Overview

Sea level and climate: measurements and causes of changes

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We review present-day observations of sea level change and variability at global and regional scales, focusing on the altimetry era starting in the early 1990s. Over the past ~18-years, the rate of global mean sea level rise has reached 3.3 ± 0.4 mm/year, nearly twice that of the previous decades, although the observed larger sea level rise rate may be influenced by decadal or longer variations in the ocean. Moreover, sea level rates are not geographically uniform; in some regions like the tropical western Pacific, rates are up to 3–4 times higher than the global mean rate. We next discuss the climate-related components of the global mean sea level rise. Over the last ~18-years, ocean thermal expansion contributes about one third to the observed rise while total land ice (glacier melting plus ice sheet mass loss) contribute the other two third. The spatial trend patterns evidenced over the altimetry period mostly result from nonuniform steric sea level changes (effects of ocean temperature and salinity), largely caused by wind-driven ocean circulation changes. Such patterns are not stationary but oscillate through time on decadal/multidecadal time scale, in response to natural modes of the coupled ocean-atmosphere system. We close up this review by briefly discussing future (21st century) sea level rise. Current limited knowledge of the future evolution of the mass balance of the Greenland and Antarctica ice sheets leads to high uncertainty on the global mean sea level rise expected for the next 50–100 years. © 2011 John Wiley & Sons, Ltd. *WIREs Clim Change* 2011 2 647–662 DOI: 10.1002/wcc.139

INTRODUCTION

On time scales from decades to millennia, climate and sea level are closely related, warm climate leading to high sea level and vice versa. This is so because, at least at global scale, sea level change and variability mostly result from changes in ocean heat content, land ice mass balance, and water mass exchange between terrestrial reservoirs and oceans. These factors are largely driven by climate change and variability, even if direct human activities may also affect terrestrial water storage, hence sea level. Since the Last Glacial Maximum, sea level rose by about 130 m and stabilized about 3000 years ago.[1,2] During the past 2000 years, global mean sea level did not vary more than a few tens of cm, until the beginning of the industrial era (late 18th to early 19th century).[3] Since then, there is clear evidence of an acceleration in sea level. This epoch marks the start of instrumental monitoring of sea level changes, by tide gauge for the historical period and by altimeter satellites for the past two decades. Hence much information on how sea level is changing globally and regionally is now available. Besides, recent developments (in particular, since about two decades) of various Earth observing systems either from space or *in situ*, allow us to estimating the various contributions to sea level, hence provide a better understanding of the causes of the observed changes. This is important in the context of on-going and future global warming. In effect, sea level is expected to continue to rise and even accelerate because of increased ocean warming and melting of the Greenland and Antarctica ice sheets and mountain glaciers. This will likely lead to adverse effects in low-lying, highly-populated coastal areas and islands. Unfortunately, long-term projections of sea level rise from coupled climate models have still uncertainty. Observation of both sea

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level changes and processes that drive them is thus an important goal, not only for improvement of our knowledge, but also for testing the ability of climate models to reproduce current changes, and eventually discriminating the driving mechanisms (i.e., natural climate variability and/or anthropogenic warming). In this article, we first review observations of present-day sea level change, globally and regionally. We then discuss the various components that contribute to the global mean rise and interannual variability. We present the sea level budget for the past two decades (the most instrumented period). We next discuss the causes of the regional variability. We close up by a brief discussion on sea level projections for the 21st century.

OBSERVATIONS OF GLOBAL AND REGIONAL SEA LEVEL CHANGES (20TH CENTURY AND LAST TWO DECADES)

After the ~130 m sea level rise associated with the deglaciation that followed the Last Glacial Maximum,[1] 21,000 years ago, geological and archeological observations indicate that the mean sea level remained almost stable over the last 2–3 millennia.[2,4,5] An upper bound of the last millennia rate of rise of 0.7 mm/year has been proposed by Miller et al.[6] This value is in agreement with recent sea level reconstructions for the last 2000 years based on salt marsh sedimentary sequences.[3] Centennial-scale mean sea level fluctuations of a few decimeters are also reported and related to the Medieval Optimum and Little Ice Age.[3,7] All these studies date the modern sea level rise acceleration in the late 18th to early 19th century, roughly in coincidence with the beginning of the industrial era (see also Refs 8 and 9).

Twentieth Century; Tide Gauge Data

Since the mid-19th century, sea level change is measured by tide gauges along continental coastlines and mid-ocean islands. The largest tide gauge data base is the Permanent Service for Mean Sea Level (PSMSL[10]) (www.pol.ac.uk/psmsl/) which contains data for the late 19th and 20th century from ~2000 sites maintained by about 200 nations. The records are somewhat inhomogeneous in terms of data length and quality. For long term sea level studies, only ~10% of this data set is useable because of data gaps and limited tide gauge distribution in the distant past. Tide gauges measure sea level relatively to the ground, hence monitor also ground motions. In active tectonic and volcanic regions, or in areas subject to strong ground subsidence due to natural causes (e.g., sediment loading in river deltas) or human activities (ground water pumping and oil/gas extraction), tide gauges also register corresponding ground motions. Post-glacial rebound, the viscoelastic response of the solid Earth (primarily mantle) to the last ice-age deglaciation (also called Glacial Isostatic Adjustment—GIA) is another process that also affects tide gauge records.

Several analyses based on good quality historical tide gauge records have attempted to construct a 'mean' sea level curve over the 20th century. Different strategies are usually developed. Some authors only consider a few tens of long (>60 years) good quality tide gauges records from tectonically stable continental and island coasts, and correct the data for GIA only.[11–13] Other studies consider a larger set of records of different length from a variety of regions and look at regional coherency to exclude some tide gauge affected by large local ground motions[14,15] or use past sea level reconstruction methods.[16] In these cases also, the only vertical motion corrected for is GIA. Since a few years, with the availability of GPS-based precise positioning at some tide gauge sites, it has become possible to directly measure vertical crustal motions. This is the third approach, developed for example by Woppelmann et al.[17] From these studies, a mean rate of rise of 1.7–1.8 mm/year has been reported for the 20th century, in particular for the past 60 years. These studies also show that the 20th century sea level rise was not purely linear. Global mean sea level is indeed subject to interannual, decadal, and multidecadal variability (in addition to shorter term fluctuations not considered here). This is illustrated in Figure 1 which shows 20th century mean sea level evolution estimated from tide gauges (data from Refs 15 and 18).

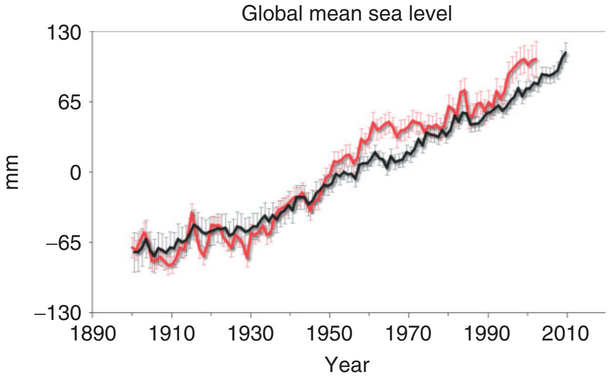

FIGURE 1 | Twentieth century mean sea level from tide gauge data. Source: Black curve—data from Church and White;[18] Red curve—data from Jevrejeva et al.[15]

Satellite Altimetry Era (Last Two Decades)

Since the early 1990s, sea level is measured by altimeter satellites. High-precision satellite altimetry started with the launch of ERS-1 in 1991 and Topex/Poseidon in 1992 and their successors, ERS-2, Jason-1, Envisat, and Jason-2 launched in 1995, 2001, 2002, and 2008, respectively. Data from these missions are routinely used to measure sea level changes. There are two main advantages for using satellite altimetry to monitor sea level changes: the quasiglobal coverage of the oceans (in about 10 days for the Topex/Poseidon and Jason satellites), providing information on both the global mean sea level and its regional variability, and the nature of the measurement itself, free from vertical land motions (except for the relatively small geoid change in the ocean due to GIA[19]).

While tide gauges measure sea level relative to the ground, satellite altimetry measures 'absolute' sea level variations with respect to a fixed reference (classically a reference ellipsoid that coincides with the mean shape of the Earth, defined within a globally realized terrestrial reference frame).

The concept of the satellite altimetry measurement is simple: the onboard radar altimeter transmits microwave radiation toward the sea surface which partly reflects back to the satellite. Measurement of the round-trip travel time provides the height of the satellite above the instantaneous sea surface (called 'range'). The quantity of interest in oceanography is the sea surface height above the reference ellipsoid. It is obtained by the difference between the altitude of the satellite above the reference ellipsoid (deduced from precise orbitography) and the range measurement within a well defined terrestrial reference frame. Various corrections need to be applied to the sea surface height measurements: the so-called ionospheric and (dry and wet) tropospheric corrections due to delay in travel time of electromagnetic waves through the ionosphere and atmosphere, bias effects due to mean electromagnetic scattering over the ocean surface, solid Earth, pole and ocean tides, etc.[20] With the orbit errors and instrumental drifts and bias, uncertainty on the wet tropospheric correction (i.e., on the atmospheric column water vapor content, usually derived from onboard microwave radiometers) represent the main source of errors on the sea surface height measurement. The current accuracy of an individual height measurement based on high precision satellite altimetry missions has now reached the 1–2 cm level. A recent estimate by Ablain et al.[21] of the total error budget due to orbit, geophysical corrections, and instrumental drifts and bias suggests a global mean sea level trend uncertainty of $\sim$0.4–0.5 mm/year, in good agreement with external calibration based on comparison with good quality tide gauge data.[22]

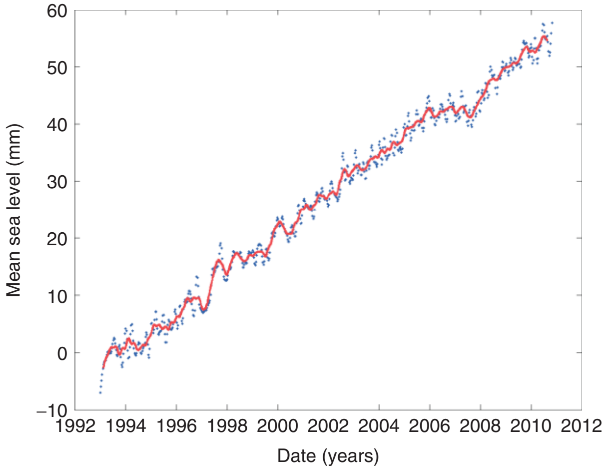

FIGURE 2 | Satellite altimetry-based global mean sea level between January 1993 and March 2011. The curve is based on the Topex/Poseidon, Jason-1, and Jason-2 data (http://www.aviso.oceanobs.com/en/data/products/sea-surface-height-products/global/msla/index.html). Most updated geophysical and environmental corrections have been applied to the data, including the inverted barometer correction (see Ref 21 for details). A correction of -0.3 mm/year is also applied to account for GIA.[19] Blue dots are 10-day data; The red curve corresponds to a 6-month smoothing of the blue dots.

The temporal evolution of the global mean sea level from satellite altimetry since early 1993 is shown in Figure 2. It displays an almost linear increase over the past 18 years (except for two temporary anomalies associated with the 1997–1998 El Nino and the 2007–2008 La Nina). After accounting for the small GIA correction (of ~ -0.3 mm/year[19]), the corresponding mean rate of sea level rise amounts to 3.3 ± 0.4 mm/year between 1993 and 2011.[21,23,24]

Church and White[25] detected an acceleration in the rate of sea level rise, of 0.013 ± 0.006 mm year^{-2} since 1870; a value confirmed by Jevrejeva et al.[15] from a global mean sea level reconstruction from 1700 to the present. Merrifield et al.[26] suggested that the recent rate of rise (of about 3.3 mm/year over the altimetry time span) reflects an acceleration that is distinct from previous decadal variations.

Regional Variability (Altimetry Era and Previous Decades)

Owing to its quasiglobal coverage of the oceans, satellite altimetry allows us to estimate regional trends in sea level. These are shown in Figure 3 for the 1993–2010 time span. We first note that sea level trends are not geographically uniform during the satellite altimetry era. We also note that in some

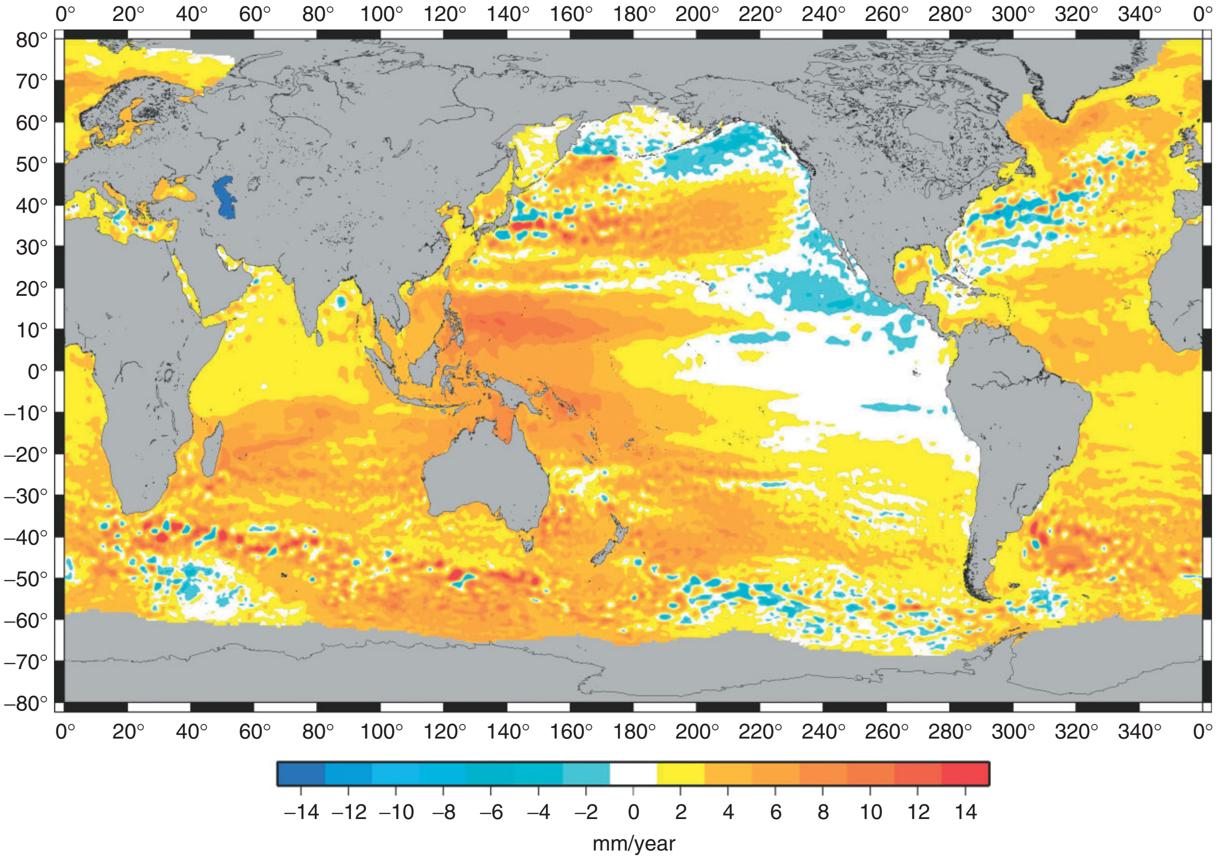

FIGURE 3 | Spatial trend patterns in sea level computed from January 1993 to October 2010 and based on the multimission (Topex/Poseidon, Jaon-1, Jason-2, ERS, and Envisat satellites), gridded sea level products available from the CLS/AVISO website (http://www.aviso.oceanobs.com/en/data/products/sea-surface-height-products/global/msla/index.html) at weekly interval.

regions, these are much larger that the global mean rate. This is the case in particular in the western Pacific where sea level rates approach 12 mm/year, that is, nearly four times the global mean rate. Higher than average rates are also observed in the Austral Ocean, in the southern part of the Indian ocean and in the north Atlantic, south of Greenland. In a few regions (eastern Pacific), rates are slower than the global mean or even slightly negative. The cause of the regional variability in sea level trends is discussed below.

CAUSES OF GLOBAL MEAN SEA LEVEL RISE (ALTIMETRY ERA)

Owing to various satellite and *in situ* data sets made available during the last two decades, considerable progress has been realized recently in quantifying the various causes of present-day global mean sea level rise. In terms of global mean, the two main contributions are ocean thermal expansion due to ocean warming and ocean mass increase due to land ice melt and change in terrestrial water storage. Change in ocean salinity can contribute to the regional variability but is negligible in terms of global mean.[27] These components are discussed below.

Ocean Temperature and Salinity Measurements

Since the mid-1950s ocean temperature has been measured *in situ* with expandable bathythermographs (XBT) predominantly along shipping routes, complemented by mechanical bathythermographs (MBT) and Conductivity-Temperature-Depth (CTD) systems in a few limited areas. During the past decade, an international program of profiling floats, Argo[28] (www.argo.ucsd.edu), has been initiated, providing temperature and salinity measurements globally. The floats go down to 2000 m with a revisit time of ~10 days. In 2011, about 3600 Argo profiling floats are operational and cover the global ocean. Calibration of temperature and salinity data is of primary importance. Recently, systematic depth-varying bias has been detected in historical XBT data.[29,30] Similarly instrumental bias has

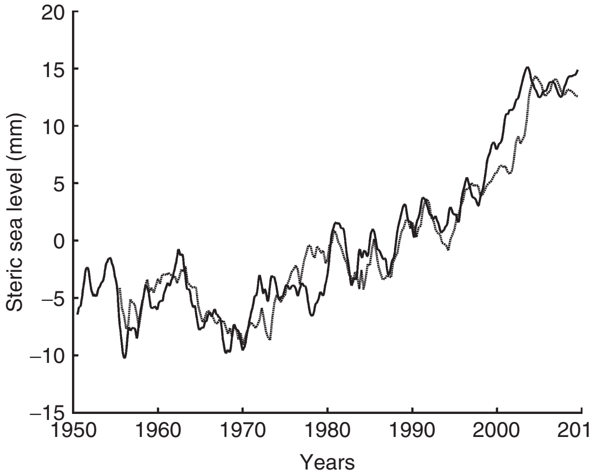

FIGURE 4 | Ocean thermal expansion since 1950/1955 based on *in situ* temperature data down to 700 m. Source: Dotted curve—data from the WOD09 database[34]; Solid curve—data from Ishii and Kimoto.[35]

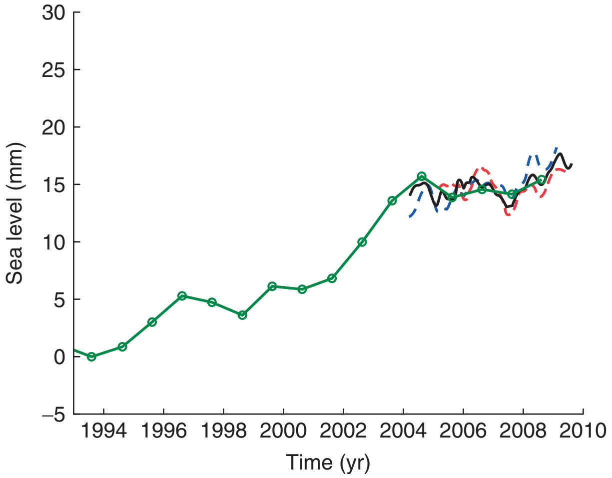

FIGURE 5 | Steric sea level evolution since January 1993. Green curve: data from WOD09; Black, red and blue curves: data from different Argo data bases (see Ref 38 for details).

affected some Argo floats.[31,32] Using corrected temperature data down to ~700 m, several groups have derived ocean heat content and thermal expansion time series for the last decades.[33–35] For example, Figure 4 shows global mean, upper ocean (above 700 m) thermal expansion since 1950/1955 based on the World Ocean database (WOD09)[34] and on Ishii and Kimoto[35] data. A clear positive trend is visible. This results indicates that a significant amount of heat (~16 × 10^{22} J) has been stored in the oceanic reservoir during the past 5–6 decades. This is about 15 times more than heat stored inside the atmosphere during the same time span.[36,37] For the period 1993–2008, Lyman et al.[31] estimate the ocean warming contribution to the total Earth's energy budget to 0.64 W m^{-2}, suggesting that about 85–90% of the current (anthropogenic) heat excess in the climate system is stored in the oceans.

Figure 5 shows the ocean thermal expansion evolution over the altimetry era based on XBT and Argo data (data from WOD09 and different Argo databases[38]). During the 1993–2003 decade, thermal expansion shows an almost linear increase (of ~1.5 mm/year in equivalent sea level). Since 2003, this rate has significantly decreased, likely a result of short-term natural variability of the coupled ocean–atmosphere system. Recent results based on different Argo data sets suggest an average rate of 0.35 ± 0.5 mm/year for 2003–2009.[38] On average over 1993–2010, the upper ocean (~700–1000 m) thermal expansion contribution to sea level rise amounts to 1 ± 0.3 mm/year. Recent studies have investigated the deep ocean contribution using ship-based data collected under the World Ocean Circulation Experiment (WOCE) and revisit cruises.[39–42] These studies report significant warming of the global abyssal and deep southern ocean waters. For example, using CTD data, Purkey and Johnson[41] estimate the 1000–4000 m deep ocean contribution to 0.14 ± 0.08 mm/year from the early 1990s to mid-2000s (note that using an ocean general circulation model, Song and Colbert[43] propose a much larger deep ocean contribution, of about 1 mm/year over the altimetry era; however, such a result would give rise to a total climatic contribution larger than the observed rate of rise, thus needs confirmation). In total, the upper plus deep (based on observations) ocean thermal expansion component has contributed by ~30% to the observed global mean sea level rise of the past two decades.[44,45]

Land Ice Loss (Ice Sheets and Glaciers)

Ice Sheets

If totally melted, Greenland and West Antarctica (the part of Antarctica which is potentially unstable) would raise sea level by about 7 and 5 m, respectively. Each year, Antarctica gains around 2200 km^3 of snow and loss the same quantity of ice, corresponding to 6 mm of sea level change (1.5 mm for Greenland, respectively), so that even a slight imbalance may produce substantial sea level rise, with adverse societal and economical impacts on vulnerable low-lying coastal regions. There are too few observations prior to the 1990s to quantify the 20th century mass balance of Greenland and Antarctica. During the last two decades, different remote sensing techniques have provided important information on the mass change of the ice sheets.[46–48] Polar region observing radar and laser altimeter satellites (e.g., ERS-1/2, Envisat and

IceSat) monitor ice sheet elevation change, a quantity that is used to infer ice volume change.[49–52] The InSAR (Synthetic Aperture Radar Interferometry) technique provides measurements of coastal glacier flow, hence ice discharge into the oceans if glacier thickness is known. When combined with independent information on the surface mass balance, the net ice sheet mass balance can be derived.[53–56] A third remote sensing technique developed in the recent years is space gravimetry (GRACE space mission launched in 2002[57]) that directly measures the ice sheet mass change.[58–65] Each technique has its own bias and limitations. GRACE, for instance, is sensitive to GIA: over Antarctica, the GIA effect is of the same order of magnitude as the ice mass change. Mass change estimates from laser and radar altimetry need assumption on ice density distribution with depth, a poorly known quantity. Induced error can reach up to 40% of the signal.[66] Moreover, radar altimetry, the longest series, suffers from poor sampling near the coast where most of the variations occur. Figure 6 shows a compilation of published results on the Greenland and Antarctica mass balance from the three techniques. In spite of significant dispersion of the results, clear acceleration in ice mass loss from the ice sheets is noticed between the early 1990s and the recent years. Combining data from InSAR and GRACE techniques, Rignot et al.[56] estimated that the total ice sheet contribution to sea level rise was 1.3 ± 0.4 mm/year in 2006 (corresponding to −475 ± 158 Gt/year ice mass loss). According to these authors, the acceleration recorded over the past 18 years is −22 ± 1 Gt/year^2 and −14.5 ± 2 Gt/year^2 for Greenland and Antarctica, respectively. For Greenland, Jiang et al.[67] detected with GPS observations an accelerated ice mass loss of −8.7 ± 3.5 Gt/year^2 and −12.5 ± 5.5 Gt/year^2, respectively, in the western and southeastern parts of the ice sheet. For Antarctica, Zwally et al.,[50] using satellite altimetry, found a near balance for the 1990–2000 period and a loss of −170 ± 4 Gt/year for the last decade. The recent acceleration in ice sheet mass loss has been attributed to the dynamical response of the ice sheets to recent warming, with most of the ice sheet mass loss resulting from coastal glacier flow. Two main processes have been invoked: (1) lubrication of the ice-bedrock interface resulting from summer melt-water drainage through crevasses,[68] and (2) weakening and break-up of the floating ice tongue or ice shelf that buttresses the ice stream.[69–71] The first mechanism plays some role in Greenland where substantial surface melting occurs in summer, but probably not in Antarctica where surface ice never melts, even in summer. The second mechanism is possibly the main driver of the recently reported dynamical changes affecting West Antarctica.[72] Because the ice shelves are in contact with the sea, changes in ocean circulation and warming of seawater may trigger basal melting and further break-up of the shelves, allowing coastal ice flow to speed up.[71]

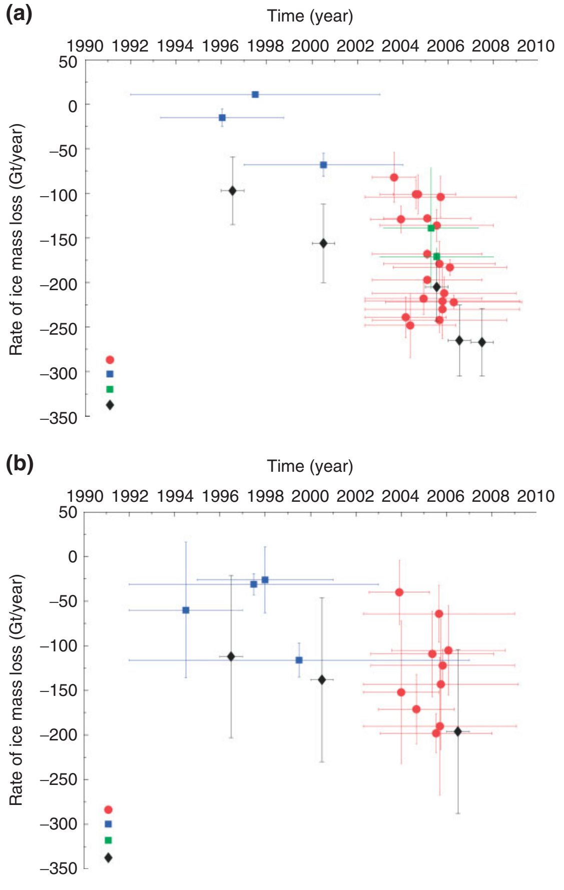

FIGURE 6 | Compilation of published estimates of the ice sheet mass balance for the past two decades. (Updated from Ref 44) (a) Greenland ice sheet; (b) Antarctica ice sheet.

Although the ice sheet contribution to sea level is clearly not constant but has increased with time, on average over the past two decades, we estimate it from Figure 6 around 1 mm/year (∼0.65 mm/year from Greenland and ∼0.4 mm/year from Antarctica) (see also Refs 44 and 45).

Glaciers

Glaciers and ice caps (all nonseasonal land-ice apart from the Greenland and Antarctic ice sheets) are very sensitive to global warming. Observations indicate that since a few decades most world glaciers are retreating and thinning, with noticeable acceleration since the early 1990s. Mass balance estimates of glaciers and ice caps are based on either *in situ* measurements (monitoring of the annual mean snow accumulation and ice loss from melt) or geodetic techniques (measurements of surface elevation and area change from airborne altimetry or digital elevation models). Fischer[73] shows that both methods are complementary, but that some unexplained systematic bias may occur. As only a small number of the world's mountain glaciers are directly measured, and the mass balance of glaciers in the same region is assumed to be similar allowing extrapolation to a global estimate. On the basis of published results, the IPCC AR4 estimated the glaciers and ice caps contribution to sea level rise to be 0.77 ± 0.22 mm/year over 1993–2003.[74] Since the IPCC AR4 publication, a few updated estimates of glacier mass loss have been proposed from traditional mass balance measurements and space-based observations (from GRACE space gravimetry, and satellite imagery.[61,62,75–79]) Kaser et al.[80] report a contribution to sea level rise of 0.98 ± 0.19 mm/year for 2001–2004, while Meier et al.[81] propose a value of 1.1 ± 0.24 mm/year for the year 2006. Recently, Cogley[82] provided an updated compilation of global average glaciers and ice caps mass balance up to 2005, indicating a 1.4 ± 0.2 mm/year contribution to sea level rise for 2001–2005, a value much larger than earlier estimates due to better representation of tidewaters glaciers. Figure 7 summarizes published estimates of glaciers and ice caps mass balances since 1950 (compilation from T. Pfeffer, updated by E. Berthier; personal communication). We note that until the early 1990s, the mean mass loss was in the range −50 to −150 Gt/year, but this value has significantly increased since then, with a clear acceleration during the past decade. On average over the past two decades, we estimate the glacier contribution slightly above 1 mm/year. However, Paul[83] shows that, because of the glacier extent and geometry change, only 30–40% of the long term glacier signal can be measured, leading to significant uncertainty of the glacier contribution.

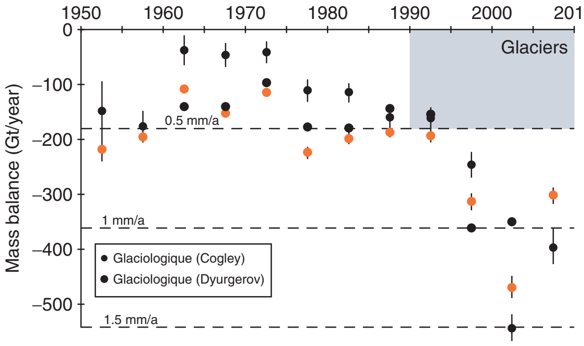

FIGURE 7 | Compilation of published estimates of glacier and ice cap mass balance (from T. Pfeffer, personal communication; updated by E. Berthier). The horizontal dashed lines represent sea level equivalent values. Black/orange dots refer to *in situ*/geodetic measurements.

Land Waters

Another potential contribution to sea level changes is the variation of water mass stored in terrestrial reservoirs (surface water bodies, soils, and underground reservoirs). A variety of factors may lead to terrestrial water storage variations: climate change and variability, and direct human intervention on the continental water cycle due to dam building, underground water mining, irrigation, urbanization, deforestation, etc. Until recently, the terrestrial water storage component to sea level could not be estimated from observations because global in situ data needed for that purpose were lacking. For that reason, past variations in global terrestrial water storage have been estimated from global hydrological models (or land surface models) developed for atmospheric and climatic studies. Using atmospheric reanalyses as external forcing, model-based studies[84,85] found no climatic long-term trend in the global storage, but instead large interannual/decadal fluctuations. Since 2002, GRACE space gravimetry allows the determination of the total (i.e., due to climate variability and human activities) land water contribution to sea level. Over the short GRACE record, the global water signal is dominated by the interannual variability and has only a modest contribution (<10%) to sea level trend over this period.[86,87] In a recent study based on space-based microwave techniques, Biancamaria et al.[88] showed that snow negligibly contributed to sea level rise of the past two decades.

Direct human intervention on land water storage also induces sea level changes. The largest contributions come from ground water pumping (either for agriculture, industrial, and domestic use), and reservoir filling.[89,90] Chao et al.[91] reconstructed the history of water impoundment in ∼30,000 reservoirs built during the 20th century to estimate the effect of dams and artificial reservoirs on sea level. They found a negative contribution of −0.55 ± 35 mm/year during the last half-century. Lettenmaier and Milly[92] suggest a slightly smaller contribution since ∼1940–1950, of ∼−0.35 mm/year, and recent stabilization since year 2000. However, other human-induced factors may at least partly cancel this effect, the main candidate being ground water mining (i.e., the excess of water withdrawal over recharge, a term potentially large in arid and semi-arid regions). Estimates of this factor are very uncertain. Huntington[89] provide values of 0.55–0.64 mm/year for the past 4–5 decades. Even larger value is proposed by Wada et al.[93] (0.8 ± 0.1 mm/year since 1960), while Milly et al.[90] adopt a more modest value of 0.2–0.3 mm/year for the recent years. In spite of the large uncertainty on the groundwater component, its effect on sea level is positive and at least partly counteracts the negative effect of reservoirs.

High-correlation between El Nino-Southern Oscillation (ENSO) indices and interannual variability of the global mean sea level has been reported for some time.[24] These interannual sea level variations have been attributed to ENSO-driven change in land water storage.[94] In particular, the positive anomaly seen in the global mean sea level in 1997–1998—the epoch of the intense ENSO event—can be fully explained by land water storage variability, with a dominant contribution from tropical river basins. During ENSO events, some of these basins suffer drier than normal conditions (because of rainfall deficit), leading to positive sea level anomaly. This is illustrated in Figure 8 which compares (detrended) global mean sea level since 1993 and global terrestrial water storage estimated from the ISBA-TRIP global hydrological model, developed at MeteoFrance[95] and constrained by GRACE data beyond 2002.

Ocean Mass Change from GRACE

With GRACE space gravimetry, it is now possible to directly measure the change in mass of the ocean caused by the net water flux into and out of the oceanic reservoir.[96,97] In principle, measured ocean mass change should agree with independent estimates of total land ice loss plus the small terrestrial water component. Published trends in global ocean mass are highly scattered, and range from low (~0.8 mm/year) to high (1.7–1.9 mm/year) values over the GRACE lifetime.[19,38,98–100] Most of this difference is because of the choice of the GIA correction that needs to be applied. In effect, the GIA signal appears as a secular trend in the gravity field that must be removed when processing the GRACE data. This correction is roughly of the same order of magnitude as the expected ocean mass trend. Unfortunately, there is disagreement between GIA models for this particular correction. The Paulson et al.'s[101] model proposes a GIA correction of ~−1.2 mm/year,[102] while Peltier's[19] model suggests larger value of ~−1.7 mm/year. So far there is no consensus on the best value to use. Comparison with published estimates of total land ice loss favors the highest value. Another possibility is that the ice component is overestimated. This question clearly deserves further investigation.

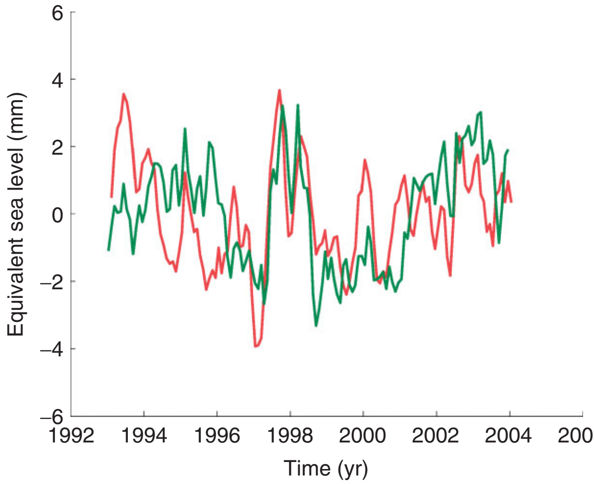

FIGURE 8 | Detrended global mean sea level between 1993 and 2004; red curve. Land water storage contribution (expressed in sea level equivalent) estimated from the ISBA-TRIP global hydrological model[95]; green curve. (Adapted from Ref 94)

SEA LEVEL BUDGET OVER THE ALTIMETRY ERA

For the 1993–2003 decade, the IPCC AR4 estimated that about 50% of the observed sea level rise was caused by thermal expansion, while glacier melting contributed by ~30% and ice sheet mass loss by ~15%.[103] For the post-AR4 period (i.e., since 2003), results report accelerated land ice loss, with a contribution to recent sea level rise as large as 75%. Meanwhile, thermal expansion rate has decreased compared to the previous (1993–2003) decade.[38] Because of this compensation effect between land ice loss and thermal expansion, sea level has continued to rise at about the same rate. On average over the altimetry period (1993–2010), thermal expansion, glaciers and ice sheets have contributed each by about 30%. Said in another way, over the past two decades, ocean warming represents about one third of the observed sea level rise, land ice melt explaining the remaining two third.

CAUSES OF REGIONAL VARIABILITY

Spatial trend patterns in sea level mainly result from ocean temperature and salinity changes reflecting changes in ocean circulation.[103] The largest regional changes in sea level trends result from ocean temperature change (i.e., from non uniform thermal expansion), as evidenced by the comparison of the satellite altimetry-based spatial trend patterns with steric patterns computed from *in situ* hydrographic data. This is illustrated in Figure 9(a) and (b) which compares spatial trend patterns over 1993–2009 from satellite altimetry (global mean rise removed) and steric data over the 0–700 m ocean depth (from the WOD09 database). However, studies based ocean

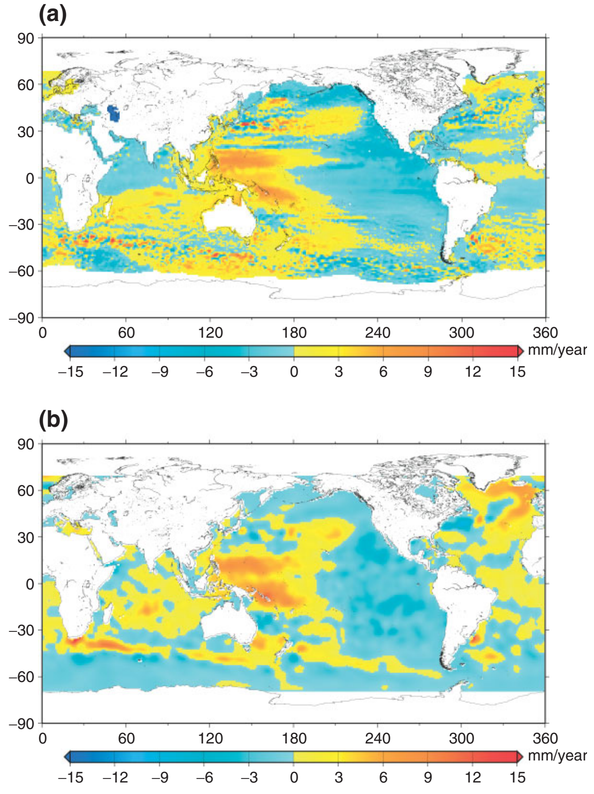

FIGURE 9 | (a) Spatial trend patterns in altimetry-based sea level over 1993–2009 with respect to the global mean rise (a uniform mean trend of 3.3 mm/year has been removed). (b) Spatial trend patterns in steric sea level over 1993–2009 (data from the WOD09 database down to 700 m[34]; uniform mean trend removed).

general circulation models (OGCMs) have shown that in some regions, change in water salinity is also important.[104–106] In several areas, positive/negative trend anomalies in temperature coincide with positive/negative trend anomalies in salinity. Because corresponding effects on sea level have opposite signs, these features partly cancel each other. But in the majority of cases, temperature effects dominate. Several studies have shown that regional steric sea level changes mostly result from changes in wind forcing and associated changes in ocean circulation.[105,107–109]

Water mass redistribution between the ice sheets and oceans due to last deglaciation and ongoing land ice melt are expected to also give rise to regional sea level changes as a result of variations in the Earth's gravity field and isostatic deformation of the solid Earth.[5,110,111] These effects should produce significant sea level fall in the vicinity of the melting ice bodies and sea level rise in the far field. Circulation changes due to freshwater flux from the ice sheet may also give rise to regional sea level variability.[112] Up to now, such effects have not been detected in the sea level observations but they may become important in the distant future if ice sheet mass loss dominate other processes.

An important question concerning the regional variability in sea level is: Are the spatial trend patterns observed during the altimetry era long-term features or not? The question of temporal stationarity of these patterns is indeed crucial when considering potential regional impacts of future sea level rise. For example, if the large positive trends seen in the western tropical Pacific during the altimetry era are long-term (on a century time scale) features, this will increase the vulnerability of small islands located in this region. In effect, in addition to the expected global mean sea level rise, the regional patterns which are superimposed will eventually amplify the rate of rise. However, according to a number of different studies conducted in the recent years, there is some evidence that the spatial trend patterns observed by altimeter satellites over the past two decades are not long-term features. The first reason is related to their dominant thermosteric origin. Observation indeed shows that trend patterns in thermal expansion are not stationary but fluctuate both in space and time in response to natural perturbations of the climate system such as ENSO, NAO (North Atlantic Oscillation), PDO (Pacific Decadal Oscillation), and other natural climate modes.[36,113] Thus the 18-year long altimetry-based sea level trends are likely transient features. Different gridded data sets available over the past few decades can help to clarify the question: (1) ocean reanalyses, and (2) past sea level reconstructions. Several ocean reanalyses spanning over the past ~50 years, based on OGCM with data assimilation, and OGCM runs without data assimilation, have been produced in the recent years. Spatial variability of the corresponding sea level also appears time-variable, and mostly reflects natural modes of variability of the ocean–atmosphere system.[105,106,114] In addition, model experiments successfully reproduce spatial trend patterns observed by satellite altimetry and suggest that in several regions (e.g., tropical Pacific and Indian ocean), these are related to wind forcing.[108]

Past sea level reconstructions have also been produced by combining long tide gauge records with gridded sea level (or sea level proxies) fields of shorter duration.[16,45,115,116] The approach consists of computing spatial modes from the gridded fields using an Empirical Orthogonal Function (EOF) decomposition and computing new EOF temporal amplitudes through a least-squares optimal interpolation that minimizes the reconstructed field and the tide gauge records at the tide gauge locations. The product is multidecade-long gridded sea level fields, very useful to compute spatial trend patterns over different time windows. Comparison (not shown) between trend patterns over the altimetry era and past 60 years (e.g., from the past sea level reconstruction of Meyssignac et al.[116]) shows large regional differences; for example in the south Indian Ocean, tropical Pacific, North Pacific, and northwestern Atlantic. EOF analyses of the reconstructed sea level show that trend patterns oscillate on time scales related to low frequency modulation of the natural ocean modes (ENSO, PDO, NAO, etc.).[115–117] This is in agreement with ocean reanalyses,[105] indicating that decadal/multidecadal regional sea level fluctuations are mostly caused by internal (dynamical) variability of the climate system, with wind stress as the main forcing mechanism.[108]

SEA LEVEL DURING THE 21ST CENTURY

Global mean sea level will continue to rise during the 21st century (and beyond) because of continuing ocean warming and land ice melt. In spite of considerable progress in understanding the various causes of recent past and present-day sea level rise, modeling of future changes still show significant uncertainty. Projections from the IPCC AR4 indicated a rise of ∼38 cm by 2100 above the 1990 level (with an uncertainty range of ±20 cm due to model results dispersion and differences in future greenhouse gases emission scenarios).[118] It has been suggested that this value is a lower bound because these projections did not account for ice sheet dynamical changes. While future ocean warming and thermal expansion contribution to 21st century sea level rise is likely well constrained, a number of studies have appeared since the IPCC AR4 publication, providing updated estimates of the glaciers and ice sheet contributions. Revised estimates have been proposed for the total glacier and ice cap contribution (if totally melted), in the range 50–65 cm equivalent sea level rise.[119] Besides, projections of the glacier and ice cap component to the 21st century sea level rise have been derived from different approaches. For example, using multimodel simulations of both temperature and precipitation, Radic and Hock[120] suggest a glacier and ice cap contribution of 0.12 ± 0.04 m, by 2100, with an important contribution from Arctic Canada and Alaska. These authors predict that the glacier volume can be reduced up to 75% in some places, with an average of 20%. Extrapolating present-day observations, Meier et al.[81] suggest a contribution range of 10–24 cm, while, Pfeffer et al.[121] on the basis of kinematics considerations come up with a wider range, from 17 to 55 cm. A lower bound of 18–37 cm has been derived by Bahr et al.[122] Thus much uncertainty about the amount of future sea level rise due to glacier and ice cap melting still remains.

New estimates of the surface mass balance of the Greenland and Antarctica ice sheets have also appeared in the last 3–4 years.[123–125] These studies more or less confirm IPCC AR4 results.[118] Incertitude still exists on both input and output ice mass variations in response to climate change. Increase of snow precipitation over the Antarctica plateau could increase at a rate of 1 mm/year (in equivalent sea level). This would reduce the Antarctica positive contribution to sea level by 10 cm over the next century.[125] On the other hand, major uncertainties remain on ice sheet dynamics and corresponding contribution to future sea level rise. There is not yet perfect understanding of the mechanisms at the origin of recently reported ice mass loss acceleration and their modeling in climate models is still immature. Kinematics extrapolation by Pfeffer et al.[121] infers possible total (i.e., surface mass balance plus dynamics) contributions to 2100 sea level of 16–54 cm for Greenland and 15–62 cm for Antarctica, but more plausible values of 16 cm (Greenland) and 13 cm (Antarctica) are preferred by the authors. Extrapolating presently observed acceleration of Greenland and Antarctica ice mass loss, Rignot et al.[56] suggest a total (Greenland plus Antarctica) contribution to sea level rise of ∼15 cm in year 2050 and ∼56 cm by 2100.

In summary, the total land ice contribution to 21st century sea level rise remains highly uncertain. But values above 50 cm by 2100 may not be ruled out. If we add the ocean warming contribution (in the range 10–40 cm; IPCC AR4), global mean sea level is expected to be significantly higher than today at the end of this century by 50 cm–1 m.

As we have seen above, present-day sea level rise is not uniform and regional variability is also expected in the future as a result of redistribution of heat and freshwater by the ocean circulation. IPCC AR4 mentioned considerable dispersion in climate model-based spatial patterns by 2100. However, some pictures emerged from stacking of the different models, with higher than average sea level rise in the Arctic Ocean and along a narrow band in the south Atlantic and south Indian ocean. Updated results have been proposed recently[126–130] which confirm these general characteristics. However, it is not clear how current climate models are capable of accurately computing the decadal/multicecadal variability which superimpose to these long-term trends. New results on decadal projections of regional sea level variability are expected in the near future. This is a challenging research area that will depend on accurate information on the ocean state needed for model initialization.

CONCLUSION

Sea level rise is a major concern for populations living in low-lying coastal regions (about 25% of human being) because it will give rise to inundation, wetland loss, shoreline erosion, saltwater intrusion in surface water bodies and aquifers, and will rise water tables.[131,132] Moreover, in many coastal regions of the world, the effects of rising sea level act in combination with other natural and/or anthropogenic factors, such as decreased rate of fluvial sediment deposition in deltaic areas, ground subsidence due to tectonic activity or ground water pumping and hydrocarbon extraction.

Besides factors that modify shoreline morphology (e.g., sediment deposition in river deltas, change in coastal waves and currents), what does matter in coastal regions is relative sea level rise, that is, the combination of sea level changes—global mean plus regional variability, and vertical ground motions. In many coastal regions of the world, sea level change and ground motion are currently of the same order of magnitude and most often of opposite sign (sea level rises and ground subsides), leading to enhanced relative sea level rise.

Measuring sea level rise and understanding its causes has considerably improved in the recent years, essentially because new *in situ* and remote sensing observations have become available. Sea level is presently rising at a sustained rate and will continue in the future decades because of expected increased global warming. However, the exact amount of sea level rise by 2100 is still an open question. The main source of uncertainty is the future behavior of the Greenland and Antarctica ice sheets in a changing climate. Improved understanding and modeling of the complex dynamical response of the ice sheets to global warming is among the priorities of the international climate research community. In parallel, observing change and variability of sea level and its different components using in synergy various in situ and space-based observing systems is another important goal. Besides, assessing potential impacts of future sea level rise in vulnerable low-elevation coastal zones is crucial. Locally, what is important for the population is the sum of several components: climate change-related global mean sea level rise, possible human-induced global sea level changes (e.g., because of reservoir building and/or ground water pumping), regional changes largely because of internal variability of the climate system, and vertical crustal motions. All these factors act in combination and in some regions may interfere positively, leading to important local (relative) sea level rise. Understanding, mitigating, and eventually looking at adaptation to this threat require collective efforts of different scientific communities within a fully multidisciplinary framework.

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