terms of global averages, the sum of global ocean mass from GRACE and global thermosteric sea level change from ARGO is roughly equal, within uncertainties, to the total sea level change observed by satellite altimetry (Dieng et al. 2015; Cazenave et al. 2014; Boening et al. 2012).

However, sea level budget cannot be assessed the same way for the twentieth century, mainly due to the lack of observational data sets for individual sea level components. There is no shortage of excellent publications (e.g., Cazenave et al. 2014) and review papers (Dieng et al. 2015; Leuliette and Willis 2011) on the topic of sea level budget during the period since 2003; however, there are only a limited number of studies (e.g., Gregory et al. 2013; Jevrejeva et al. 2012; Moore et al. 2011) about sea level budget during the twentieth century.

In this paper, we present a summary of the progress in understanding of the cause of sea level rise during the twentieth century and highlight the main challenges facing the interdisciplinary sea level community in understanding the complex nature of sea level changes.

2 Progress in Understanding the Twentieth-Century Sea Level Budget

Since the 1990s each of the Intergovernmental Panel on Climate Change (IPCC) reports has produced an assessment of the twentieth-century sea level rise. The First Assessment Report (FAR) (Houghton et al. 1990) provided the foundation for our current understanding of sea level change. FAR concluded that there was observational evidence that sea level had risen at an average rate of 1.0–2.0 mm year^{-1} during the twentieth century, and that the rate had increased compared to the eighteenth and nineteenth centuries. The causal factors that could explain the twentieth-century sea level rise were ocean thermal expansion and ice mass loss from glaciers and the margins of the Greenland ice sheet (Warrick and Oerlemans 1990). The sea level budget for the twentieth century from FAR is presented in Table 1.

The Second Assessment Report (SAR) introduced additional contributions from surface water and groundwater storage, which was labeled as “very uncertain and speculative” (Warrick et al. 1996). In addition, SAR discussed a contribution from ice sheets suggesting that there was “simply insufficient evidence, either from models or from data, to say whether the average mass balances have been positive or negative” (Warrick et al. 1996). SAR concluded that the difficulty in reconciling the past change in sea level components emphasizes the uncertainties in projections of future sea level rise.

Table 1 Estimated contributors to sea level rise over the twentieth century (in cm) from FAR (Warrick and Oerlemans 1990; based on Table 9.8 in the FAR)

Contributor	Low	Best estimate	High
Thermal expansion	2	4	6
Glaciers	1.5	4	7
Greenland ice sheet	1	2.5	4
Antarctic ice sheet	−5	0	5
Total	−0.5	10.5	22
Observed	10	15	20

The global sea level budget for 1910–1990 was analyzed in the Third Assessment Report (TAR) (Church et al. 2001) and for the period 1961–2003 in the Fourth Assessment Report (AR4) (Bindoff et al. 2007), where the individual contributions summed to less than the observed rate of sea level rise. For example, the AR4 assessed the mean observational rate for 1961–2003 as 1.8 ± 0.5 mm year^{-1}, and the sum of the budget terms as 1.1 ± 0.5 mm year^{-1} (Bindoff et al. 2007; Hegerl et al. 2007). However, the large uncertainties in estimates of the contributions of individual components and total sea level demonstrate the difficulties in closing the sea level budget.

The Fifth Assessment Report (AR5) concluded that the observational sea level budget cannot be rigorously assessed for 1901–1990 or 1971–2010 (Table 2), due to insufficient observational information to estimate ice sheet contributions with high confidence before the 1990s, and in addition ocean data sampling is too sparse to permit an estimate of global-mean thermal expansion before the 1970s (Church et al. 2013).

Several publications about the sea level budget for the historical time period are focused on the second part of the twentieth century. In a study by Jevrejeva et al. (2008) the sea level budget for the period 1955–2003 was analyzed, and the observed sea level rise rate of 1.6 mm year^{-1} was partially explained by the 0.41 mm year^{-1} contribution from thermal expansion and 0.75 mm year^{-1} due to ice loss from glaciers and ice sheets in Greenland and Antarctica, suggesting that 25% of the sea level rise (0.44 mm year^{-1}) was associated with the so-called unexplained contribution. That unexplained component was described as a combination of a long-term trend and variability that was likely caused by underestimating the contribution from ice masses (the linear trend component) and decadal variability associated with the hydrological cycle and changes in continental water storage contribution (Jevrejeva et al. 2008). Domingues et al. (2008) presented a sea level budget for 1963–2003 with an improved estimate of the contribution from upper-ocean thermal expansion and suggested a possible contribution from a deep-ocean component. The sum of contributors 1.5 ± 0.4 mm year^{-1} was in good agreement with the 1.6 ± 0.2 mm year^{-1} estimate of global sea level rise from Church and White (2006). For the second part of the twentieth century several studies demonstrated that the sea level budget could be closed by climate-related contributors, assuming some contribution from ice sheets, in a study by Moore et al. (2011), or with a small -0.1 ± 0.2 mm year^{-1} contribution from change in land water storage (Church et al. 2011). Nevertheless, large uncertainties in sea level components and in observed total sea level still remain (Church et al. 2013; Gregory et al. 2013) largely due to the lack of observational data to estimate contributions from the Greenland and Antarctica ice sheets.

Gregory et al. (2013) published an overview of estimates of individual sea level contributions over the twentieth century, partly data-based and partly model-based, and sea level rise estimates from several global sea level reconstructions. The range of possible sea levels obtained by combining all individual estimates in various combinations (total 144 combinations) suggested that the observed sea levels lie at the very edge of the range and a residual trend is needed to make up for the discrepancy, selecting the largest or smallest estimates for individual contributors. Gregory et al. (2013) concluded that if the residual trend can be interpreted as a long-term Antarctic contribution, an ongoing response to climate change over previous millennia, the budget can be satisfactorily closed. Arguably, results from Gregory et al. (2013) demonstrate that the only possibility to close the sea level budget is to select the most sensitive models and the largest individual estimates.

Recently published results by Slangen et al. (2016) suggest that for the period 1900–2005 the sum of modeled contributors of sea level rise (125.22 ± 21.97 mm) agreed with observed ensemble (174 ± 71 mm) within 2σ uncertainties (Table 2), implying

Table 2 Global-mean sea level budget (mm year^{-1}) over the twentieth century (two time intervals) from observations and model-based contributions, based on Table 13.1 in Church et al. (2013) with updated estimates from the recent publications by Slangen et al. (2016), Marzeion et al. (2015) and Hay et al. (2015)

Source	1901–1990 (Church et al. 2013)	1971–2010 (Church et al. 2013)	1900–2005 (Slangen et al. 2016)	1902–2005 (Marzeion et al. 2015)
Observed contributions				
Thermal expansion	–	0.8 [0.5 1.1]		
Glaciers except in Greenland and Antarctica	0.54 [0.47 0.61]	0.62 [0.25 0.99]		80.4 ± 21.1 mm[b] 63.2 ± 7.9 mm[c]
Glaciers in Greenland	0.15 [0.10 0.19]	0.06 [0.03 0.09]		
Greenland ice sheet	–	–		
Antarctic ice sheet	–	–		
Land water storage	−0.11 [−0.16 −0.06]	0.12 [0.03 0.22]		
Total contributors	–	–		
Observed sea level rise	1.5 [1.3 1.7] 1.2 [1.0 1.4][d]	2.0 [1.7 2.3]	174 ± 71 mm	
Modeled contributions				
Thermal expansion	0.37 [0.06 0.67]	0.96 [0.51 1.41]	36.7 ± 18.8 mm	
Glaciers except in Greenland and Antarctica	0.63 [0.37 0.89]	0.62 [0.41 0.84]	69.6 ± 7.1 mm	
Glaciers in Greenland	0.07 [−0.02 0.16]	0.10 [0.05 0.15]		
Greenland ice sheet			14.1 ± 2.9 mm	
Antarctic ice sheet			7.8 ± 8.8 mm	
Total including land water storage	1.0 [0.5 1.4]	1.8 [1.3 2.4]	125.2 ± 22.0 mm[e]	
Residual[a]	0.5 [0.1 1.0]	0.2 [−0.4 0.8]		

Uncertainties in brackets are 5–95%

[a] Observed GMSL rise- modeled thermal expansion- modeled glaciers- observed land water storage (see Church et al. 2013, Table 13.1)

[b] Estimate for global integrated glacier mass change reconstructions (excluding Antarctic periphery) updated from Leclercq et al. (2011)

[c] Estimate for global integrated glacier mass change reconstructions (excluding Antarctic periphery) updated from Marzeion et al. (2012)

[d] Estimate of 1.2 ± 0.2 mm year^{-1} for total sea level rise from 1901 to 1990 (Hay et al. 2015)

[e] Total including ice sheet/deep-ocean contributions of 13.8 ± 23.7 mm

progress in closing the twentieth-century budget. However, the sum of best estimates is still smaller than the observed rise. Of the four time series used to construct the observation ensemble (Church and White 2011; Ray and Douglas 2011; Jevrejeva et al. 2014; Hay et al. 2015), three are within the modeled range and only the largest observed sea level rise (Jevrejeva et al. 2014) is outside the modeled range (Slangen et al. 2016).

Studies of historical sea level budget by Moore et al. (2011) and Jevrejeva et al. (2012) and the sea level budget over the twentieth century by Gregory et al. (2013) demonstrated that progress has been made toward accounting for the long-term sea level changes. A study by Mitrovica et al. (2015) has demonstrated that use of the lowest estimates of sea level components of the twentieth century obtained from the AR5 IPCC report (Church et al. 2013), improved modeling of the GIA process and the correction of the eclipse record for a signal due to angular momentum exchange between the fluid outer core and the mantle reconciles all three Earth rotation observations discussed in Munk (2002) as an enigma. Nevertheless, there is a substantial gap in our knowledge about the contribution from the main components to the twentieth-century sea level rise, in particular for the first half of the century. All these studies acknowledged that there are still large uncertainties in estimates of global sea level rise, its components and how these components relate to climate forcing.

3 Challenges to Improve the Historical Records

It might never be possible to determine contributions from sea level components to the twentieth-century sea level rise to the same accuracy as has been archived for the past 10–20 years. However, it remains important to understand better the magnitude and uncertainties of the physical processes that contributed to sea level rise and variability during the twentieth century.

One of the challenges is to explain the observed temporal and spatial variability in sea level records from tide gauges, which provide instrumental data prior to the satellite altimetry and are widely used to estimate global sea level rise during the twentieth century. Individual tide gauge observations (Douglas 1997), global sea level reconstructions using tide gauge data (Gornitz et al. 1982; Jevrejeva et al. 2006; Grinsted et al. 2007; Jevrejeva et al. 2008; Merrifield et al. 2009; Wenzel and Schroter 2010; Ray and Douglas 2011; Jevrejeva et al. 2014), reconstructions that jointly use satellite altimetry and tide gauge records (Church and White 2006, 2011) and a reconstruction which combines tide gauge records with physics-based and model-derived geometries of the contributing processes (Hay et al. 2015) provide a wide range (from 1.2 ± 0.2 to 1.9 ± 0.3 mm year$^{-1)}$ of estimates of global sea level rise during the twentieth century. There is a good agreement between estimates of global sea level rise from several sea level reconstructions (Church and White 2011; Jevrejeva et al. 2008; Hay et al. 2015) for the past 60 years shown in Hay et al. (2015); however, considerable differences are demonstrated for the first part of the twentieth century. Large differences in global sea level rise estimates could be explained by the use of different methods, selection of different tide gauges and choice of vertical land movement corrections (Jevrejeva et al. 2014; Hay et al. 2015; Hamlington and Thompson 2015; Thompson et al. 2016). It seems that in time with sufficient enough coverage of tide gauge data, for example during the last 20 years, all reconstructions are in good agreement with estimates from satellite altimetry, e.g., the rate of 3.1 ± 0.6 mm year^{-1} from tide gauge-based reconstruction is almost the same as 3.2 ± 0.4 mm year^{-1} calculated from satellite altimetry (Jevrejeva et al. 2014). In a study by Hamlington and Thompson (2015) the impact of tide gauge selection is explored by calculating global-mean trends using selected tide gauge data sets in recent sea level reconstructions by Church and White (2011), Ray and Douglas (2011) and Hay et al. (2015). The calculated trends over 1900–2013 from the original reconstructions were: 1.95 ± 0.24 mm year^{-1} for Church and White (2011), 1.82 ± 0.13 mm year^{-1} for Ray and Douglas (2011) and 1.34 ± 0.25 mm year^{-1} for Hay et al. (2015). However, the Hay et al. (2015) reconstruction included a large number of high-latitude stations. Hamlington and Thompson (2015) recalculated the reconstructions without tide gauges from Scandinavia, Alaska and the western coast of Canada for all reconstructions and, in addition, excluding the high-latitude gauges in Hay et al. (2015), resulting in estimates of 2.01 ± 0.12 mm year^{-1} (Ray and Douglas 2011), 2.12 ± 0.18 mm year^{-1} (Church and White 2011) and 2.13 ± 0.19 mm year^{-1} (Hay et al. 2015). This suggests that the differences between estimates of the twentieth-century sea level rise in these three studies are not entirely due to distinct methods, but at least partially due to the selection of tide gauge records. In addition, a recently published study using long tide gauge records concludes that it is highly unlikely that the rate of global average sea level rise was <1.4 mm year^{-1} during the twentieth century, while the most likely value was closer to 1.7 mm year^{-1} (Thompson et al. 2016).

Going back in time, estimates of sea level rise are based only on a limited number of tide gauges (Fig. 1), most of them located in Europe and North America, with only few tide gauges in Southern Hemisphere available from the 1900s (Holgate et al. 2013).

Figure 2 shows the last year of the data available from stations that existed during the period 1895–1905. Most of the long-term records overlapping with satellite altimetry observations are in Europe and USA, with only two records from the Southern Hemisphere. Our understanding of sea level rise for the first part of the twentieth century is based largely on the North American and European records with some information available from Australia, Argentina and New Zealand (www.psmsl.org).

Data archeology could improve spatial and temporal coverage of historical sea level observations, as many historical tide gauge data exist in non-digital form (Pouvreau 2008; Holgate et al. 2013; Caldwell 2012; Talke and Jay 2013; Bradshaw et al. 2015), mostly paper-based data sets. These data could contribute greatly to the extension of existing sea level records as far back as possible in order to permit a better understanding of the timescales of sea level rise and variability.

The location of the data uncovered by an extensive search of US and Canadian archives for North American and Pacific Tidal Data (Talke and Jay 2013; Caldwell 2012) and data held in French archives (Pouvreau 2008) are presented in Fig. 3. The color of the data point indicates the length of the record, and the shape indicates the earliest year of data found. It would take some time to digitize these data and make them available for the scientific community. Several publications with extended records for Marseille (Wöppelmann et al. 2014), Brest (Wöppelmann et al. 2008), Cadiz (Marcos et al. 2011) and particularly valuable records from Southern Hemisphere on Saint Paul Island in the Indian Ocean (Testut et al. 2010) have already contributed to our understanding of past sea level changes.

The sea level data archeology community is actively looking for improvements in technology, such as faster automated digitization of tide gauge charts and automatic

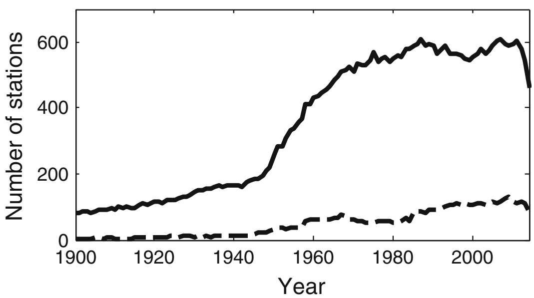

Fig. 1 Data availability as a function of time, number of tide gauges in the Northern Hemisphere represented by *solid line* and by *dashed line* in the Southern Hemisphere

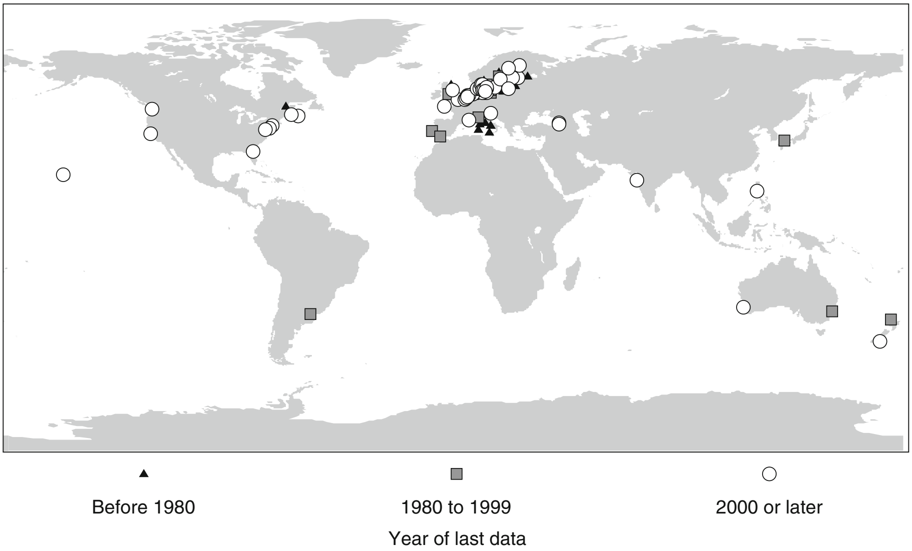

Fig. 2 Distribution of long-term research quality (RLR) records with sea level measurements started in 1900 (www.psmsl.org)

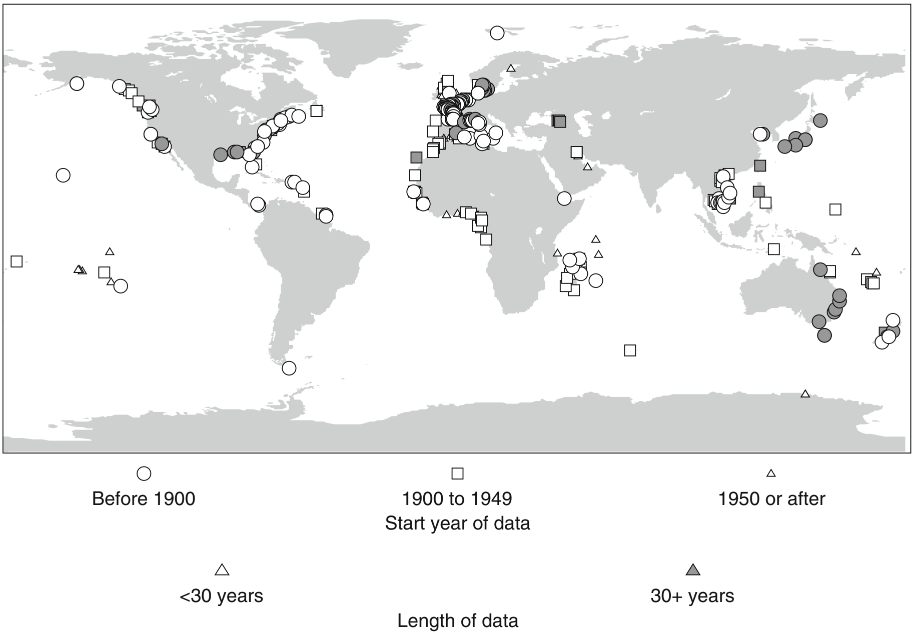

Fig. 3 Data uncovered by Caldwell (2012), Talke and Jay (2013) and Pouvreau (2008). The *color* of the *data point* indicates the length of the record, and the *shape* indicates the earliest year of data found

transcribing of handwritten ledgers. The Global Sea Level Observing System (GLOSS) Group of Experts (GE) is taking the first steps in coordinating the efforts and sharing the knowledge in sea level data archeology (Bradshaw et al. 2015).

The lack of long-term tide gauge records is not the only limitation of utilizing the historical data sets. Tide gauges are attached to the land, which can move vertically and introduce highly localized signals in tide gauge measurements (Douglas 1997; Holgate et al. 2013; Church et al. 2013; Wöppelmann and Marcos 2016; Thompson et al. 2016). One way to remove the impact of vertical land movement on estimates of global-mean sea level rise in the twentieth century is to measure the land motion component using the global positioning system (GPS) and remove it from tide gauge records. Estimates of vertical land movement from GPS have been used for individual tide gauge locations (Wöppelmann et al. 2009; Becker et al. 2012; King et al. 2012); however, the number of available GPS sites close to the tide gauge locations is limited to 100–300 globally (see Figure 1, in King et al. 2012), and most of the GPS sites are in Europe, North America and Japan. The polar regions, long coastal lines in South America, Africa, Southeast Asia, coastal areas of Indian Ocean and a large part of Australian coast are not covered by the GPS observations. GPS-derived vertical land movement corrections are available only for 10% of more than 1300 tide gauge records available for sea level studies from PSMSL (King et al. 2012; Jevrejeva et al. 2014). In addition, the rates of land motion from the global positioning system are obtained from a relatively short times series (<10 years), and these corrections might be less applicable in regions where the recent land motion might not represent that for the past 10–100 years. The lack of information about corrections for geophysical and anthropogenic signals over a range of spatial scales presented in tide gauge data (e.g., vertical land movement due to earthquakes, groundwater extraction and sedimentation) lead to the dismissal of some tide gauge records for estimates of long-term changes.

The long-term tide gauge records in Europe and North America in Fig. 2 are contaminated by the vertical land movement due to glacial isostatic adjustment (GIA). The selection of GIA corrections is important for these historical sea level records. Modeled GIA corrections are available for each tide gauge location and have been used in all sea level reconstructions (Church and White 2011; Ray and Douglas 2011; Jevrejeva et al. 2006, 2008, 2014; Hay et al. 2015; Wöppelmann and Marcos 2016; Thompson et al. 2016). Figure 4 shows the difference ranging from −4 up to 5 mm year^{-1} between the GIA corrections from ICE 6G and ICE 5G, and from ICE 6G and ICE 4G in more than 1000 tide gauge locations. Large uncertainties introduced by the choice of GIA corrections in the long-term trend for individual tide gauge records, regions and global reconstructions have been explored in studies by Jevrejeva et al. (2014) and Hay et al. (2015), and these uncertainties have been discussed as one of the challenges in the assessment of the twentieth-century sea level rise (Wöppelmann and Marcos 2016).

Unlike the time series available for steric sea level from CMIP5 model simulations and reconstructions of the contributions from mountain glaciers (Leclercq et al. 2011; Marzeion et al. 2012, 2015), the large ice sheets have no continuous extensive records or model simulations of ice mass loss during the twentieth century. One of the challenges to close the budget of the twentieth century is to estimate how much ice sheets in Greenland and Antarctica have contributed to the twentieth-century sea level rise.

The contribution to sea level rise from the Greenland ice sheet and its response to the climate forcing during the twentieth century remain contentious (Gregory et al. 2013; Church et al. 2013). Mitrovica et al. (2001) estimated a contribution of 0.6 mm year^{-1} from Greenland during the twentieth century by analyzing the regional pattern of global sea level rise from tide gauges in comparison with regional patterns expected from modeled ice mass loss from Antarctica and mountain glaciers. Using historical aerial images over the past 80 years Bjork et al. (2012) concluded that many land-terminated glaciers underwent a more rapid retreat in the 1930s than in the 2000s, with additional

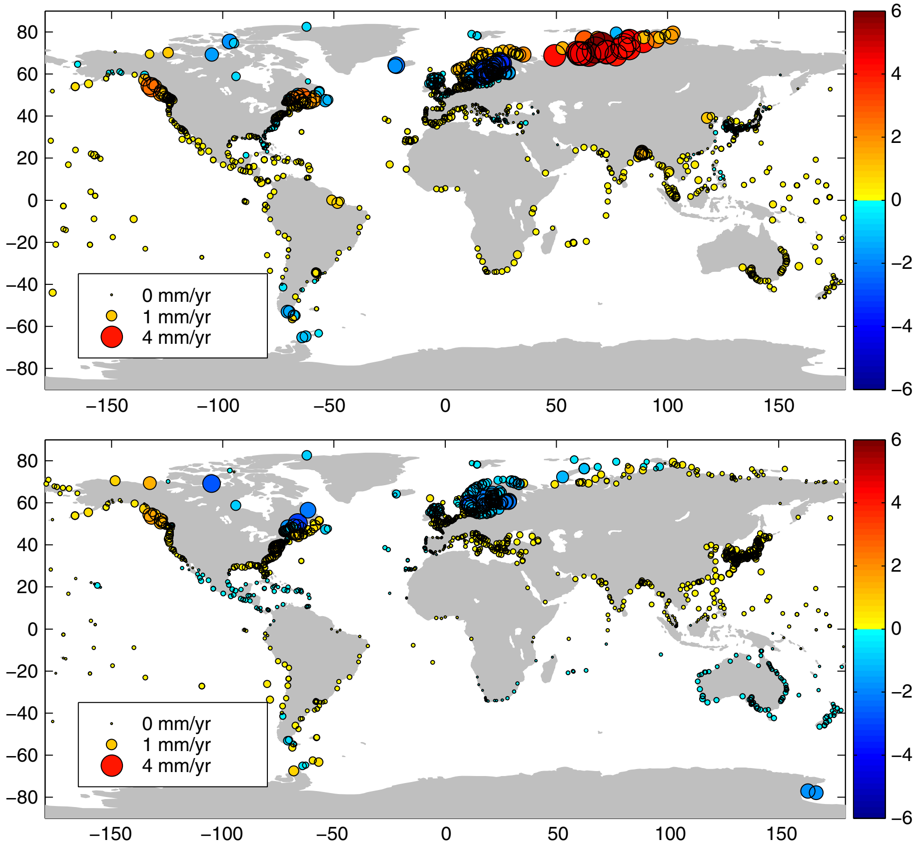

Fig. 4 Maps of differences between GIA corrections from ICE 6G and ICE 4G (*top*) and ICE 6G and ICE 5G (*bottom*) at individual locations of tide gauges. *Color bar* in mm year^{-1} and *circle size* in mm

contributions from marine-terminating glaciers and the ice sheet. Recently published observation-based findings (Kjeldsen et al. 2015) show the Greenland ice sheet contributed at least 25.0 ± 9.4 millimeters of global-mean sea level rise during the twentieth century, providing observation-based evidence of considerable mass loss from the Greenland ice sheet and minimizing the unexplained residuals in global sea level rise during the twentieth century. Continuous time series of mass loss from the Greenland ice sheet (Kjeldsen et al. 2015) contribute enormously to our gap in knowledge regarding the ice sheet response to the climate forcing.

4 Outlook

Much progress has been made over the past few decades in identifying the physical processes contributing to twentieth-century sea level rise, although large uncertainties remain. Tremendous steps forward in understanding the cause of sea level rise and closure of sea level budget for the period since the 1990s are mainly due to the development of a global observing system for sea level components and total sea levels. The observational data sets available through satellite monitoring have played a dominant role in the rate of progress.

It is crucial to maintain the current level of sea level observations (both satellite and in situ systems); longer time series and improvement of models will contribute to interpretation of sea level components and their changes as the planet continues to adjust to the warming climate.

For the twentieth-century budget and an understanding of the main contributors to global sea level rise, the remaining challenges require a coordinated and sustained multidisciplinary effort by oceanographers, geodesists, glaciologists, climate, ice sheet and solid Earth modelers to provide reliable estimates and realistic error bars for sea level and its main contributors. Understanding of the key processes contributing to the twentieth-century sea level rise and variability, such as the response of the ice sheets and glaciers to changing climate forcing, the role of the ocean (e.g., heat uptake by the ocean, role of deep ocean, ocean dynamics), the interaction between the ocean and ice sheets and the redistribution of ocean mass due to gravitational forcing are the main challenges for the decade to come.

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References

Becker M et al (2012) Sea level variations at tropical Pacific islands since 1950. Glob Planet Change 80–81:85–98

Bindoff NL et al (2007) Observations: oceanic climate change and sea level. In: Solomon S et al (eds) Climate change 2007: the physical science basis. Cambridge University Press, Cambridge, pp 385–432

Bjork et al (2012) An aerial view of 80 years of climate-related glacier fluctuations in southeast Greenland. Nat Geosci 5:427–432

Boening C et al (2012) The 2011 La Niña: so strong, the oceans fell. Geophys Res Lett 39:L19602. doi:10.1029/2012GL053055

Bradshaw E et al (2015) Sea level data archaeology and the Global Sea Level Observing System (GLOSS). GeoResJ 6:9–16

Caldwell P (2012) Tide gauge data rescue. In: Duranti L, Shaffe E (eds) Proceedings of the memory of the world in the digital age: digitization and preservation. Vancouver 2012, pp 134–149

Cazenave A, Nerem RS (2004) Present-day sea level change: observations and causes. Rev Geophys 42:RG3001. doi:10.1029/2003RG000139

Cazenave A, Llovel W (2010) Contemporary sea level rise. Annu Rev Mar Sci 2:145–173

Cazenave A et al (2009) Sea level budget over 2003–2008: a reevaluation from GRACE space gravimetry, satellite altimetry and Argo. Glob Planet Change 65:83–88

Cazenave A et al (2012) Estimating ENSO influence on the global mean sea level, 1993–2010. Mar Geodesy 35:82–97. doi:10.1080/01490419.2012.718209

Cazenave A et al (2014) The rate of sea-level rise. Nat Clim Change 4:358–361

Church JA, White NJ (2006) A 20th century acceleration in global sea-level rise. Geophys Res Lett 33:L01602. doi:10.1029/2005GL024826

Church JA, White NJ (2011) Sea-level rise from the late 19th to the early 21st century. Surv Geophys 32:585–602

Church JA et al (2001) Changes in sea level. In: Houghton JT, Ding Y, Griggs DJ, Noquer M, van der Linden PJ, Dai X, Maskell K, Johnson CA (eds) Climate change 2001: the scientific basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, Cambridge, pp 639–693

Church JA et al (2011) Revisiting the Earth's sea-level and energy budgets from 1961 to 2008. Geophys Res Lett 38:L18601. doi:10.1029/2011GL048794

Church JA et al (2013) Sea level change. In: Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds) Climate change 2013, the physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge

Dieng HB et al (2015) The sea level budget Since 2003: inference on the deep ocean heat content. Surv Geophys 36:209–229

Domingues CM et al (2008) Improved estimates of upper-ocean warming and multi-decadal sea level rise. Nature 453:1090–1093

Douglas BC (1997) Global sea rise: a redetermination. Surv Geophys 18:270–292

Grinsted A et al (2007) Observational evidence for volcanic impact on sea level and the global water cycle. *PNAS* 104:19730–19734. doi:10.1073/pnas.0705825104

Gornitz V et al (1982) Global sea level trend in the past century. Science 215:1611–1614. doi:10.1126/science.215.4540.1611

Gregory JM et al (2013) Twentieth-century global-mean sea level rise: is the whole greater than the sum of the parts? J Clim. doi:10.1175/JCLI-D-12-00319.1

Hallegatte S et al (2013) Future flood losses in major coastal cities. Nat Clim Change 3:802–806. doi:10.1038/nclimate1979

Hamlington B, Thompson P (2015) Considerations for estimating the 20th century trend in global mean sea level. Geophys Res Lett 42:4102–4109. doi:10.1002/2015GL064177

Hay C et al (2015) Probabilistic reanalysis of twentieth-century sea-level rise. Nature 517:481–484. doi:10.1038/nature14093

Hegerl GC et al (2007) Understanding and attributing climate change. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp 663–745

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

Houghton et al (1990) Climate change 1990: the science of climate change. Cambridge University Press, Cambridge

Intergovernmental Panel on Climate Change (IPCC) (2013) Summary for policymakers. In: Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds) Climate change 2013: the physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge

Jacob T et al (2012) Recent contributions of glaciers and ice caps to sea level rise. Nature. doi:10.1038/nature10847

Jevrejeva S et al (2006) Nonlinear trends and multi-year cycle in sea level records. J Geophys Res 111 **(2005JC003229)**. doi:10.1029/2005JC003229

Jevrejeva S et al (2008) Relative importance of mass and volume changes to global sea level rise. J Geophys Res 113:D08105. doi:10.1029/2007JD009208

Jevrejeva S et al (2010) How will sea level respond to changes in natural and anthropogenic forcings by 2100? Geophys Res Lett 37:L07703 **(2010GL042947)**

Jevrejeva S et al (2012) Potential for bias in 21st century semiempirical sea level projections. J Geophys Res 117:D20116. doi:10.1029/2012JD017704

Jevrejeva S et al (2014) Upper limit for sea level projections by 2100. Environ Res Lett 9:104008

King MA et al (2012) Regional biases in absolute sea-level estimates from tide gauge data due to residual unmodeled vertical land movement. Geophys Res Lett 39:L14604

Kjeldsen KK et al (2015) Spatial and temporal distribution of mass loss from the Greenland Ice Sheet since AD 1900. Nature 528:396–400

Leclercq PW, Oerlemans J, Cogley JG (2011) Estimating the glacier contribution to sea-level rise over the period 1800–2005. Surv Geophys 32:519–535. doi:10.1007/s10712-011-9121-7

Leuliette EW, Scharroo R (2010) Integrating Jason-2 into a multiple-altimeter climate data record. Mar Geodesy 33:504

Leuliette EW, Willis JK (2011) Balancing the sea level budget. Oceanography 24:122–129

Marcos M et al (2011) The long sea level record at Cadiz (southern Spain) from 1880 to 2009. J Geophys Res 116(C12):1978–2012

Marzeion B et al (2012) Past and future sea-level changes from the surface mass balance of glaciers. Cryosphere 6:1295–1322

Marzeion B, Leclercq PW, Cogley JG, Jarosch AH (2015) Brief communication: global reconstructions of glacier mass change during the 20th century are consistent. Cryosphere 9:2399–2404. doi:10.5194/tc-9-2399-2015

Meehl GA et al (2007) Global climate projections. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate change 2007: contribution of Working Group I to the Fourth Assessment Report of the IPCC. Cambridge University Press, Cambridge

Merrifield MA et al (2009) An anomalous recent acceleration of global sea level rise. J Clim 22:5772–5781. doi:10.1175/2009JCLI2985.1

Mitrovica JX et al (2001) Recent mass balance of polar ice sheets inferred from patterns of global sea-level change. Nature 409:1026–1029

Mitrovica JX et al (2015) Reconciling past changes in Earth rotation with 20th century global sea-level rise: resolving Munk's enigma. Sci Adv 1(11), Article e1500679

Moore JC et al (2011) The historical sea level budget. Ann Glac 52:59

Moore JC et al (2013) Semi-empirical and process-based global sea level projections. Rev Geophys. doi:10.1002/rog.20015

Munk W (2002) Twentieth century sea level: an enigma. Proc Natl Acad Sci USA 99:6550–6555

Neckel et al (2014) Glacier mass changes on the Tibetan Plateau 2003–2009 derived from ICESat laser altimetry measurements. Environ Res Lett 9:014009. doi:10.1088/1748-9326/9/1/014009

Peltier WR (2001) Global glacial isostatic adjustment and modern instrumental records of relative sea level history. In: Douglas BC, Kearney MS, Leatherman SP (eds) Sea level rise. Elsevier, New York, pp 65–93

Peltier WR (2004) Global glacial isostasy and the surface of the ice-age earth: the ICE-5G (VM2) model and GRACE. Annu Rev Earth Planet Sci 32:111–149

Peltier WR et al (2015) Space geodesy constrains ice age terminal deglaciation: the global ICE-6G_C (VM5a) model. J Geophys Res Solid Earth. doi:10.1002/2014JB011176

Pouvreau N (2008) Trois cents ans de mesures marégraphiques en France: outils, méthodes et tendances des composantes du niveau de la mer au port de Brest. Université de La Rochelle. Ph.D. thesis

Ray RD, Douglas BC (2011) Experiments in reconstructing twentieth-century sea levels. Prog Oceanogr 91:496–515. doi:10.1016/j.pocean.2011.07.021

Schutz BE et al (2005) Overview of the ICESat Mission. Geophys Res Lett 32:L21S01. doi:10.1029/2005GL024009

Shepherd A et al (2012) A reconciled estimate of ice-sheet mass balance. Science 338:1183–1189

Slangen A et al (2016) Anthropogenic forcing dominates global mean sea-level rise since 1970. Nat Clim Change 6:701–705. doi:10.1038/NCLIMATE2991

Talke SA, Jay DA (2013) Nineteenth century North American and Pacific tidal data: lost or just forgotten? J Coast Res 29(6a):118–127

Testut L, Miguez BM, Wöppelmann G, Tiphaneau P, Pouvreau N, Karpytchev M (2010) Sea level at Saint Paul Island, southern Indian Ocean, from 1874 to the present. J Geophys Res (1978–2012) 115(C12028). doi:10.1029/2010JC006404

Thompson et al (2016) Are long tide gauge records in the wrong place to measure global mean sea level rise? Geophys Res Lett. doi:10.1002/2016GL070552

von Schuckmann K, Le Traon PY (2011) How well can we derive Global Ocean Indicators from Argo data? Ocean Sci 7:783–791

Warrick RA, Oerlemans J (1990) Sea level rise. In: Climate change, The IPCC Scientific Assessment, pp 260–281

Warrick RA et al (1996) Changes in sea level. In: Houghton JT, Meira LG, Callander A, Harris N, Kattenberg A, Maskell K (eds) Climate change 1995: the science of climate change. Contribution of WGI to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp 359–405

Wenzel M, Schroter J (2010) Reconstruction of regional mean sea level anomalies from tide gauges using neural networks. J Geophys Res. doi:10.1029/2009JC005630

Wöppelmann G, Marcos M (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 et al (2008) Tide gauge datum continuity at Brest since 1711: France's longest sea-level record. Geophys Res Lett 35:L22605. doi:10.1029/2008GLO35783

Wöppelmann G et al (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 et al (2014) Rescue of the historical sea level record of Marseille (France) from 1885 to 1988, and its extension back to 1849–1851. J Geodesy 88:869–885