Surveys in Geophysics (2019) 40:1631–1653
https://doi.org/10.1007/s10712-019-09559-3

Climate Model Uncertainty and Trend Detection in Regional Sea Level Projections: A Review

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Received: 6 November 2018 / Accepted: 18 July 2019 / Published online: 10 August 2019

Abstract
Projections of future sterodynamic sea level change from global climate models are associated with different sources of uncertainty. From a scientific, societal and policy-making perspective, it is relevant to both understand and reduce uncertainty in projections of climate change. Here, we review recent findings which describe, and shed light on, climate model uncertainty focusing particularly on two types of model uncertainty that contribute to the currently large spread in dynamical sea level patterns (i.e., regional sea level relative to the global mean). These uncertainties are: (1) intermodel uncertainty due to differences in models' responses in a warming climate and (2) internal model variability due to an individual model's own climate variability. On timescales longer than about 50 years from now, anthropogenic sterodynamic (dynamic plus global mean) sea level trends from middle- and high-end forcing scenarios will be larger than internal model variability. By 2100, these anthropogenic trends will also be larger than intermodel uncertainty when global mean thermosteric sea level rise and/or melting contributions from land ice are considered along with dynamic sea level changes. Furthermore, we discuss projections of future coastal sea level from the perspective of global climate models as well as from downscaled efforts based on regional climate models. Much knowledge and understanding has been achieved in the last decade from intermodel experiments and studies of sea level process-based model; here, the prospects for improving coastal sea level and reducing sea level uncertainty are discussed.

Keywords Sea level · Climate projections · Regional sea level · Uncertainty · Trends · Trend detection · Time of emergence · Climate model

1 Introduction

Global mean sea level (GMSL) will continue to rise over the next centuries as a consequence of increases in global mean temperature caused by anthropogenic climate forcing. About 70% of global coastlines are projected to experience a relative sea level

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change within 20% of global mean sea level rise by the end of this century (Church et al. 2013). Proper appraisal of uncertainty in projections of global and dynamic sea level is essential for risk assessment in policy responses and results in more effective risk management as part of adaptation and mitigation efforts (IPCC 2014: Summary for Policymakers).

Sea level projections are typically made using coupled climate models (e.g., Yin 2012; Church et al. 2013), statistical (e.g., Perrette et al. 2013) and semiempirical methods (e.g., Moore et al. 2013). While statistical and semiempirical methods can both provide an estimate of sea level change along with some measure of uncertainty, ensembles of coupled climate models directly provide both an estimate of intermodel uncertainty—which is the sensitivity of dynamical sea level projections to model structure, parameterizations and numerics—and an estimate of the uncertainty due to natural variability over different timescales. In these multi-model projections, uncertainty arises from different sources, with their relative significance varying as a function of lead time and spatiotemporal averaging scales (Hawkins and Sutton 2009; Northrop and Chandler 2014). Models under discussion in this review are largely models contributing to phase 5 of CMIP (Coupled Model Intercomparison Project, hereafter CMIP5; Taylor et al. 2009).

Climate models also provide valuable process-based information, such as low-frequency climate variability and anthropogenically forced trends on timescales up to centuries, which can be used for detecting the emergence of anthropogenic sterodynamic (often referred to as “regional” or “local”) sea level trends. These trends are detected when their signal emerges above the “background noise”, that is, above the range of variability which is externally forced by natural processes (e.g., solar and volcanic) and variability internal (unforced) to the climate system (e.g., known climate modes of variability). Such detection efforts can be used to assess how quickly sea level changes outside the range of natural variability will impact a specific coastal region. Thus, detection of anthropogenic sea level trends is crucial not only to better understand physical processes by climate scientists but also to the public sector and local governments to inform urban planning and elaboration of effective climate change adaptation and mitigation strategies. However, it is important that climate models can accurately estimate both internal variability and regional responses to anthropogenic forcings in order for such detection methods to yield results with confidence.

This review focuses on recent advances into understanding the spread in model projections of local, sterodynamic sea level change related to ocean processes, i.e., ocean heat uptake, mass, heat and freshwater redistribution. The ways in which this has been achieved, as well as the problems and answers which have been found so far, inform on how well we can directly estimate or infer future sea level changes at the coast and regionally in the open ocean and how much confidence we are able to place on them. Though sea level rise due to mass loss from the Greenland and Antarctic ice sheets is expected to increase (e.g., Church et al. 2013), the respective sea level fingerprints are still obscured by the decadal to multidecadal sea level variability observed in satellite altimetry. Richter et al. (2017b) showed that the internal decadal to multidecadal (modeled) contribution of glaciers mass change to sea level variability is small compared to ocean variability. Little is known, however, about the internal variability of the Greenland and Antarctic ice sheets.

As we employ various specific terms regarding sea level, variability and uncertainty, a terminology list is found in the following subsection. These terms will be linked to those found in Gregory et al. 2019, where possible. In Sect. 2, we cover relevant literature on the sources of climate model uncertainty for projected local, sterodynamic sea level trends and on model representation of internal climate variability of sea level in comparison with satellite altimetry and tide gauge observations. Some focus is specific to understanding model internal climate variability, a partially irreducible source of uncertainty in trend detection given that it is a natural feature of the climate system.

Research into trend detection for anthropogenic sterodynamic sea level change is presented in Sect. 3. As an application of the uncertainties explored in Sect. 2, here we summarize model studies that assess the effect of internal variability and intermodel spread on the detection of future sterodynamic sea level trends. These studies provide a timeframe proxy for anthropogenic sea level trends that are expected to emerge from natural variability in the observational record. A subset of these results that are applied specifically at the coasts is also presented.

In Sect. 4, we examine research which covers the coastal aspect of sea level projections, including recent downscaling efforts based on regional models of considerably higher spatial grid resolution than global climate models, and what still needs to be accomplished or improved in coastal sea level projections. Sources of uncertainty that are specific to modeled coastal sea level projections are explored. Finally, Sect. 5 contains some brief concluding remarks.

1.1 Terminology

- *Dynamic sea level*—the spatially and time-dependent sea level referenced to the geoid and provides geostrophic surface currents, chosen such that its global mean is zero; dynamic sea level here does not contain any other sea level signal (e.g., no global mean thermosteric sea level, no land ice melt, no land motion, no inverse barometer effects). This is term N13 ocean dynamic sea level change in Gregory et al. 2019, minus the inverse barometer (IB) correction, and is the same as the "zos" variable reported for CMIP5 models.
- *Global mean thermosteric sea level*—the increase in global mean sea level through thermal expansion of warming water (e.g., Domingues et al. 2008), where the global mean is being derived from ocean model density via a common calculation (Greatbatch 1994) in which a mean, time-independent salinity is used. In CMIP5 model output alone, this is normally synonymous with global mean sea level. This is term N17 in Gregory et al. (2019).
- *Sterodynamic sea level*—in modeling studies often called "regional or local sea level," it is the dynamic sea level plus global mean thermosteric sea level; the sterodynamic sea level (associated with changes in ocean density and circulation, see Gregory et al. 2019) can be derived directly from coupled climate models and does not include any other sea level components which are not commonly calculated in CMIP5 models. This is term N20 in Gregory et al. (2019).
- *Total sea level*—the sterodynamic sea level, plus all other known components to sea level that contribute a substantial amount to the sterodynamic sea level changes relative to the adjacent coast, or the ocean floor, as presented in the AR5 report (Church et al. 2013; i.e., land ice melt, vertical land motion from glacial isostatic adjustment, land water storage and inverse barometer (IB) effects). It is the IB-corrected relative sea level change (see term N15, Gregory et al. 2019), the sea level measured relative to the sea floor, and therefore includes the contribution from vertical land motion, but includes also changes in the geoid and the change in total mass (volume) of the ocean. This is the only quantity in this paper that relies on data external to the typical CMIP5 coupled climate models' ocean component model.

- *Internal variability*—dynamic sea level variability occurring within the pre-industrial control runs of individual models.
- *Intermodel uncertainty*—differences between models in dynamic sea level changes over a fixed time frame.
- *Uncertainty*—a general term used for the property of statistical uncertainty or error associated with changes (usually mean differences or trends) in dynamic, sterodynamic or total sea level over a specified time interval, but also used as a term for the range of values obtained when applying a set of different forcings in model experiments that may not span the range of possible forcing values due to unknown or unknowable factors. An example of the latter is scenario uncertainty (Yip et al. 2011; see Sect. 2).
- *Time of emergence (ToE)/trend detection*—the length of time over which a trend from linear least squares fitted to sterodynamic sea level will be statistically significant against the local, unforced, sea level variability (i.e., the internal variability) is the time of (signal) emergence; the process is also called trend detection. In order to identify the ToE for anthropogenic sterodynamic sea level change, one must estimate sterodynamic sea level variability from internal climate processes on a wide range of timescales (e.g., Becker et al. 2014; Carson et al. 2015; Little et al. 2015; Han et al. 2018; see Sect. 3 for uncertainty arising from internal variability).
- *Regional*—this adjective is used to draw specific attention to the fact that a spatially local property is being examined, as opposed to a global or global mean property.

2 Climate Model Uncertainty in Future Sea Level Projections

Future projections of sterodynamic sea level are generally developed based on multi-model ensembles all using the same forcing protocol design (e.g., Eyring et al. 2016). These global climate model simulations are averaged together to provide a mean estimate, called the ensemble mean, as this averages out random noise and transient dynamic features. The multi-model ensemble also provides an uncertainty estimate found from the spread of the ensemble members (Fig. 1). Note that the averaging, however, does not remove systematic errors that might be common to the ensemble of models.

The major sources of uncertainty related to changes in global mean thermosteric and dynamic process-based sea level projections include:

1. internal variability due to differences in the timing, spatial patterns and magnitudes of multidecadal climate variability (e.g., the interdecadal Pacific Oscillation, Di Lorenzo et al. 2008) within and among individual models (e.g., Hu and Deser 2013; Bordbar et al. 2015; Carson et al. 2015; Hu et al. 2017, Hu and Bates 2018); due to these differences, the ensemble average of different model results may not be able to fully remove the internal climate variability and its associated sea level variability (although it can be greatly reduced, see below);
2. intermodel uncertainty due to differences in responses among projections of different climate models under the same forcing scenario (e.g., Church et al. 2013; Melet and Meyssignac 2015; Gregory et al. 2016);
3. scenario uncertainty due to the future path of anthropogenic forcing (Moss et al. 2010; Yip et al. 2011); and
4. model–scenario uncertainty "due to the variation of model deviations from the ensemble mean across different scenarios" (Yip et al. 2011).

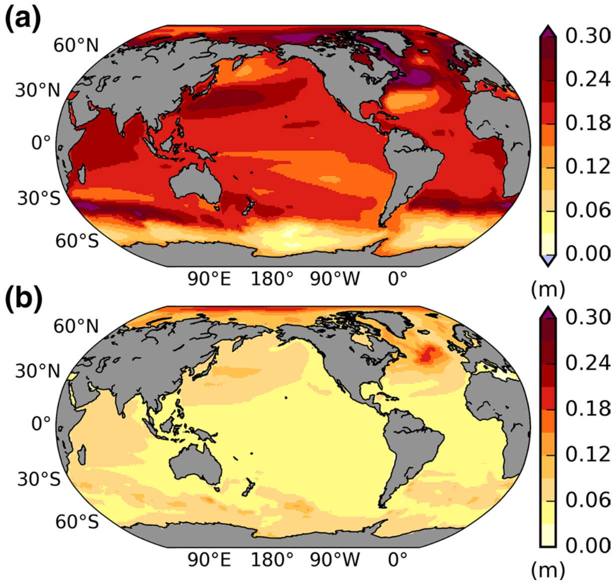

Fig. 1 From AR5, Chapter 13, Fig. 13.16. Projections of future sterodynamic (dynamic plus global mean thermosteric) sea level change resulting from the RCP4.5 scenario forcings, as a difference of the 2081–2100 mean minus the 1986–2005 mean sea level. The RCP4.5 scenario is a prescribed "middle" scenario for climate projection model experiments that includes some anthropogenic climate forcing mitigation through 2100 (Moss et al. 2010). **a** The ensemble mean sea level change from 21 ensemble members, in meters (m). **b**) The spread in sea level among ensemble members, calculated as the RMS (root mean square) deviation around the ensemble mean [in (**a**)], in m. Note that, because we only show results from RCP4.5, the ensemble spread does not contain any deviations due to differing forcing scenarios

These types of uncertainty apply to projections of both global mean thermosteric sea level change (e.g., Melet and Meyssignac 2015) and regional anomalies from the global mean, dynamic sea level (e.g., Yin 2012; Gregory et al. 2016). The model spread of global mean thermosteric sea level change is generally smaller than the model spread in dynamic sea level change by 2100 in most regions outside the tropics (Yin 2012; Church et al. 2013), by more than a factor of two in parts of the North Atlantic and Arctic regions. In the tropics, the ensemble spread of global mean thermosteric sea level change is of similar magnitude to the total spread in sterodynamic (global mean thermosteric + dynamic) sea level.

To allow for the partitioning of the relative contribution of the four types of uncertainty listed above, with respect to the total uncertainty in the projections, Yip et al. (2011) proposed the use of a statistical procedure known as analysis of variance (ANOVA, e.g., Von Storch and Zwiers 2001).

Using this approach and the same subset of CMIP5 models as in the IPCC AR5 (Church et al. 2013), Little et al. 2015 found that the total uncertainty in RCP4.5 projections of sterodynamic sea level rise by 2090 was composed of 40–70% due to intermodel uncertainty; 30–40% due to scenario uncertainty; and a smaller fraction (< 5%) due to internal variability and model–scenario uncertainty. All of these relative contributions vary locally due to the magnitude of both forced (anthropogenic or natural) and unforced (control-run) variability. At regional scales and on the relatively shorter timescales of 10–50 years, the largest uncertainties in future projections of sterodynamic sea level arise from intermodel differences and internal variability (Lyu et al. 2014, 2015; Richter and Marzeion 2014; Carson et al. 2015; Little et al. 2015; Han et al. 2018). Therefore, we will focus on the sources and causes of these two model-derived uncertainties for the rest of this section.

2.1 Sources of Intermodel Uncertainty

Several techniques have been employed in order to assess the causes of uncertainty in ocean-only sea level projections from global climate models, i.e., sterodynamic sea level. Bouttes and Gregory (2014) applied surface flux changes from different models to a single coupled climate model and found that heat flux and wind changes dominate both the patterns of sterodynamic sea level change and their intermodel spread. The CMIP6-endorsed FAFMIP project (Flux-Anomaly-Forced Model Intercomparison Project) is being carried out to quantify the drivers of dynamic sea level variability in models and the key ocean processes responsible for the large spread in projections (Gregory et al. 2016). Initial results based on a small number of CMIP5 model simulations show that heat flux perturbations are largely responsible for the modeled sterodynamic sea level changes over most of the ocean, except in the Southern Ocean, where wind forcing has a comparable contribution in driving the strong sea level gradient across the Antarctic Circumpolar Current (Gregory et al. 2016).

Based on an eddy-permitting ocean model, Saenko et al. (2015) also found that surface heat forcing is a dominant process in driving dynamic sea level changes under the RCP4.5 scenario. In this eddy-permitting experiment, both wind and heat surface forcing contributed to the large belt of sea level changes along the Southern Ocean, as in FAFMIP, but wind forcing drove larger sea level changes in the North Pacific and Atlantic compared to FAFMIP. Using a different approach from FAFMIP, Huber and Zanna (2017) tested the magnitudes of uncertainties from air–sea fluxes versus ocean model parameterizations and found that the uncertainties from air–sea fluxes were larger than those from ocean parameterizations, especially for the Atlantic Meridional Overturning Circulation (AMOC) and Atlantic Ocean heat content. In a similar vein to FAFMIP, Garuba and Klinger (2018) and Zanna et al. (2018) explored individual surface flux perturbations on ocean-only models, finding that heat, freshwater and wind flux perturbations all have various, and large, regional responses in ocean heat uptake, and therefore sterodynamic sea level. In addition, Melet and Meyssignac (2015) find that the majority of the model spread in global mean thermosteric sea level in coupled simulations is due to differences in ocean heat uptake efficiency, and the overall effective climate feedback parameter of models. Combining results from ocean-only simulations together with coupled models can shed light on processes responsible for intermodel spread in ocean heat uptake and associated sterodynamic sea level change (Kuhlbrodt and Gregory 2012; Marshall and Zanna 2014; Saenko et al. 2018).

To quantify uncertainty introduced by internal variability, most studies used multi-model ensembles (Yin et al. 2010; Little et al. 2015) or sea level projections from a single model, where each realization was forced by the identical scenario, but run with perturbed initial conditions. By taking this approach, Bordbar et al. (2015) demonstrated that the sterodynamic sea level projections by 2100 were strongly dependent on ocean initial conditions. In the same way, Hu et al. (2017), who analyzed a large ensemble from a single model, found that perturbations on initial ocean conditions led to larger changes in sterodynamic sea level rise than initial atmospheric perturbations. To improve our understanding and estimation of the internal variability uncertainty on sea level projections, studies analyzing both atmospheric and oceanic initial conditions effects are required.

Although the text above does not summarize all possible mechanisms responsible for uncertainty in ocean-only sea level changes from process-based models, it lists the major sources of uncertainty causing spread in dynamic sea level projections.

2.2 Quantifying Internal Climate Variability

The internal variability of dynamic sea level is the main source of interannual and decadal variability of sterodynamic sea level, which could overwhelm any early anthropogenic signals of sterodynamic sea level change (Meyssignac et al. 2012; Zhang and Church 2012). It is also possible, but not clearly detected, that land ice volume low-frequency (multidecadal) variability might also be able to drive some sterodynamic sea level variability (Chylek et al. 2004; Bjørk et al. 2012). Therefore, climate model simulations have been evaluated against historical observations with the goal of evaluating model performance in simulating internal sea level variability.

To what extent the climate models can simulate realistic internal sea level variability is an open question (e.g., Bordbar et al. 2015; Hu et al. 2017). Even when a model reproduces dynamic sea level of similar magnitude to the real ocean, the internal variability in model simulations is not in phase and future projections differ in spatial patterns for regional variability on the timescales of 10–40 years and in spatial patterns of regional trends over 80–100 years (Richter and Marzeion 2014; Carson et al. 2015; Little et al. 2015). Internal variability, combined with model errors and cross-model differences, therefore yields a complex picture of uncertainties that apply to projected sea level changes.

Comparisons of modeled and observed sea level variability over multidecadal periods are possible using tide gauge data (e.g., Becker et al. 2016; Meyssignac et al. 2017). The extraction of the dynamic sea level signal from tide gauges is complicated by the fact that they constitute point measurements that can be contaminated by land motion (Emery and Aubrey 1991; Santamaría-Gómez et al. 2014), and tide gauges also measure all other sources of local, relative sea level, such as land ice melt, groundwater retention and vertical land motion. Tide gauge variability on decadal timescales—i.e., not secular trends—is usually associated with dynamic sea level variability (e.g., in the North Atlantic: Calafat et al. 2012; Richter et al. 2012; Ezer et al. 2013; Dangendorf et al. 2014a), or in certain cases with global mean thermosteric sea level (e.g., large volcanic eruptions, Church et al. 2011) or large transient water mass changes (Fasullo et al. 2013).

Meyssignac et al. (2017) compared 27 historical tide gauge records (> 70 years) with an ensemble mean of 12 CMIP5 models. They showed that the simulated sea level in CMIP5 models is generally in close agreement with multidecadal variability from the tide gauge record during 1900–2015. They pointed out, however, that the interannual variability in models may overestimate or underestimate tide gauge variability, depending on the region. These differences are due to a variety of effects that models do not represent well, including river runoff, extreme ENSO events and ocean variability in shallow seas (Meyssignac et al. 2017). Becker et al. (2016) also found mismatches in variability between climate model ocean and tide gauges. Their analysis employed the methods developed by Lennartz and Bunde (2009) and was based on the property of sea level fluctuations to exhibit long-term correlations modeled as outcomes of stochastic power-law processes (Agnew 1992; Beretta et al. 2005; Barbosa et al. 2006, 2008; Hughes and Williams 2010; Bos et al. 2013; Becker et al. 2014; Dangendorf et al. 2014b). By comparing scaling properties in sea level changes simulated in 36 CMIP5 models to those in 23 historical tide gauge records (> 100 years), Becker et al. (2016) found that the majority of models overestimates the scaling of sea level fluctuations, particularly in the North Atlantic. Consequently, the models may underestimate a portion of sea level rise due to external forcing, in particular the anthropogenic footprint in the twentieth-century projections. This is likely, in part, due to not including volcanic forcing in the control runs of some models, which lead to lower estimates of ocean heat content uptake for these models (Gregory et al. 2013).

There are also studies comparing internal sea level variability in climate model simulations to historical datasets using satellite altimeter observations and other sea level products, including ocean reanalyses and sea level reconstructions that are available for longer time periods than altimetry data. Climate models generally reproduce large-scale features of the interannual and decadal sea level variability patterns, despite considerable intermodel spread. Monselesan et al. (2015) showed that the climate models can also simulate the spatially coherent features that interannual sea level variability is predominantly in the tropics, and on longer timescales, the sea level variance moves to higher latitudes. However, compared to available observations, most climate models underestimate the magnitude of internal sea level variability in the Pacific on both interannual and decadal timescales (Landerer et al. 2014; Lyu et al. 2016; Peyser and Yin 2017).

3 Sterodynamic Trend Signal Detection

3.1 Trend Detection in Future Model Projections

The time of emergence (or ToE, in trend detection) is the length of time needed to be able to detect significant secular trends in sterodynamic sea level against the background climate variability. If reliable model estimates of sea level variability can be made, then the statistical significance and ToE of sterodynamic sea level trends can also be estimated. The significance estimate provides confidence both in the estimated sea level trends and in the estimated ToE, thereby delivering a possible time frame of detectable sea level changes for the purposes of, e.g., civil engineering project planning, among other sociopolitical uses. In this section, we review the current state of estimating the time frame for projected sterodynamic sea level trend detection (time of signal emergence). Note that all statistical significance tests are for trends over a specified time period that emerge from the background internal climate variability of the model.

A common method of estimating an individual model's internal climate variability, which examines the model's control runs and calculates the variability of arising from control simulation data on a variety of timescales, is used in many of the studies discussed here. This yields an important question: Is sterodynamic sea level variability expected to remain of the same magnitude or substantially change when under additional, changing, climate forcing conditions? The IPCC AR5 report found changes in the ensemble interannual variability of detrended data between the intervals 1951–2005 and 2081–2100 to be mostly below 10% for the RCP4.5 scenario, outside of the high-latitude Arctic region (Church et al. 2013). This includes both positive and negative changes in the intensity of interannual variability, though there are large positive changes in Arctic variability (Fig. 13.15, Church et al. 2013). Hu and Bates (2018) report that decadal variability changes, as compared to future changes in interannual variability in the AR5, are more consistently positive in sign, and larger in magnitude, over more of the ocean, and more so for RCP8.5 than for RCP4.5.

In contrast to the AR5 report, Hu and Bates (2018) use a single model with a larger ensemble of projections. Further modeling studies to explore the commonality of these variability changes between different models, forcings and resolutions will prove useful.

Hu and Deser (2013) used a large ensemble of projected sea level runs from a single model, under the same forcing but with different initial conditions, and estimated that the 95% uncertainty on sea level trends (2000–2060) was greater than the magnitude of sterodynamic trends in the Southern Ocean and Arctic and nearly equal to the trend magnitude in parts of the equatorial Pacific and high latitudes in the Pacific and Atlantic. Thus, trends in these regions were not statistically significant. However, for the rest of the ocean, sterodynamic sea level trends were statistically significant over this time frame.

Using multi-model ensembles from the CMIP5 project, three studies explored regional trend signal detection using differing methodologies and different sets of the models (Lyu et al. 2014; Richter and Marzeion 2014; Carson et al. 2015). A common aspect of their methodologies is that the test of trends (of varying time frames) against the internal climate variability, from control runs, is performed on a per-model basis, with a central estimate for the ensemble presented. Lyu et al. (2014) and Richter and Marzeion (2014) consider the spread in control-run-based trends between models in some way (see the details in each study below), although Carson et al. (2015) only show results for the central estimate of the ensemble's control-run internal variability. Also, sea level variability due to volcanic forcing is not considered, as internal variability is estimated from control runs. All results generally converge on a range of values between ~ 40 and 60 years for the length of a future sea level record needed to resolve a trend in sterodynamic (dynamic plus global mean thermosteric) sea level larger than the underlying internal variability for ocean processes alone.

Lyu et al. (2014) also compared a more complete sea level projection signal containing land ice, water impoundment and glacial isostatic adjustment (GIA) to model control-run estimated internal variability. They estimated internal variability threshold to be two times the standard deviation of 200-year, annual detrended control-run time series in each grid box. For the sterodynamic sea level projection that includes both regional dynamic and global mean thermosteric sea level rise, sea level rise is detected from the noise of internal variability over half of the ocean by the 2040s; by 2080, most of the ocean outside of the Southern Ocean shows a significant trend (Fig. 3). When including all other known components contributing to future sterodynamic sea level change, i.e., "total sea level" as defined above, this time frame is much shorter, with significant trends found over half of the ocean by 2020, relative to the reference period 1986–2005. Only regions where at least 84% of the models in the ensemble exhibit signal emergence by 2080 are shown, as a measure of ensemble uncertainty (Fig. 3, right panels).

Richter and Marzeion (2014) estimated internal variability by computing overlapping trends from control-run data (per grid box) on a sequence of window lengths, from 10- to 100-year windows. Then, the sequence of trends from the RCP4.5 scenario, including both dynamic and global mean thermosteric sea level, was computed, and the time point at which the 95% anthropogenically forced trend uncertainty no longer intersects with the 95% uncertainty of the internal variability trends (and afterward for all future time points) is found to be the time of emergence at that location. They find that most of the ocean (again, outside of the Southern Ocean, and some high-latitude regions) shows significant sea level trends by 2040 or 2050, depending on the time frame over which the forced trend is estimated (cf. their Fig. 4). In a follow-up study, Richter et al. (2017b) showed that the addition of the glacier contribution increases the signal-to-noise ratio of sterodynamic sea level changes, thus leading to an earlier emergence by 10–20 years away from the sources of ice mass loss.

Carson et al. (2015) uses a very similar approach to Richter and Marzeion (2014) for estimating internal model variability: overlapping trends calculated for specific time frames. While the paper's focus is not on time of emergence, it was found that sea level trends are larger than two times the internal variability estimate over most regions of the ocean, for RCP4.5's dynamic plus global mean thermosteric sea level (their Fig. 3). This is in good agreement with the results from the other studies discussed above, though here looking at the ensemble mean trend and not individual trends from a single run.

When considering the same data as in these previous studies but restricting the analysis to coastal-only grid boxes, most coastal regions should expect statistically significant sea level trends by the mid-twenty-first century (Table 1). This statistical significance is higher in the lower and mid-latitudes, due to the presence of higher multidecadal variability at high latitudes in models. Although using somewhat different methodologies, with differing models and aims, these four papers (Hu and Deser 2013; Lyu et al. 2014; Richter and Marzeion 2014; Carson et al. 2015) generally agree that dynamic plus global mean thermosteric sea level trends over large portions of the ocean will have emerged from the background climate variability present in the models by the mid-twenty-first century.

Common to the studies that only examine sterodynamic sea level in climate models is that the trend and its emergence from the noise are certainly underestimated, as land ice melt is expected to contribute an ever increasing amount to sea level over the next few centuries. Glacial isostatic adjustment (GIA) and land water storage change are also expected to lower sea level trends in some locales, but increase them in others (Church et al. 2013, Slangen et al. 2014a). Studies that include additional components of sea level change, such as land ice, groundwater storage changes and vertical land motion contributions (Lyu et al. 2014; Richter et al. 2017b), give an earlier emergence time. Accelerations in sea level changes (changes in the local or global rate of change of sea level) would also be a sign of a change in the climate likely due to anthropogenic forcing, much like trend detection. Haigh et al. (2014), in a study that artificially extended tide gauges using the scaling from an ensemble of model projections and added random noise to represent variability, found that accelerations in local sea level should be detectable within the next two decades. The results from Haigh et al. (2014) mirror the finding in Lyu et al. (2014) when including the additional non-ocean model sea level components (total sea level) and are also reflected in Dieng et al. (2017), who find that an already detectable acceleration in GMSL (as opposed to local) is driven largely by Greenland mass loss. Nevertheless, several questions remain unanswered: How much real variability exists, and will exist, in these additional non-ocean sea level components and thus how much would such variability modify the noise part of the signal-to-noise ratio and the emergence of anthropogenic trends.

The estimated ToE is less certain in some areas compared to others, with the regions of low overall ensemble spread having a better estimate than regions of higher ensemble spread. Better ToE estimates are likely in much of the tropical Atlantic, the eastern side of large ocean basins, and possibly in the tropical ocean regions in general, since decadal variability is generally lower in these regions in climate models than mid- and high-latitude regions (see Fig. 1b and also Carson et al. 2015, their Figs. 3b and 4b). Moreover, the coarse resolution of models does not allow capturing of the oceanic mesoscale turbulence, a manifestation of intrinsic ocean fluctuation, i.e., it emerges without any atmospheric interaction (Sérazin et al. 2016; Zanna et al. 2018; Llovel et al. 2018; Llovel et al. 2018). At similar interdecadal timescales, the trend detection results cited here for regions of high intrinsic variability also may not provide accurate estimates of time of emergence. These regions happen to also coincide with the regions of larger ensemble spread, so the same regions listed above probably have better ToE estimates relative to this unmeasured internal variability as well, compared to the mid- and high-latitude and western boundary current regions.

3.2 Trends in Historical Data and Model Simulations

As outlined in the previous section, detection of an anthropogenically forced local trend can only be expected by the mid-twenty-first century due to the low signal-to-noise ratio on regional scales. In order to compare the ability of model simulations to accurately capture trends, and to explore the issues surrounding trend estimation in observed data, we discuss the results of different studies on the trend estimates over historical periods from observed data and model simulations. Richter et al. (2017b) showed that extensive spatial smoothing is necessary to detect a forced signal in steric and dynamic sea level change on regional scales within historical observations, depending on the time period. On global scales, various studies found an anthropogenically forced signal in mean thermosteric sea level change (Marcos and Amores 2014; Slangen et al. 2014b), in the glacier mass balance contribution (Marzeion et al. 2014) and in global sea level rise (Dangendorf et al. 2015; Slangen et al. 2016). These studies distinguish between internal and forced signals by comparing unforced control simulations to simulations with selected forcings (Marcos and Amores 2014; Slangen et al. 2014b, 2016; Marzeion et al. 2014), or by using statistical methods (Becker et al. 2014; Dangendorf et al. 2015) to compare the results of either approach with observations to detect an externally forced signal.

There are some difficulties attached to comparing model simulations of historical sea level changes to the available historical observations. Satellite altimetry covers much of the ocean for the time after 1993, but this is still a short time frame for low-frequency sea level variability on some regional scales (e.g., Bilbao et al. 2015). Tide gauges can have much longer time series, and while there are sometimes issues of gaps and instrument changes, the largest source of errors comes from unmeasured vertical land motion (Douglas 1991; Wöppelmann and Marcos 2016). The papers in this section generally attempt to account for vertical land motion by making corrections to the tide gauge data; this information can be found in the individual citations. Other sources of sea level rise not normally accounted for in climate models, such as land ice mass loss, are measured by tide gauges and altimetry, and studies cited below draw some conclusions regarding how well model data compare with observations when including or not including offline estimates of land ice contributions.

Comparisons between satellite altimetry and model simulations for the altimetry era have been examined to explore the quality of model hindcasts and projections in producing realistic trends (Gregory et al. 2001; Meyssignac et al. 2012, 2017; Landerer et al. 2014; Bilbao et al. 2015; Monselesan et al. 2015; Richter et al. 2017a; Watson 2018). These studies have shown that CMIP5 models tend to simulate well recent global mean sea level rise, i.e., trends, particularly during the satellite altimetry era. However, before the satellite era, the discrepancies are larger, due to not including other components of local sea level change such as changes in land ice and water impoundment (Meyssignac et al. 2017). While Meyssignac et al. (2017) found that model trends over the same 20-year period generally have weaker trends than in satellite altimetry data, they note that other contributing factors to sterodynamic sea level, such as land ice, are not present in CMIP5 coupled climate models. When taking the land ice contribution into account (Meyssignac et al. 2017; Richter et al. 2017a), observed trends in the northern North Atlantic over 1993–2012 are reproduced to varying degrees, depending on the climate model.

Marcos and Amores (2014) provided an analysis based on empirical orthogonal function (EOF; Preisendorfer 1988) that maximizes the signal-to-noise ratio, estimated the forced sea level response in historical CMIP5 simulations and found that natural variability enhanced the basin-mean anthropogenic thermosteric sea level rise in the North Atlantic over the period 1970–2005 while the opposite was true in the Western Pacific Ocean (Marcos and Amores 2014, their Fig. 2). A more widely used approach for detecting an anthropogenically forced trend in sterodynamic sea level is through calculation of a multi-model

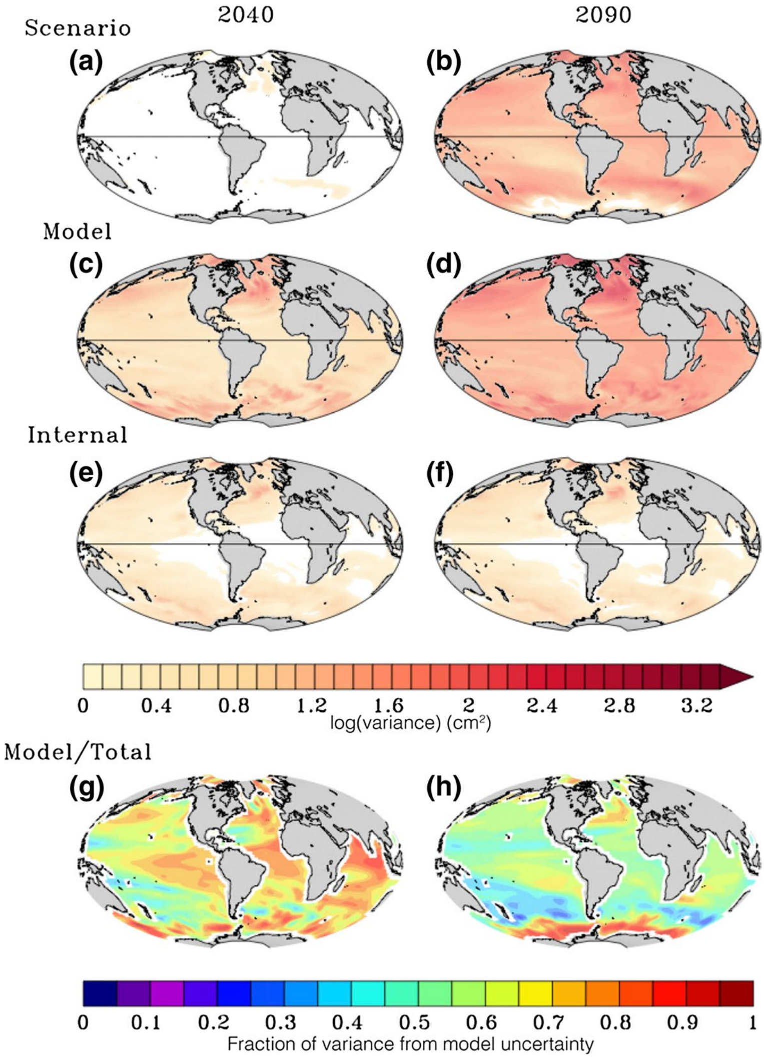

Fig. 2 From Little et al. (2015), Fig. 4. Sterodynamic sea level change variance in cm^2 by 2040 (left column) and by 2090 (right column) for the following uncertainty components: **a**, **b** scenario uncertainty (RCPs 2.6, 4.5, 6.0, 8.5); **c**, **d** intermodel uncertainty (16 models, with various numbers of realizations); **e**, **f** internal climate variability uncertainty; and **g**, **h** fractional variance of the intermodel uncertainty (from **c**, **d**) divided by the total uncertainty

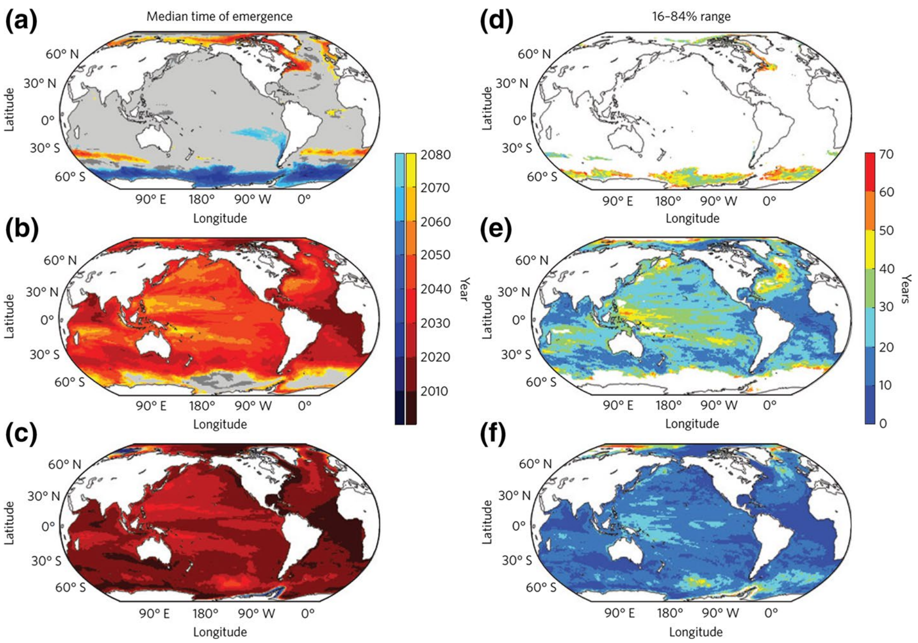

Fig. 3 From Lyu et al. (2014), Fig. 2. Time of emergence (multi-model ensemble median) of regional sea level change signal under RCP8.5 relative to 1986–2005, by year, for: **a** dynamic sea level, **b** dynamic plus global mean thermosteric sea level and **c** all contributing components to regional sea level (total sea level). Gray color means that no signal has yet emerged by 2080 or no agreement among models. The 16–84% uncertainty ranges for the same sea level change projection estimates are shown in the right panels. The ranges are only shown where at least 84% of the models in the ensemble exhibit signal emergence before 2080

ensemble mean over the period of interest. Given a model ensemble large enough (e.g., 16 models in Little et al. (2015), see Sect. 2), this approach assumes that internal variability is strongly reduced by averaging when computing an ensemble mean, which then largely displays the anthropogenic response, in addition to other external natural forcings, like volcanic aerosol and solar forcings. This pattern, together with modeled internal variability (from control simulations), is compared to the observed pattern of sterodynamic sea level change. Using this approach, Richter et al. (2017a) concluded that the observed dynamic sea level rise over the period 1993–2012 in the North Atlantic subpolar gyre is consistent with internal variability and therefore not anthropogenically forced. Similarly, Meyssignac et al. (2012) found the unusual sea level rise pattern in the tropical Pacific over the period 1993–2009 to be not anthropogenically forced. However, these conclusions strongly depend on the model's ability to reproduce and simulate the geographical pattern and strength of naturally forced variability realistically. For the tropical Pacific Ocean, this has been challenged. While the modeled spatiotemporal patterns are consistent with observations, their magnitudes may be underestimated (Bilbao et al. 2015).

In the Indian Ocean, Han et al. (2018) analyzed sea level trends using a set of reanalysis products for winds and sea level, as well as large ensembles from climate models. From 1958 to 2005, sea level rose in the eastern Indian Ocean (after removing the global mean sea level, and including coastal regions) but fell in the western basin, with the largest drop

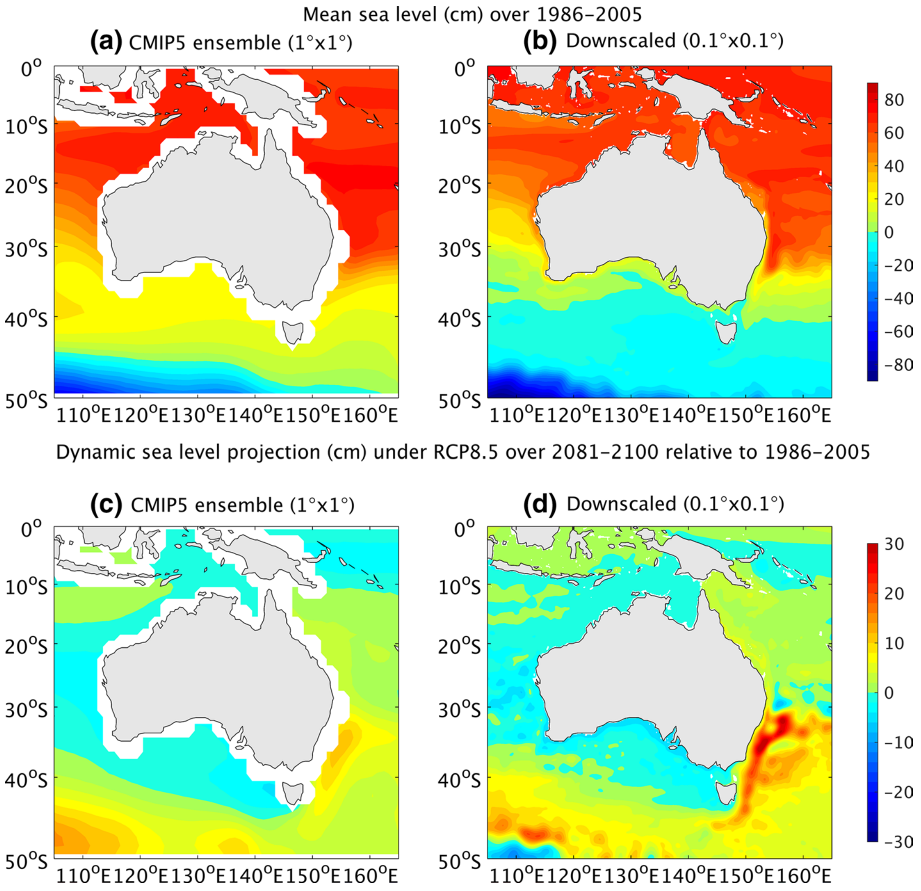

Fig. 4 Mean fields (cm; average over 1986–2005) and future change projections under RCP8.5 (cm; difference between averages of 1986–2005 and 2080–2099) for dynamic sea level around Australia, based on CMIP5 multi-model mean (left panels) and 1/10° ocean model dynamical downscaling (right panels). Redrawn from Zhang et al. (2016, 2017)

Table 1 Sea level rise by 2050 in the RCP4.5 scenario

References	% of total coastline	% of coastline between ± 58°
Lyu et al. (2014)	80.3	82.6
Richter and Marzeion (2014)	91.4	99.2
Carson et al. (2015)	97.2	100

Percentage of the coastline where sea level trends statistically emerge from the background natural sea level variability by 2050, based on estimates from multi-model CMIP5 climate model control runs (only constant climate forcings are applied). The first column is for the whole global coastline, as a percentage of coastline length, the second column is for the coastline between 58°S and 58°N, to mask out Antarctica and high-latitude Northern Hemisphere regions of lower population density. These regions contain more model uncertainty and natural, low-frequency variability. Data are provided by the authors as used in the listed references occurring over the Seychelles. Using the twentieth-century simulations from the 100-member ensemble of the Max-Planck Institute of Meteorology model and 40-member ensemble of the National Center for Atmospheric Research (NCAR) Community Earth System Model version 1 (CESM1), Han et al. (2018) found that the observed maximum sea level fall over the Seychelles results largely from natural internal variability, with anthropogenic forcing contributing 19% ± 2.4%. For decadal sea level anomalies, the uncertainties of external forcing are comparable to the signals, with a standard deviation ratio of externally forced/observed decadal sea level anomalies being 18% ± 17% over Seychelles and 17% ± 11% near the Indonesian Throughflow regions. Even for the ensemble means of large-ensemble members, externally forced sea level trend patterns in that region differ largely (even being opposite in sign in some areas) between the two models, which suggests a strong model dependence of external forcing effects on sterodynamic sea level trends.

It should also be noted that trend detection in historical data using models suffers the same kind of intermodel uncertainty that could plague trend detection in future projections (discussed at the end of the previous section). Thus, while regions of large interdecadal variability like the North Pacific or the high-latitude North Atlantic (Zanna et al. 2019) would be additionally difficult regions for trend detection (due to larger internal variability and intermodel spread there), "quieter" regions like southern parts of the Atlantic and Pacific basins might yield a detectable sea level signal sooner. Marcos et al. (2017) also provide a review regarding the estimation and separation of internal variability and anthropogenically forced signals in sea level.

4 Connecting Open-Ocean Projections to Coastal Regions

The state-of-the-art global climate models provide important information about how the large-scale ocean circulation and sterodynamic sea level could change in the future. Since the local relative sea level change at the coast is what the coastal communities essentially care about, it is important to link large-scale ocean changes to coastal sea level and identify the contributing to similarities or differences between coastal and open-ocean changes, and how drivers of this relationship might change in the future. In some specific regions, there have been well-established dynamical connections between changes in coastal sea level and large-scale ocean circulation. In other many regions, decoupling between shallow and deep water sea level variations, observed by satellite altimetry, is evident on timescales shorter than several months (Hughes and Williams 2010). Rates of sea level change at the coast can differ significantly from the open ocean nearby for several reasons, particularly through (1) coastal topography acting as barriers to the propagation of open-ocean signals, (2) open-ocean changes just being local and (3) local processes such as the coastal winds, currents, atmospheric pressures and river runoff playing important roles (White et al. 2005; Deng et al. 2011; Vinogradov and Ponte 2011; Bingham and Hughes 2012; Williams and Hughes 2013; see also Durand et al. 2019 in this volume).

The connections between large-scale ocean circulation and coastal sea level in the western boundary regions have been explored in a number of studies. Particularly along the eastern coast of North America, coastal sea level variations and changes across a range of timescales are significantly modulated by ocean dynamics (Ezer et al. 2013; Yin and Goddard 2013; Fraser et al. 2019). For example, a robust feature from climate model projections is a rapid dynamical sea level rising near the northeastern coast of North America associated with a weakening of meridional overturning circulation in the Atlantic (Yin et al. 2009). McCarthy et al. (2015) proposed that an index defined as coastal sea level differences between north and south of Cape Hatteras is a good indicator for ocean circulation changes, which drive phase changes in the Atlantic decadal climate variability through ocean heat transport. Calafat et al. (2018) showed that changes in the amplitude of sea level annual cycle along the Gulf of Mexico and the United States Southeast coasts are primarily induced by incident Rossby waves from the open ocean that generate boundary waves.

The open-ocean signals usually do not exert impacts on the coastal sea level in a direct and uniform way. Sasaki et al. (2014) identified that westward propagating Rossby waves along the Kuroshio Extension have different impacts on coastal sea level around Japan. While the resulting sea level changes are largest along the southeastern coast due to meridional shifts of the Kuroshio Path, the excited coastal waves propagate southwestward and also induce a large signal in the western coast of Japan but leave the northeastern coast as the shadow zone. Recently Minobe et al. (2017) proposed a theory based on Johnson and Marshall (2002) to explain western boundary sea level changes by considering both incoming Rossby waves from ocean interior, which bring mass input to the western boundary layer and mass redistribution along the western boundary in the form of equatorward wave propagation. Their theoretical framework can explain the main features of western boundary dynamical sea level future changes from climate model projections, e.g., the lower sea level near the coast of Japan and Argentina relative to the nearby open ocean, and coastal sea level rise of similar magnitude to the open ocean along the US East Coast (see Fig. 1a). Including a continental slope yields a similar situation, but the magnitude of the impact of open-ocean sea level rise on the coasts is sensitive to model resolution and friction (Wise et al. 2018), indicating the importance of topography on coastal sea level anomalies. Long continental slopes at high latitudes such as along the Mid-Atlantic Bight also strongly suppress the influence of open-ocean mesoscale eddies (Hughes et al. 2018).

In light of the close relations of coastal sea level to large-scale ocean circulation and nearby boundary currents, the uncertainties for coastal sea level projection arise from not only the poor representation of coastal processes in current coarse-resolution climate models (generally ~ 1° for the ocean model component) but also from model deficiencies and biases in simulating ocean dynamics in the ocean interior and surrounding regions. To reduce these uncertainties and to provide sea level information closer to the coastline than climate models can, there have been some efforts using high-resolution ocean models to downscale ocean changes from climate model projections, either regionally or globally. For example, Liu et al. (2016) used a regional ocean model with an eddy-permitting horizontal resolution of 0.25° to downscale future projections from three CMIP5 models in the western North Pacific region. Recently, a near-global eddy-resolving (0.1°) ocean model was used to downscale both historical changes and future projections of the ocean state throughout 1979–2101, driven by atmospheric forcing fields from reanalysis and the ensemble average of 17 CMIP5 models (Zhang et al. 2016, 2017). It has been shown that ocean models with refined spatial resolution better represent the strong western boundary currents and associated large sea level gradient (Fig. 4a, b). Penduff et al. (2010) have also shown that increasing the ocean model horizontal resolution would improve the sea level simulations in terms of mean sea level and also the magnitudes and spatial patterns of interannual sea level anomalies. For the future projections, dynamical downscaling models show a narrow band of large sea level changes off the coast as a result of future changes in western boundary currents, e.g., up to 30 cm around the East Australian Current (Zhang et al. 2017), which are rather smoother, weaker (~ 10 cm) and further offshore located in CMIP5 models (Fig. 4c, d). Differences between high-resolution and low-resolution projections are relatively smaller along the coastline than offshore. Zhang et al. (2017) reported that the downscaled dynamic sea level changes around the Australian coastline are generally larger by 1–3 cm than for the CMIP5 ensemble. Given the substantial computational resources required, these dynamical downscaling products represent valuable resources to assess the uncertainties of coastal sea level projection from coarse-resolution models. Also, further downscaling toward the coast with a nested coastal model would be useful to better resolve fine-scale details in local topography and land–sea interfaces as well as to consider the interaction with tides, waves, storm surges and other dynamical processes near the coast.

Vertical land motions, either geological or due to human-induced activities, add additional uncertainties for coastal sea level projections that can be comparable or even larger than climate-induced sea level change over the same period (e.g., Wöppelmann and Marcos 2016). For example, Ballu et al. (2011) estimated that from 1997 to 2009 the relative sea level rise rate (total sea level rise) around the Torres Islands in the Southwest Pacific was 12 mm/year, of which 9.4 mm/year was due to island subsidence. Raucoules et al. (2013) reported that the difference between altimetry data and tide gauge record near Manila city implies a land subsidence of ~ 10 mm/year over the altimetry era (since 1993) mainly due to intensive groundwater pumping. In addition to these smaller-scale uncertainties, there are also large-scale uncertainties in sterodynamic sea level rise due to uncertainty in projections of land ice melt and glacial isostatic adjustment (e.g., Church et al. 2013; Slangen et al. 2014a). All these sources of uncertainties added together affect our capability to deliver reliable sea level projections near the coast, which would be essential for coastal community adaptation and mitigation planning.

5 Concluding Remarks

Intermodel uncertainty is the dominant climate model uncertainty in ensemble projections of multidecadal to centennial sterodynamic sea level change, for the ocean-only components of dynamic sea level plus global mean thermosteric sea level (Little et al. 2015). Scenario uncertainty is large, but it is due to a range of forcings applied to models, and not a function of the models themselves. Other contributions to sea level projections are calculated "offline," i.e., not within the models themselves (Church et al. 2013). Intermodel comparison studies (e.g., Gregory et al. 2016) and model data comparisons (with tide gauges and altimetry products) provide a better understanding of the origins of climate model differences and inform improvements for the next generation of climate models. Such improvement will yield more confidence in sterodynamic sea level projections. But, with changes in model resolution (in addition to other possible changes to climate models) in the upcoming Coupled Model Intercomparison Project, phase 6 (CMIP6) models, there may be new difficulties to overcome, such as uncertainty due to intrinsic ocean variability (Sérazin et al. 2016), and interaction with better resolved coastal shelves (Durand et al. 2019).

The time of emergence for anthropogenic signals in sea level can be estimated by applying internal model variability to trend estimates of sea level projections. Detection of sea level trends on a global scale is easier than at regional scales due to its higher signal-to-noise ratio. There have been mixed and disputed results in detecting regional forced sea level trends (secular and not part of the background variability), although detection of the global trend is virtually certain, along with a likely acceleration (e.g., Church et al. 2013;

Cazenave et al. 2018). At local scales, only some long-term individual tide gauges are available, but they are affected by, among others, decadal variability and vertical land motion contaminating the signal, making them trickier to use. In addition, continuous worldwide coverage of sterodynamic sea level has only been possible since the advent of continuous satellite altimetry in late 1992. Even though this altimetry record is now 26 years long, there are still not enough data to corroborate some of the longer multidecadal sea level signals suspected in certain regions, nor to unambiguously resolve the anthropogenic signal-to-internal variability noise ratio completely, although progress continues to be made (Fasullo and Nerem 2018; Hamlington et al. 2019). Maintaining the tide gauge network and calibrating the costal altimetry product would be also essential to provide high-quality coastal sea level observations (Cipollini et al. 2017).

On the modeling side, reliable detection of trends moving forward depends on how well models produce natural (i.e., non-anthropogenic) variability that matches real-world sea level variability, on long timescales. For the previous generation of models, as presented in the AR5 report (Church et al. 2013), the results converge to the vast majority of ocean coastlines experiencing statistically significant anthropogenic sea level rise by mid-twenty-first century, not including contributions from land ice and water impoundment (Lyu et al. 2014; Richter and Marzeion 2014; Carson et al. 2015). These trends are expected to be detectable sooner and be significantly larger when these components are included (Lyu et al. 2014). It is also useful to note that the intermodel uncertainty from climate model ensembles is not generally the largest local uncertainty for coastal sea level projections, when compared to sea level components not included in climate models, such as land ice mass loss, GIA, and groundwater storage changes (Carson et al. 2016). In addition, these uncertainties have interdependencies, and Le Bars (2018) uses models to explore the correlations and dependencies between sea level components in projections.

The dynamics of how large-scale changes in ocean dynamics in a warming scenario will impact coastal regions are still being studied, with substantial progress having been made over the last 10 years. However, further work to understand links between open-ocean sea level rise and coastal risks is required. Improved theoretical frameworks along with sustained observations from the coast to the open-ocean and higher-resolution modeling will help to improve our understanding of regional and coastal sea level changes, to better characterize and reduce sources of uncertainty and, ultimately, to better inform policy and decision making.

Acknowledgements Thanks to the ISSI for hosting the Workshop on Coastal Sea Level from which this paper was conceived and to Xuebin Zhang for his help in producing Fig. 4. And thanks to Chris Little for his comments on an early version of the manuscript. MC was supported in part through the DFG funded CliSAP Excellence Cluster of the University of Hamburg, through the BMBF (Federal Ministry of Education and Science) Project RACE and through a DFG-funded special research effort on regional sea level (SPP1889). KR is funded by the Austrian Science Fund (FP302560). KL is funded by CSHOR, a joint research Centre for Southern Hemisphere Oceans Research between QNLM and CSIRO. CMD is supported by Australian Research Council FT130101532 and DP160103130. LZ is funded by the Natural Environment Research Council (NE/R000727/1 and NE/P019218/1) and thanks to Princeton AOS and GFDL visiting faculty program for additional support. MB is supported by the French National Centre for Space Studies (CNES) TOSCA program.

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