Projected sea level rise on the continental shelves of the China Seas and the dominance of mass contribution

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Abstract
We analyze the projected sea level rise (SLR) for the 21st century for the China Seas (the Bohai Sea, Yellow Sea, East China Sea, and South China Sea) using the Coupled Model Intercomparison Project Phase 5 dataset. We find that the projected SLR over the shallow continental shelves of the China Seas is nearly the same as the global mean sea level change in all future emission scenarios, with a magnitude of 43.6 cm (20.8–67.7 cm, 90% confidence interval) in RCP2.6 and 74.5 cm (41.7–112.8 cm, 90% confidence interval) in RCP8.5 by the year 2100 relative to 1986–2005. We further analyze the causes of SLR and find that more than 90% of the total projected SLR over the continental shelves of the China Seas will result from mass contributions and only a minor contribution will result from local steric height adjustments. This increase in water mass over the continental shelves is not only caused by the loss of land ice, but also from the change in sterodynamic, which tends to push water mass onto the continental shelves from the open oceans.

1. Introduction

Observations show that global mean sea level (GMSL) has undergone a relatively rapid rise of around 15 cm over the past century (Church and White 2011, Dangendorf et al 2017, Oppenheimer et al 2019). GMSL is projected to rise even more rapidly throughout the remainder of this century with a rising magnitude between 29 and 110 cm, depending upon which future emission scenario is assumed (Oppenheimer et al 2019). GMSL rises from two primary processes: (a) the increase in total oceanic water volume caused by thermal expansion and (b) the increase in total oceanic water mass resulting from losses of land ice and/or ground water storage (Church et al 2013). Recent research indicates that since 1900, the melting of land ice has caused twice as much sea level rise (SLR) as has thermal expansion (Frederikse et al 2020).

However, regional SLR may deviate substantially from the global mean value in warmer climates (Pardaens et al 2011, Church et al 2013, Bouttes and Gregory 2014, Slangen et al 2014, Chen et al 2019a). For instance, a much higher than GMSL rise has been observed and is simulated along the Atlantic coast of North America (Sallenger et al 2012), while the projected SLR for the Arctic Ocean, the subpolar North Atlantic Ocean and off the western Antarctica coast are less than the projected GMSL rise (Slangen et al 2014). Regional sea level change is driven by three main factors (figure 1): (a) changes in ocean processes, such as thermal expansion and the circulation driven changes (Yin et al 2010, Lyu et al 2020), which is called sterodynamic sea level change (Gregory et al 2019), (b) gravitational, rotational and deformational (GRD) effects caused by land ice discharge and ground water storage, leading to variability in the spatial patterns of SLR (Mitrovica et al 2001,
Total Sea Level Rise (SLR) for the China Seas

Sterodynamic (OCN)

Manometric (Mass)

Land Ice (LNDICE)

Ground Water Storage (GRW)

Ocean Mass Redistribution (OMR)

Local Steric

Glacier Isostatic Adjustment (GIA)

Figure 1. A schematic overview of regional SLR and its causes. Letters in brackets indicate abbreviations of each component. The terminology 'sterodynamic' and 'manometric' sea level are newly introduced in Gregory et al (2019), with the former representing the sea level change due to the change in ocean density and circulation, and the later representing the part of sea level change that is due to the change in time-mean local mass of the ocean per unit area.

Wada et al (2012), which is called barystatic-GRD fingerprint (Gregory et al 2019), and (c) long term processes caused by glacial isostatic adjustment (GIA, Peltier 2004) that lead to horizontal and vertical land movement. Both the sterodynamic and barystatic-GRD fingerprint are important contributors to the geographic patterns of SLR that deviate from the global mean value (Church et al 2013, Carson et al 2016).

Reliable estimates of future SLR in specific regions, especially in the shallow coastal seas, are crucial to advance planning of adaptive strategies by local governments and industries, which have a vested interest in anticipating the degree of SLR at their localities (Carson et al 2016, Jevrejeva et al 2018). The China Seas are marginal seas of the western North Pacific, and include the Bohai, Yellow, East China and South China Seas (figure 2(a)). The China Seas have one of the most extensive continental shelves in the world (e.g. area of water depth less than 300 m exceeds 1800 000 km²), which makes the China Seas very sensitive to SLR (Xu and Gong 2018). The majority of studies on SLR along the coast of the China Seas have been based on global climate model projections (Chen et al 2018, Qu et al 2019). However, most of these global climate models have relatively coarse resolution that cannot fully resolve the dynamic processes that are important in determining the distribution of sea level change in marginal seas and along the coasts. While some studies have indicated that sea level change has distinctly different characteristics and mechanisms between the deep open oceans and the shallow marginal seas (Landerer et al 2007, Chen et al 2014). To address these issues, this study will consider sea level change in the China Seas, focusing on the area-averaged sea level over the shallow continental shelves in comparison to the deep open oceans, rather than on the regional distributions inside the marginal seas.

Based on tidal gauges and satellite altimetry data, several studies have shown that the rate of SLR in the China Seas has outpaced the global mean rate over the last two to five decades (China Sea Level Bulletin of 2019 http://gi.mnr.gov.cn/202004/t20200430_2510978.html, Marcos et al 2012, Guo et al 2015, Feng and Cheng 2019, Qu et al 2019). Further it has been shown that SLR in the China Seas has been affected by low-frequency sea level variability (Han and Huang 2008, Moon and Song 2017). In this study, using climate model projections, we found that the projected SLR on the continental shelves of the China Seas during the 21st century will be similar in height to the global mean rise. More importantly, we found that the water mass loading onto the continental shelves will play the dominant role in the SLR over the continental shelves. To the best of our knowledge, the significance of ocean water mass loading of the continental shelves in the China Seas and its dominant role in the future SLR has not been previously reported.

2. Data and data processing

2.1. Study area and data

The study area ranges from 14° to 42° N latitude and from 105° to 132° E longitude (figure 2(a)). The focus of this study is on the continental shelves of the China Seas, where the water depth is shallower than 300 m. The Kuroshio, the strong western boundary current, flows along the eastern edge of the East China Sea and across the southeast corner of the study area.
In order to estimate the SLR in the China Seas over the 21st century, we use simulation data from the Integrated Climate Data Center (ICDC) at the Hamburg University (https://icdc.cen.uni-hamburg.de/ar5-slr.html). This dataset was generated from the Coupled Model Intercomparison Project Phase 5 (CMIP5, Taylor et al 2012) climate models that were used for regional sea level projections (Church et al 2013). It provides projections from 2007 to 2100 and yearly 1° × 1° resolution spatial maps of sea-level rise and its components based on three representative concentration pathways (RCP2.6, 4.5 and 8.5). The sea level change includes a stericodynamic component from 21 CMIP5 coupled models (dynamic sea level, global thermosteric anomaly, and inverse barometer effect), a land ice component (Antarctic and Greenland dynamic ice and surface mass balances, and glaciers), a GIA component, and a ground water storage component. Hereafter, this dataset will be referred to as the ICDC-CMIP5 data. While CMIP5 climate models explicitly compute sea-level change associated with the stericodynamic component, the land ice and ground water storage components are calculated offline from the predicted temperature and precipitation changes, by computing the changes in gravitational field, rotational properties of the Earth, and solid-earth deformation (Perrette et al 2013).

In addition, we also use the ocean temperature and salinity data from the 21 CMIP5 models to calculate the steric sea level change. Only one simulation run (r1i1p1) is used from each model to ensure equal weighting in the ensemble-mean analysis. For each model, variables are interpolated onto a common 1° × 1° latitude–longitude grid with 50 levels.

Table 1. SLR (cm) over the continental shelves of the China Seas relative to the 1986–2005 climatology under three emissions scenarios (RCP2.6, 4.5, and 8.5). Values are the central estimate with the 90% confidence interval in parentheses. For comparison, the values for the global ocean mean SLR are given in italics.

| Scenario | 2030 | 2060 | 2100 |
|----------|------|------|------|
| RCP2.6   | 12.6 (6.4–19.1) | 27.6 (14.1–41.7) | 43.6 (20.8–67.7) |
| RCP4.5   | 12.5 (6.2–19.0) | 28.4 (15.0–42.7) | 52.0 (27.3–78.8) |
| RCP8.5   | 13.4 (6.2–20.9) | 33.9 (18.7–50.4) | 74.5 (41.7–112.8) |

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14.0 (6.0–22.2) 34.4 (19.4–50.6) 75.2 (42.7–113.1)
in vertical. For each variable, the change due to climate warming is calculated by subtracting the 20 year mean of 1986–2005 in the historical simulation from the 2081–2100 mean in the RCP runs.

2.2. Data processing
This section introduces the methodology used to calculate the manometric sea level change (figure 1). Manometric sea level change is defined as the part of sea level which is due to the change in time-mean local mass of the ocean per unit area (Gregory et al 2019). It can also be described as the total mass contribution to sea level change.

In most CMIP5 models, the ocean module uses the Boussinesq approximation and conserves volume rather than mass (Griffies and Greatbatch 2012). As a consequence, the sea surface height output of CMIP5 models is computed from the ocean volume conservation equation rather than the mass conservation equation, which does not include the effect of the global mean thermal expansion (Greatbatch 1994, Griffies and Greatbatch 2012). To correct for this, a spatially uniform time-varying correction term must be added to adjust the sea level for any net expansion or contraction of the water column from changes in the mean density in the model domain (Greatbatch 1994). Based on equations from Mellor and Ezer (1995), the non-Boussinesq steric component of sea level (ζ_{OCN}) (figure 1) can be written as:

\[ \Delta \zeta_{OCN} (x, y, t) = \zeta_{b} (x, y, t) + \zeta_{e} (t) + \zeta_{GS} (x, y, t) \] (1)

where \( \zeta_{b} \) is the Boussinesq sea level, \( \zeta_{e} \) is GMSL due to expansion or contraction of the water column and \( \zeta_{GS} \) is an unknown but negligibly small error, which is largely attributable to the so-called Goldsborough–Stommel gyres, a non-Boussinesq vortex stretching effect caused by density change.

In a warming climate, the regional change of the steric dynamic component sea level (\( \Delta \zeta_{OMR} \)) can be decomposed into two major components: the local steric sea level change (\( \Delta \zeta_{Steric} \)), calculated from local sea water density change, and the sea level change induced by ocean mass redistribution (\( \Delta \zeta_{OMR} \)) (figure 1). \( \Delta \zeta_{OCN} \) is available from the ICDC-CMIP5 dataset (see section 2.1), and \( \Delta \zeta_{Steric} \) can be calculated by vertically integrating density anomalies at each grid point and each time step according to (Landerer et al 2005):

\[ \Delta \zeta_{Steric} = \int_{0}^{H} \frac{\rho(S, T, p) - \rho(S_0, T_0, p)}{\rho(S_0, T_0, p)} \, dz \] (2)

where \( S, T, \) and \( p \) are the salinity, temperature, and pressure, respectively, and \( S_0 \) and \( T_0 \) are their respective reference state values. \( \rho \) is a nonlinear function of \( S, T, \) and \( p \). The ocean mass redistribution component of sea level change can be calculated by (Landerer et al 2007, Chen et al 2014):

\[ \Delta \zeta_{OMR} (x, y, t) = \Delta \zeta_{OCN} (x, y, t) - \Delta \zeta_{Steric} (x, y, t) \] (3)

So that the manometric contribution to sea level change (\( \Delta \zeta_{Mass} \)) is the combination of ocean mass redistribution (\( \Delta \zeta_{OMR} \)), the change of land ice component (\( \Delta \zeta_{LNDICE} \)) and change in ground water storage (\( \Delta \zeta_{GRW} \)) (figure 1):

\[ \Delta \zeta_{Mass} (x, y, t) = \Delta \zeta_{OMR} (x, y, t) + \Delta \zeta_{LNDICE} (x, y, t) + \Delta \zeta_{GRW} (x, y, t) \] (4)

It should be noted that the change in manometric component alters the ocean bottom pressure with an equivalent change of sea level of \( \Delta \rho_b / \rho_0 g \), where \( \rho_b \) being the bottom pressure, \( g \) being the gravitational acceleration, and \( \rho_0 \) the reference ocean water density.

3. Results

3.1. Projected SLR on the continental shelves of the China Seas
Figures 2(b)–(d) show the time series of spatially-averaged sea level on the continental shelves of the China Seas for RCP2.6, RCP4.5 and RCP8.5, respectively. Since these are multi-model ensemble-means, the natural variabilities are absent. The sea level is expected to rise in all emission scenarios, with the magnitude of the rise strongly dependent upon which RCP emission scenario is considered. The lowest SLR is projected under the RCP2.6 scenario and the highest SLR is under the RCP8.5 scenario, which correspond to the lowest and highest future global warming scenarios, respectively. An accelerated rise is readily apparent in both the RCP4.5 and RCP8.5 scenarios. Table 1 outlines the details of the mean sea level changes, including the mean estimate and the 90% confidence interval, for 2030, 2060, and 2100. In 2030, the magnitudes of SLR among all of the different emission scenarios are nearly identical, indicating the limited effect of greenhouse gas concentration on the near-term response of sea level. However, the discrepancies in SLR among the different RCP scenarios become more and more noticeable as time progresses, especially by the end of 21st century. Sea level will rise between 43.6 cm (20.8–67.7 cm, 90% confidence interval) in RCP2.6 and 74.5 cm (41.7–112.8 cm, 90% confidence interval) in RCP8.5 by 2100 relative to the 1986–2005 mean sea level (table 1).

Observations have shown that the SLR in the China Seas has outpaced the global mean value over the last few decades (Feng and Cheng 2019). So, it is worth investigating whether this trend will likely still hold in future scenarios. For comparison, the time evolutions of the GMSL are overlayed on those for the China Seas in figures 2(b)–(d). It is apparent that the sea levels in the China Seas are likely to
Figure 3. SLR and contributing processes in the RCP4.5 scenario. (a1)–(a3) The area-averaged sea level change on the continental shelves of the China Seas. (b)–(i) The spatial patterns of sea level change. The SLR is defined as the sea level differences between 2081–2100 and 1986–2005. The process abbreviations can be found in figure 1. The thick black line indicates the 300 m isobath. The continental shelf here is defined as the region with water depth shallower than 300 m. The units are cm.

rise at nearly the same rate or slightly slower than the GMSL change rate in all scenarios. For example, the SLR by 2100 over the continental shelves of the China Seas under the RCP4.5 scenario is projected to be 52.0 cm, a value just below the global mean SLR of 54.0 cm. However, note that the observed sea level change in the China Seas is strongly influenced by low frequency climate variabilities (Han and Huang 2008, Moon and Song 2017), which may contribute to the higher than global mean SLR over the last few decades (Feng and Cheng 2019). While the multi-model ensemble mean in ICDC-CMIP5 data subtract this internal climate variability and, therefore only reflect the forced change of sea level (figures 2(b)–(d)).

In addition to the regional mean SLR, the regional pattern of SLR in the RCP4.5 scenario is subsequently examined (figure 3(b)). The SLR in the northwestern Pacific is projected to be between 42 and 52 cm by the end of this century relative to 1986–2005 sea level. The most striking feature of this rise is the different magnitudes of the SLR in deep versus shallow water regions. For example, in regions where the water depth is deeper than 300 m, like the region east of the Kuroshio, the SLR is projected to exceed the GMSL rise, whereas the SLR over the continental shelves is projected to be roughly equal to the GMSL rise (Chen et al 2019b). The projections under the RCP2.6 and RCP8.5 scenarios (supplemental figures S1(b) and S2(b) (available online at stacks.iop.org/ERL/16/064040/mmedia)), while quantitatively different, show similar spatial patterns to those under RCP4.5 (figure 3(b)).

3.2. The causes of the projected sea level rise
Changes in regional sea level are the net result of a combination of many geophysical and climatological processes. Determining how each of these factors influence SLR will be key to our understanding of the drivers of SLR under a warming climate. Following the traditional methodology (Chen et al 2017, Frederikse et al 2020), we decompose the total SLR into the contributions from land ice loss, steric, dynamic, ground water storage and GIA (figures 1 and 3(a1)). For RCP4.5, the sea level over the continental shelves of the China Seas is projected to rise roughly 46.5 cm by 2081–2100 relative to 1986–2005,
with the largest contribution coming from melting of land ice (25.3 cm) and from changes in the stericodynamic component (21.2 cm, figures 3(a1) and (b)–(f)). This larger contribution to SLR from melting land ice over the changes in the stericodynamic SLR in the China Seas is consistent with assessments of the GMSL budget over the satellite era (Chen et al. 2017), the 20th century (Frederikse et al. 2020) and 21st century (Oppenheimer et al. 2019). Ground water storage makes only a small positive contribution (2.0 cm), while GIA makes a small negative contribution (−2.4 cm). With respect to their regional distributions (figures 3(c)–(f)), all components contribute to the pattern of total SLR (figure 3(b)), with higher values in the open ocean and relatively lower values over the continental shelves.

Analyzing the stericodynamic sea level change, the most predominant feature is that it causes a higher SLR offshore in the North Pacific subtropical gyre and lower SLR over the shelves (figure 3(d)). This feature indicates that there will be an increase of the cross-Kuroshio sea surface height gradient (~4 cm difference), corresponding to a projected intensification of the Kuroshio (figure 3(d), Chen et al. 2019b). Previous studies indicated that the intensification of the Kuroshio was forced by sea surface warming through strengthened ocean stratification and downward heat mixing (Wang et al. 2015, Chen et al. 2019b). To understand the detailed dynamic response, we decompose the stericodynamic sea level change into local steric and ocean mass redistribution components using equations (2) and (3). The projected local steric SLR is positive for all regions (figure 3(h)) due to the warming and/or freshening of sea water over the entire domain. Large steric SLR of up to 18 cm appear in the deep western Pacific and SCS as the warming penetrates deeper into the ocean. In contrast, the shallow water columns over the continental shelves only permit small steric expansion, resulting in a much smaller SLR than in the deep-water region. This pattern in steric SLR feeds into a sharpened horizontal sea surface height gradient (>14 cm steric height difference) from the deep-water region to the shallow continental shelves (figure 3(h)), a result that was also reported in Landerer et al. (2007) and Chen et al. (2014) based on CMIP3 data. However, the surface warming will cause only a small intensification of the Kuroshio (Chen et al. 2019b), and the change in the ocean currents will not be sufficient to balance the steric height induced sea surface height gradient. So, fast barotropic gravity waves will rapidly redistribute the steric anomaly from the deep open ocean region to the shallow seas, thereby inducing a net mass loading onto the continental shelves (figure 3(g)). Although this steric driven ocean mass redistribution causes zero changes in GMSL, it can be an important contributor to the regional sea level. For the RCP4.5 scenario, ocean mass redistribution contributes 14.8 cm to the ocean processes SLR for the continental shelves of the China Seas, more than twice the local steric component of 6.5 cm (figure 3(a2)).

For GMSL, the manometric sea level change is equal to the barystatic sea level change, and considered as the changes in land ice (glaciers, Greenland and Antarctic ice sheets) and ground water storage (Gregory et al. 2019). While for regional sea level change, as the analysis above shows, the stericodynamic contribution also result in a mass redistribution to the continental shelf zone. Combining all these factors using equation (4), gives the manometric sea level change. Figure 3(a3) shows that the projected manometric component of SLR is 42.3 cm over the continental shelves of the China Seas by 2081–2100 relative to 1986–2005, explaining 91.0% of the total SLR, with only relatively small contributions from the local steric height (14.0%) and GIA (−5.2%) components to the total SLR. These results suggest manometric sea level change will likely play the dominant role in the future SLR over the continental shelves of the China Seas. It should be noted that this dominance of manometric sea level is not sensitive to scenario selection, as its projected contribution to total SLR in RCP2.6 and RCP8.5 are 94.2% and 90.5%, respectively (supplemental figures S1 and S2).

4. Conclusion and discussions

We investigate the projected SLR in the China Seas for the 21st century based on the ICDC-CMIP5 dataset and find that the sea level change on the continental shelves of the China Seas is close to the GMSL change in all scenarios (figure 2 and table 1). This result likely arises for two reasons. First, the regional pattern of SLR driven by land ice loss is through gravitational-rotational and deformational effects. Only the regions near land ice (the Arctic, around Greenland and Western Antarctica) will have significant relative sea level changes that differ from the global mean, while the low- and mid-latitude regions (e.g. the China Seas) will see relatively small spatial variation tracking the GMSL change (figure 4(a), supplemental figures S3(a) and (b), Slangen et al. 2014, Brunnabend et al. 2015). Second, with respect to the stericodynamic component of SLR, generally the Northwestern Pacific will likely have a larger SLR than the global mean SLR (Wang et al. 2015, Chen et al. 2019b, Lyu et al. 2020). However, on the continental shelves the projected SLR will remain close to the global mean rate, as the intensifying Kuroshio will be associated with a larger SLR offshore in the North Pacific subtropical gyre but a smaller SLR near the coast (Chen et al. 2019b), as indicated by both CMIP5 (figure 4(b), supplemental figures S3(c) and (d)) and CMIP6 (Lyu et al. 2020). This is totally different from the SLR along East Coast of North America, where the stericodynamic sea level change will be much higher than global mean because the Gulf Stream and Atlantic meridional ocean circulation are projected to weaken.
Figure 4. The global distribution of projected SLR (cm) due to changes in (a) land ice (glaciers and the Greenland and Antarctic ice sheets), and (b) stereodynamic sea level in the RCP4.5 scenario. The change is defined as the difference between 2081–2100 and 1986–2005. The projected SLR in each panel is shown relative to its global mean, with negative (positive) values indicating a smaller (larger) sea level rise than the global mean. The black box shows the study domain.

under a warming climate (Yin et al 2009, Chen et al 2019b, figure 4(b)).

We also analyze the causes of SLR on the continental shelves of the China Seas. We find that the changes in land ice and ground water storage would add water mass to the continental shelves (figures 3(a1), (c) and (e)) increasing sea level. In addition, changes in the stereodynamic component would also drive a net transfer of mass from the deep open ocean onto the shallow continental shelves (figure 3(g)) though the inhomogeneous warming and changes in ocean circulation (e.g. Kuroshio). Combing all these factors together yields a manometric sea level change (known as mass contribution) that explains more than 90% of the total projected SLR, leaving the local steric height changes and GIA to explain the remaining projected change (figure 3(a3)). The causes of the observed SLR in the 20th century was studied recently by Frederikse et al (2020). They reconstructed the GMSL since 1900 from tide-gauge records and compared it to the sum of the contributing processes. Because there are no global measurements of ocean mass (bottom pressure) before 2002, it was not possible to calculate the contribution from ocean mass redistribution due to changes in ocean processes on regional sea level change. However, since 2002, the Gravity Recovery and Climate Experiment (GRACE) data does provide important information about the mass contribution to the sea level change (Tapley et al 2019) that can help to study the regional sea level budget under a warming climate from observation in the future. Closing the budget in the regional sea level change is also possible in pre-GRACE era, only where permanent GPS station data, tide gauge observations and steric data are available, for example, using reconstruction method introduced in Frederikse et al (2016).

It is known that the mass contributions could alter the ocean bottom pressure, thus affecting Earth’s gravity field and its moment of inertia (Chao et al 1995, Wahr et al 1998). Previous studies have shown that ocean mass increases (positive ocean bottom change) effects the elastic deformation of the ocean bottom (Frederikse et al 2017), and that the mass transfers between basins could even change the length-of-day by $-0.12$ ms over the next 200 years (Landerer et al 2007). However, it is also valuable to investigate the possible consequences of large positive ocean bottom pressure changes and mass loading onto the continental shelves in the China Seas under a future warming climate.

In this study, coarse resolution ($\sim 1^\circ$) CMIP5 models for the ocean processes are used to study the projected SLR (figures 3(d), (g) and (h)). While these results facilitate the discussion of the differing dynamics between deep and shallow ocean regions, the model resolution is more than adequate for studying the regional patterns of SLR over the inner
continental shelves and along the coasts of the China Seas. However, it certainly is vitally important to project the patterns of SLR onto the continental shelves for both decision-making and for the development of successful adaptive strategies to climate change for coastal and low-lying regions. High-resolution eddy-resolving global model simulations (Van Westen et al. 2020) or high-resolution regional model dynamical downscaling simulations (Nishikawa et al. 2021, Liu et al. 2016, Zhang et al. 2017) are effective methods for these later efforts, and will be applied to the China Seas in future studies of sea level change.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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References

Boussinesq N and Gregory J 2014 Attribution of the spatial pattern of CO2-forced sea level change to ocean surface flux changes Environ. Res. Lett. 9 034004
Brunnabend S E, Schroetter J, Rietbroek R and Kusche J 2015 Regional sea level change in response to ice mass loss in Greenland, the West Antarctic and Alaska J. Geophys. Res. Oceans 120 7136–28
Carson M, Ko Brunnabend S E, Schroeter J, Rietbroek R and Kusche J 2015 Development of high-resolution future ocean regional downscaling of future sea level change in the western North Pacific using ROMS J. Oceanogr. 72 2723–83
Jevrejeva S, Jacobsen L B, Grinsted A, Lincke D and Marzeion B 2018 Flood damage costs under the sea level rise with warming of 1.5 ◦C and 2 ◦C Environ. Res. Lett. 13 074014
Landerser F W, Jungclaus J H and Marotzke J 2007 Ocean bottom pressure changes lead to a decreasing length-of-day in a warming climate Geophys. Res. Lett. 34 L06307
Liu Z J, Minobe S, Sasaki Y N and Terada M 2016 Dynamical downscaling of future sea level change in the north-western Pacific using RCM J. Clim. 29 1905–22
Lombard A, Cazenave A, Le Traon P Y and Ishii M 2005 Contribution of thermal expansion to present-day sea level change revisited Glob. Planet. Change 47 1–16
Lyu K, Zhang X and Church J A 2020 Regional dynamic sea level change simulated in the CMIP5 and CMIP6 models: mean biases, future projections, and their linkages J. Clim. 33 6377–98
Marcos M, Timmermans M N and Calafat F M 2012 Inter-annual and decadal sea level variations in the north-western Pacific marginal seas Prog. Oceanogr. 105 4–21
Mellor G L and Ezer T 1995 Sea level variations induced by heating and cooling: an evaluation of the Boussinesq approximation in ocean models J. Geophys. Res. 100 20565–77
Mitrovica J X, Tamisiea M E, Davis J L and Milsen G A 2001 Recent mass balance of polar ice sheets inferred from patterns of global sea-level change Nature 409 1026–9
Moon J H and Song Y T 2017 Decadal sea level variability in the East China Sea linked to the North Pacific Gyre Oscillation Cont. Shelf Res. 143 278–85
Nishikawa S, Wakamatsu T, Ishizaki H, Sakamoto K, Tanaka Y, Tsujiro H, Yamamata G, Kamachi M and Ishikawa Y 2021 Development of high-resolution future ocean regional
projection datasets for coastal applications in Japan Prog. Earth Planet. Sci. 8 1–22
Oppenheimer M et al 2019 Sea level rise and implications for low-lying islands, coasts and communities IPCC Special Report on the Ocean and Cryosphere in a Changing Climate ed H O Pörtner et al (Cambridge: Cambridge University Press)
Pardaens A K, Gregory J M and Lowe J A 2011 A model study of factors influencing projected changes in regional sea level over the twenty-first century Clim. Dyn. 36 2015–33
Peltier W R 2004 Global glacial isostasy and the surface of the ice-age earth: the ICE-5G (VM2) model and GRACE Annu. Rev. Earth Planet Sci. 32 111–49
Perrette M, Landerer F, Riva R, Frieler K and Meinshausen M 2013 A scaling approach to project regional sea level rise and its uncertainties Earth Syst. Dyn. 4 11–29
Qu Y, Jevrejeva S, Jackson L P and Moore J C 2019 Coastal sea level rise around the China Seas Glob. Planet. Change 172 454–63
Sallenger A H, Doran K S and Howd P A 2012 Hotspot of accelerated sea-level rise on the Atlantic coast of North America Nat. Clim. Change 2 884–8
Slangen A B A, Carson M, Katsman C A, Van De Wal R S W, Köhl A, Vermeersen L I A and Stammer D 2014 Projecting twenty-first century regional sea-level changes Clim. Change 124 317–32
Tapley B D et al 2019 Contributions of GRACE to understanding climate change Nat. Clim. Change 9 358–69
Taylor K E, Stouffer R J and Meehl G A 2012 An overview of CMIP5 and the experiment design Bull. Am. Meteorol. Soc. 93 485–98
Van Westen R M et al 2020 Ocean model resolution dependence of Caribbean sea-level projections Sci. Rep. 10 14599
Wada Y, Beek L P H V, Weiland F C S, Chao B F, Wu Y H and Bierkens M F P 2012 Past and future contribution of global groundwater depletion to sea level rise Geophys. Res. Lett. 39 L10402
Wahr J, Molenaar M and Bryan F 1998 Time variability of the Earth's gravity field: hydrological and oceanic effects and their possible detection using GRACE J. Geophys. Res. 103 30205–29
Wang G, Xie S-P, Huang R and Chen C 2013 Robust warming pattern of global subtropical oceans and its mechanism J. Clim. 28 8574–84
Xu N and Gong P 2018 Significant coastline changes in China during 1991–2015 tracked by landsat data Sci. Bull. 63 883–6
Yin J, Griffies S M and Stouffer R J 2010 Spatial variability of sea level rise in twenty-first century projections J. Clim. 23 4585–607
Yin J, Schlesinger M E and Stouffer R J 2009 Model projections of rapid sea-level rise on the northeast coast of the United States Nat. Geosci. 2 262–6
Zhang X, Church J A, Monroešan D and McClunes K I 2017 Sea level projections for the Australian region in the 21st century Geophys. Res. Lett. 44 8481–91