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Special Collection:
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Key Points:

- There exist diverse sea level projection requirements in coastal areas beyond current state of the art regional projections
- Ocean dynamics across scales is crucial in linking open ocean to shelf sea to coastal sea level variability and change
- Steps for improvement of sea level projections along the global coastline are proposed, focusing on seasonal-decadal variability

Supporting Information:

Supporting Information may be found in the online version of this article.

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Challenges, Advances and Opportunities in Regional Sea Level Projections: The Role of Ocean-Shelf Dynamics

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Abstract Future sea level rise and changes in extreme weather will increase the frequency of flooding and intensify the risks for the millions of people living in low-lying coastal areas. Concerns about coastal adaptation have been broadened due to societal awareness of the threat from rising seas, leading to a large set of potential adaptation users with diverse needs for adequate sea level projections in coastal areas beyond the current state of the art regional projections. In this paper, we provide an overview of the potential steps for improvement of regional sea level projections along the global coastline, with specific focus on the contribution from ocean dynamics to seasonal-decadal variability of coastal sea level, and its implications for changes in frequency and magnitude of extreme sea levels. We discuss the key gaps in our knowledge and predictive capability of these dynamics as they relate to sea level variability on seasonal to decadal timescales, and conclude by suggesting ways in which these knowledge gaps could be addressed.

Plain Language Summary In the next few decades sea level rise and changes in extreme weather will increase the frequency of flooding and intensify the risks of inundation for the millions of people living in low-lying coastal areas. The sustainable future of coastal communities in small settlements and populous megacities alike will depend on the efficacy of new coastal defense infrastructure and adequate decisions about adaptation options. The planning for these management solutions is fundamentally based on local sea level projections. Providing sea level projections at the coast is a complex task, because sea level in coastal areas is impacted by numerous local drivers (e.g., wind, bathymetry, and limited connection with the open ocean), changing water motion in time and space. We highlight several potential research avenues to improve simulations of sea level changes in coastal areas that are urgently required for improved localized sea level projections for effective coastal management in a changing climate.

1. Introduction

In the next few decades sea level rise and changes in extreme weather will increase the frequency of flooding and intensify the risks for the millions of people living in low-lying coastal areas (IPCC, 2022). By 2100 all global coastlines will experience the present-day 1 in 100-year extreme sea level event at least once a year and the global-mean sea level will rise by up to 2 m (IPCC, 2022; Jevrejeva et al., 2023). The effects of sea level rise are not just about the impact of flooding, loss of marshes, wetlands and erosion of the beaches, but also coastal aquifers are vulnerable to salt-water intrusion, rendering them unfit for drinking water or agriculture and leading to population migration and huge economic damage (IPCC, 2022). The sustainable future of coastal communities in small settlements and populous megacities alike will depend on appropriate coastal defense planning and adequate decision making about adaptation options, based on local sea level projections (IPCC, 2022; Kopp et al., 2019). Approaches for regional sea level projections have been evolving since 2013 (Slangen et al., 2023), providing valuable information for impact studies and vulnerability assessment along the global coastlines (IPCC, 2022; Brown et al., 2021). There are efforts to advance current regional sea level projections, used in Intergovernmental Panel on Climate Change (IPCC) assessments, by improving the representation of future changes in global-mean sea level and their manifestation in coastal areas, by improved representation of physical processes in shelf seas and along the coastline (Jevrejeva et al., 2019; Ponte et al., 2019).

Historical observations of sea level show substantial regional variations from the global mean (Ponte et al., 2019). Near the coast, variability in sea level is locally driven by winds over the shelf, atmospheric pressure, river runoff, shelf-sea circulation and the tides that are in addition to the large-scale oceanic drivers (Holt et al., 2017; Jevrejeva et al., 2019; Ponte et al., 2019). How these “coastal ocean” phenomena modulate the large-scale changes in future

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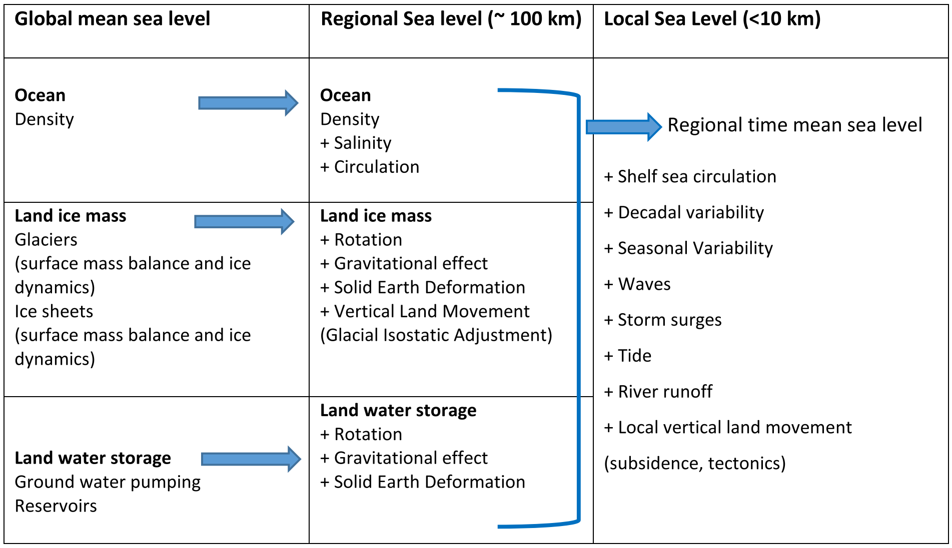

Figure 1. Schematic representation of the main processes contributing to sea level change at a wide range of spatial and temporal scales. Column 1 represents the main processes considered for global mean sea level. Column 2 describes a common approach for regional sea level projections, with processes simulated by Coupled Model Intercomparison Project Phase (CMIP) style models for individual contributions to sea level rise. Column 3 is a schematic representation of the physical mechanisms currently lacking in CMIP style simulations and potentially leading to the improvement of the local sea level projections for end users.

sea level projections along the coast is currently not well understood. Increasingly, there is a demand for sea level projections over shorter timescales (seasonal-decadal) and spatial scales from a few kms or even <km near the coast and for these to be re-evaluated regularly as models develop and new understanding emerges.

There is a complex challenge to reconcile the modeling gap between IPCC-class global climate models and regional ocean-only models that are required to deliver fine-scale future sea level projections tailored for needs of local users. In recent years global climate models have made substantial improvements, for example, in resolution and large scale transport processes, including ocean circulation and it's heat and freshwater transport (C. Jin et al., 2023). However, the challenges of accurately capturing the scales and processes needed to represent coastal sea level variability are immense and the current generation of global climate models still fall short of meeting this.

The aim of this paper is to provide an overview of the potential steps for improvement of regional sea level projections along the global coastline, with specific focus on contributions from ocean dynamics and shelf sea physics to the seasonal-decadal variability of coastal sea level and potential implications for changes in frequency and magnitude of extreme sea levels. We focus on changes in dynamic sea levels considering that, on seasonal-decadal time scales, coastal sea level variability is driven by wind, atmospheric pressure, ocean-shelf mass transport and terrestrial freshwater fluxes. On the longer time scales future sea level rise will be determined primarily by the contribution from mass loss from ice sheets in Greenland and Antarctica, and thermal expansion of the ocean, both of which have been studied intensively over past few decades (Fox-Kemper et al., 2021). For the long-term regional sea level projections, changes in the geoid and the earth's rotation, deformation effects due to contemporary mass redistribution and Glacial Isostatic Adjustment (GIA) will be the main contributors, alongside ocean dynamics, and thermal expansion (Fox-Kemper et al., 2021; Figure 1). However, regional patterns in sea level rise are shaped essentially by the ocean dynamics, which drive coastal sea level variability over the seasonal-to-decadal timescales. Recently published work (C. Jin et al., 2023) reveals that CMIP6 high-resolution models simulate better spatial patterns and magnitudes of dynamic sea level (DSL) climatology, seasonal cycle, and interannual variability compared to the coarser resolution CMIP6 Atmosphere-Ocean General Circulation Models (AOGCMs) and Earth System Models (ESMs). The C. Jin et al. (2023) study highlights that to advance simulations of DSL variability in different regions requires not only an improvement in resolution but also an accurate representation of various complex physical processes.

Our objective is to explore the role of shelf-sea and ocean dynamics in coastal sea level variability over seasonal to decadal time scales, its link to heat and mass transport and the mechanisms of interaction between open-ocean and shallow coastal areas. We also describe potentially innovative modeling approaches to improve regional sea level projections and their impact on the magnitude and frequency of extreme sea levels along the global coastline. Extreme sea levels, associated with storm surges and waves, are mainly triggered by meteorological conditions (e.g., tropical/extratropical cyclones). The commonly used statistical approach to derive projections of extreme sea levels from observational tide gauge data (e.g., Fox-Kemper et al., 2021; Figure 9.32 in Fox-Kemper et al., 2021) is grounded on the assumption that the distribution of extreme sea levels associated with meteorological conditions do not change significantly into the future. It is thus assumed that the tidal, wave and storm surge regime does not change significantly in a future climate. There is emerging evidence that future extremes associated with atmospheric forcing (e.g., waves, storm surges) are changing compared to those previously observed (e.g., Jevrejeva et al., 2023; Muis et al., 2023; Ranasinghe et al., 2021; Vousdoukas, Mentaschi, Voukouvalas, Bianchi, et al., 2018; Vousdoukas, Mentaschi, Voukouvalas, Verlaan, et al., 2018). Recent IPCC reports (Fox-Kemper et al., 2021; IPCC, 2018) and some earlier studies (Vitousek et al., 2017; Vousdoukas, Mentaschi, Voukouvalas, Bianchi, et al., 2018; Vousdoukas, Mentaschi, Voukouvalas, Verlaan, et al., 2018) and post IPCC publications (Jevrejeva et al., 2023; Tebaldi et al., 2021) suggest that regional sea level change will be one of the main drivers for a substantial increase in the frequency of extreme sea levels, with extreme sea levels that used to occur once per century in the recent past, occurring about 20–30 times more frequently by 2050.

Regional sea level projections are typically based on outputs from global climate models, with seasonal to decadal sea level changes being averaged out and/or not adequately represented in sea level projection analysis, and therefore not taken into account in impact studies (Brown et al., 2021; Jevrejeva et al., 2018). Since sea level variations affect the probability of extreme sea level events, including seasonal variability in regional sea level projections, for example, as demonstrated for European coasts by Fernández-Montblanc et al. (2020), will have a substantial effect on risk and impact assessments (Kirezci et al., 2020; Tebaldi et al., 2021; Vousdoukas, Mentaschi, Voukouvalas, Bianchi, et al., 2018).

We highlight the need for improvement in the representation of the driving mechanisms that cause regional coastal sea level variability on different spatiotemporal scales in the models currently used for regional sea level projections. This will lead to better understanding, quantification and prediction of potential coastal flood hazards.

In this paper we present a short overview of the current methodology for the regional sea level projections based on process-based models (IPCC sea level projections) and examples of recent development in coastal sea level projections, tailored to provide more detailed local sea level information, meeting the growing demands from policy makers, coastal engineers and coastal communities (Section 2). In Section 3 we overview and discuss the current knowledge and longstanding questions about the mechanisms of seasonal to decadal sea level variability near the coast that are not included in current Coupled Model Intercomparison Project Phase (CMIP) projections and might be considered to further improve sea level projections near the coast. In Sections 4 and 5, we briefly discuss the roles of large scale ocean circulation, focusing mainly on how the open ocean to shelf sea transition influences sea level variability near the coast. In Section 6 we focus on modeling dynamical changes in extremes. Section 7 explores ways in which new or emerging developments in numerical modeling could be harnessed to improve regional sea level projections. We conclude by summarizing key gaps in our knowledge and predictive capabilities related to sea level variability on seasonal to decadal timescales near the coast and suggest potential ways in which these gaps could be resolved.

2. Background and Motivation

By the end of the twenty-first century projected coastal flood damage cost for global sea level rise of 1 and 2 m ranges from US $14 trillion per year to US $27 trillion per year, with some counties facing up to 30% of their annual Gross Domestic Product (GDP) at risk due to coastal flood damage (Brown et al., 2021; Jevrejeva et al., 2018). Concerns about coastal adaptation have broadened with time as societal awareness of the threat from rising sea level is growing. Today, there is a large set of potential adaptation users with diverse needs (Hinkel et al., 2019; IPCC, 2022; Le Cozannet et al., 2017; Simm et al., 2021). Some adaptation planners consider time scales far into the future due to asset life cycles of 100 years or more (e.g., water and wastewater systems) or for high impact events (such as London's flood defenses or for coastal nuclear power stations, where safety is paramount (Ranger et al., 2013; Wilby et al., 2011)). However, there are many other adaptation decisions that are shorter term and more easily adjusted over time, such as immediate beach sand nourishment requirements (Hanson et al., 2002), which are updated on a 10–20-year cycle and hence might use sea level and erosion observations rather than projections. Banks and insurance companies are in the process of developing policies to estimate flooding risk from extreme storms and sea level rise on residential housing, which requires scenarios tailored to shorter-term decision making, typically ≤30 years, matching the typical domestic real estate mortgage lifetime (Lawrence et al., 2021). For specific port infrastructure investments (e.g., crane systems and other one-generation assets) a time horizon of around 30 years or less (Simm et al., 2021) is considered for sea level changes. To make optimal decisions on future coastal protection and adaptation measures there is an urgent need for a range of sea level projections that are more customized than the current IPCC reports.

The IPCC approach for regional sea level projections was introduced in the IPCC AR5 (Church et al., 2013; Kopp et al., 2019). According to the IPCC, regional sea level projections are defined at a scale of approximately 100-km resolution; the typical ocean horizontal grid scale of the Coupled Model Intercomparison Project Phase 3–6 (CMIP) experiments (e.g., https://www.wcrp-climate.org/wgcm-cmip). These regional projections are usually at decadal intervals and focused on timescales longer than 100 years. Regional sea level changes require an integrative view of the changes in the main components of sea level rise on a wide range of spatial and temporal scales (Figure 1, Church et al., 2013). The conventional approach for future regional sea level projections (e.g., the IPCC approach) is to simulate the main components of sea level rise under specific emission scenarios and combine them (Equation 1) and their uncertainties (Church et al., 2013):

$$\mathrm{RSL} = F(T) + F(G) + F(\mathrm{Gr}) + F(A) + F(\mathrm{LW}) + F(\mathrm{GIA}) \quad (1)$$

where the RSL—regional sea level, $F(T)$—patterns (or "fingerprints") of sterodynamic sea level, which is the sum of ocean Dynamic Sea Level (DSL) change (including the Inverse Barometer [IB] correction) and global mean thermosteric sea level rise; $F(G)$—the fingerprint associated with ice loss from glaciers (surface mass balance), $F(\mathrm{Gr})$—the fingerprint associated with ice loss from Greenland (surface mass balance and ice dynamics), $F(A)$—the fingerprint associated with ice loss from Antarctica ice sheet (surface mass balance and ice dynamics), $F(\mathrm{LW})$—the fingerprint associated with contribution from land water, including water storage in artificial reservoirs and ground water mining. Ice mass loss from the land to the ocean and redistribution of mass perturbs Earth's gravitational field, deforms Earth's crust, and changes the orientation and rate of Earth's rotation (Mitrovica et al., 2001), also leading to regional sea level fingerprints. In the IPCC approach for projections, focused on the long-term (e.g., end of the twenty-first century) sea level rise, changes in the geoid, earth's rotation, deformation effects due to contemporary mass redistribution and GIA are the main contributors, in addition to ocean dynamics, and thermal expansion (Figure 1, column 2). The $F(\mathrm{GIA})$ component is added to the regional sea level projections to account for the vertical land movement due to GIA, which is a non-climate related component. Each sea level component in Equation 1 is simulated with particular type of model, for example, AOGCMs and ESMs, are used for fingerprints of thermal expansion of the ocean and dynamical changes in sea surface height. CMIP model based regional sea level projections are simulated with emission scenarios (e.g., O'Neill et al., 2016) and the ocean dynamics are simulated within an interactively coupled atmosphere and ocean; hence the main mechanisms for heat uptake, heat transport, redistribution of heat and mass in the ocean are adequately addressed.

However, the ability of AOGCMs and ESMs to resolve fine-scale processes is limited and there is a lack of representation of the physical mechanisms of ocean dynamics in shallow areas (Holt et al., 2017). There are a limited number of models with higher resolution (∼25 km) from the High Resolution Model Intercomparison Project (HighResMIP) of the CMIP6 (Haarsma et al., 2016), which are currently used for other applications (e.g., Samanta et al., 2021) and potentially could be used for future sea level projections. While kilometer scale global models are emerging (e.g., Uchida et al., 2022 and references therein) and provide highly valuable process-based information, the need for multidecadal simulations and treatment of uncertainty (as discussed in Section 7.3) makes these models not yet practical in the context considered here. To overcome these limitations and refine projections, dynamical downscaling methods are used at local/regional scales by increasing spatial resolution (typically 3–10 km) and including additional processes (column 3 in Figure 1). Dynamical downscaling (for full physics models) has not yet been applied for regional sea level projections along the whole global coastline (although a barotropic global tide-surge model has been developed by Deltares, e.g., Verlaan et al., 2015). However, there are studies in individual regions demonstrating advantages to simulating sea level changes with dynamical downscaling. Differences of up to 15 cm in DSL projections between simulations with GCMs and a regional ocean model (NEMO AMM7) by 2100 for the Northwestern European shelf are discussed in Hermans et al. (2020a, 2020b) and are attributed to better representation of ocean dynamics in coastal areas. Improved simulations of sea level changes using dynamical downscaling with regional ocean models for the Mediterranean Sea (Sannino et al., 2022), for marginal seas in the Northwest Pacific (Kim et al., 2021) and along the Chinese coast (Y. Jin et al., 2021) demonstrate emerging new approaches for sea level projections, starting to address the needs for improved representation of ocean dynamics near the coast.

Dynamical downscaling provides an opportunity to resolve some local changes in tide, waves and storm surges for coastal areas. These processes could then be incorporated into local sea level projections (Chaigneau et al., 2022). However, it is challenging to include large scale ocean processes, for example, self-attraction and loading related to the ocean mass redistribution and large scale ocean circulation, demonstrated in Chaigneau et al. (2022). Representation of several local impacts, for example, from river runoff, could be included using nested models or multiscale models for urban scales (De Dominicis et al., 2020) to address the needs of coastal communities regarding future sea level rise and changes in magnitude and frequency of extreme sea levels. Currently, storm surges, waves and tides are usually simulated individually with specific numerical or statistical models and then combined with projections of future sea level rise (Jevrejeva et al., 2023; Kirezci et al., 2020; Tebaldi et al., 2021; Vousdoukas, Mentaschi, Voukouvalas, Bianchi, et al., 2018; Vousdoukas, Mentaschi, Voukouvalas, Verlaan, et al., 2018). For coastal communities, knowledge about the expected changes in the height and frequency of extreme sea level events is crucial for decision about cost-effective adaptation strategies (Stammer et al., 2019).

In this paper, we focus on the physical mechanisms for sea level variability associated with ocean and shelf sea dynamics highlighted in the third column (Figure 1), with discussion about advancing the understanding of potential future sea level changes for the global coastline, considering that decisions on adaptation and mitigation are also made on a local scale.

3. Current Knowledge and Longstanding Questions About the Mechanisms of Seasonal to Decadal Sea Level Variability Near the Coast

At a local level, sea level rise is superimposed on a background of considerable low-frequency variability on time scales ranging from months to decades. While this variability is, by its nature, transitory, it can still have profound impacts on coastal regions, both by itself and by compounding the damaging effects of long-term sea level rise (Moftakhari et al., 2015; Morris et al., 1990; Theuerkauf et al., 2014). Taking account of sea level variability is, therefore, crucial to the success of coastal adaptation measures. Motivated by this need, substantial efforts in sea level research have been devoted in recent decades to explaining the causes of sea level variability, with special emphasis on coastal areas. Such efforts have shown that both the origin and magnitude of the sea level variability are different in different regions and also that they vary with time scale. In the following, we describe what we know about seasonal to decadal sea level variability and then highlight the key questions that remain unanswered.

At the most basic level, seasonal changes in sea level occur largely as a response, of the ocean-atmosphere system, to seasonal variations in incoming solar radiation. The mechanisms and forcings that intervene in this response vary considerably with location, as do the amplitude and phase of the seasonal cycle (Etcheverry et al., 2015; Qu et al., 2022; Ray et al., 2021; Tsimplis & Woodworth, 1994; Vinogradov & Ponte, 2010). Analyses of tide gauge data show that the amplitude of the sea level annual cycle is smaller than 150 mm along most of the world's coastlines (Tsimplis & Woodworth, 1994), but it can reach values as large as 500 mm or more at sites located near major rivers such as in the Ganges and Irrawaddy Deltas. A more complete picture can be obtained using data from satellite altimetry, which reveals that the amplitude of the sea level annual cycle tends to be larger in coastal areas as well as in regions of the open ocean dominated by major ocean currents such as the Gulf Stream in the Western North Atlantic and the Kuroshio in the Western North Pacific (Figure 2a). The sea level annual cycle explains between 60% and 95% of the variance in detrended monthly sea levels in many coastal regions as well as in large areas of the open ocean (Figure 2b), making it the most energetic signal in such regions.

In many coastal regions, much of the sea level annual cycle can be explained by the expansion and contraction of the water column above the seasonal thermocline due to seasonal changes in surface heat flux (e.g., Calafat et al., 2018), though in some regions the sea-level response to changing wind can also play a role (e.g., Amiruddin et al., 2015). Such steric signals originate mostly in the deep ocean and are communicated to the coast through an

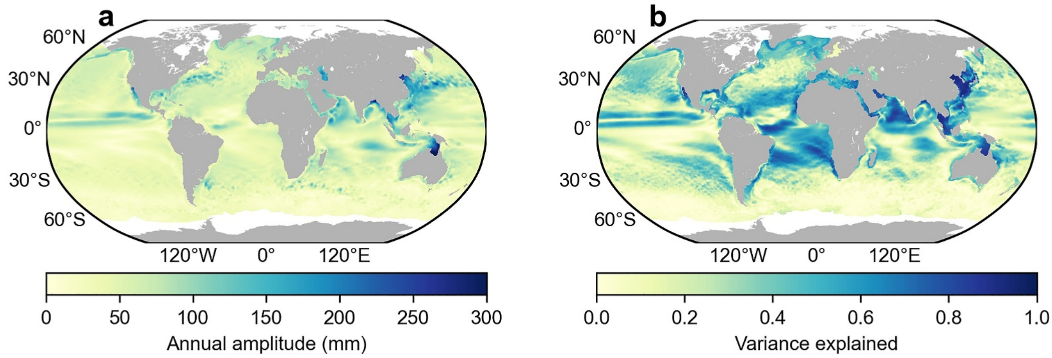

Figure 2. (a) Amplitude of the sea level annual cycle calculated from satellite altimetry data for the period 1993–2020. (b) Percentage of detrended sea level variability explained by the sea level annual cycle for the period 1993–2020. The satellite altimetry data have been obtained from the multi-mission gridded sea surface heights product provided by the Copernicus Marine Environment Monitoring Service (SEALEVEL_GLO_PHY_L4_MY_008_047; CMEMS, 2023).

indirect effect on ocean bottom pressure. Because sea level changes are related to the time-integral of surface heat flux, the annual cycle of sea level typically peaks several weeks later than the heat flux cycle (e.g., Calafat et al., 2018). Observational studies also show that annual amplitudes tend to be larger in coastal regions than in the nearby deep ocean (Vinogradov & Ponte, 2010), primarily due to the contribution from coastal processes such as upwelling (Torres & Tsimplis, 2012), piling up of water through Ekman transport (Amiruddin et al., 2015) or river discharge (Piecuch & Wadehra, 2020), among others. The effect of these coastal processes is often confined to the coast and, along some coastlines such as those of the South China Sea and the Gulf of Thailand, can be the dominant contributor to the sea level annual cycle.

Just like for the seasonal cycle, the mechanisms of intra-annual to decadal sea level variability also involve an intricate interplay between local and remote oceanic, atmospheric and hydrological processes. This means that the magnitude and nature of the sea level variability vary considerably with both location and timescale. The variability tends to be larger at higher latitudes and higher frequencies (Piecuch et al., 2019). The average standard deviation of nonseasonal monthly sea level from tide gauge records globally is about 70 mm (e.g., Piecuch et al., 2019), but there are significant regional differences. The strongest monthly variability is found in the North Sea, the Siberian Seas, and the Baltic Sea, where standard deviations can reach values of 150 mm or more (Dangendorf et al., 2014; Piecuch et al., 2019; Proshutinsky et al., 2004). Some of the smallest standard deviations of monthly sea levels (<40 mm) are found in the Caribbean Sea (Piecuch et al., 2019). While, in general, the magnitude of the variability decreases with decreasing frequency, the spatial structure remains largely unchanged (i.e., the regions showing the strongest and weakest variability are similar).

The mechanisms driving the sea level variability are different for different timescales. On monthly timescales, the barotropic response to variations in wind and atmospheric pressure explain a large fraction (often >50%) of the nonseasonal variance in many regions (Piecuch et al., 2019), especially at high latitudes. At longer timescales, baroclinic processes, both local and remote, play an increasingly important role and the overall picture becomes more complex. A salient feature of the low-frequency coastal sea level variability is its strong anisotropy: the variability is often highly coherent in the alongshore direction but decoupled from changes in the nearby open ocean (Calafat et al., 2012, 2013; Hogarth et al., 2020; Hughes & Meredith, 2006; Hughes et al., 2018). Numerical simulations suggest that this anisotropy is closely tied to coastal trapped waves in such a way that the waves communicate signals along the coast over large distances while also restricting the transmission of oceanic signals toward the coast (Hughes et al., 2019; Huthnance, 2004; Wise et al., 2018, 2020). While the origin of these large-scale coherent coastal signals is still subject to debate, there is broad consensus about some key features. Along eastern boundaries, a combination of remote equatorial forcing by wind-driven Kelvin waves (especially in the Pacific Ocean) and alongshore wind forcing seem to play an important role (Calafat & Chambers, 2013; Calafat et al., 2012, 2013; Chafik et al., 2019; Dangendorf et al., 2014). Fluctuations in alongshore wind and, by implication, in coastal sea level tend to be significantly correlated with modes of natural variability such as the North Atlantic Oscillation (NAO) and the El Niño–Southern Oscillation. On western boundaries, alongshore wind fluctuations also appear to be important (e.g., Woodworth et al., 2014), but such boundaries are also strongly influenced by open-ocean forcing through westward Rossby wave propagation (Calafat et al., 2018; Hong et al., 2000; Minobe et al., 2017; Sasaki et al., 2014). Finally, recent studies have demonstrated that river discharge can also have a significant effect on coastal sea level variability, on both eastern and western boundaries (Piecuch et al., 2018).

Despite remarkable progress in understanding the causes of coastal sea level variability, there are still fundamental questions that remain unanswered. First, there is compelling observational evidence that both the amplitude and phase of the sea level annual cycle can change considerably through time (Amiruddin et al., 2015; Barbosa et al., 2008; Calafat et al., 2018; Feng et al., 2015; Marcos & Tsimplis, 2007; Torres & Tsimplis, 2012; Wahl et al., 2014), but the causes of such changes are varied and complex and, in many regions, remain unclear. Aslo, little is known about whether and how climate change will affect the sea level annual cycle in the future. Answers to these questions are required for effective coastal management because if climate change were to amplify the annual cycle and/or cause its peak to shift toward the storm season this could potentially change the risk of flooding.

Second, while several processes have been identified as likely drivers of nonseasonal variability in coastal sea level, there is still no consensus about the relative importance of each driver and how their role may change in the future under climate change. In particular, the respective roles of shelf-sea dynamics and open-ocean forcing, including the influence of the Atlantic Meridional Overturning Circulation (AMOC), are unclear. Furthermore, in most observational studies, the causes of sea level variability are posited based on correlational analysis rather than demonstrated through physical modeling. There is, therefore, a need for targeted numerical simulations, along the lines of Hermans et al. (2020a, 2020b) and Tinker et al. (2020), in order to shed light on past studies.

Third, while it is widely recognized that coastal sea level variability can be decoupled from open-ocean variability and that coastal trapped waves play an important role in this, we do not understand exactly how, where, and to what extent, this occurs. Numerical simulations suggest that regions where wave decay is weak should show increased alongshore sea level coherence and reduced ocean-to-coast transmission (Huthnance, 2004; Wise et al., 2018). Yet differences in observed sea level variability between the coast and the open ocean are inconclusive in this respect. In our view, the extent to which open-ocean changes affect coastal sea level and how this depends on time-space scales is one of the key puzzles we are currently grappling with in sea level research.

A crucial point to note is that many of the processes that are important for explaining coastal sea level variability act on small spatial scales of the order of the baroclinic Rossby radius of deformation (<20 km at high latitudes), especially in the cross-shelf direction. Such scales are too small to be resolved by most numerical models currently used for the projection of future sea level changes. Hence, addressing the knowledge gaps discussed above requires not only sustained measurements of sea level along the coast and across the continental shelf but also numerical simulations with an adequate spatial resolution.

4. Processes Affecting Open Ocean Dynamic Sea Level Variability and the Boundary Conditions at Continental Shelf-Slope Margins

In this section we focus on open ocean DSL, the height of the sea surface above the geoid, related to circulation and density-driven processes. A key consideration when discussing future DSL change is its spatial distribution. The drivers of coastal sea level variability (anthropogenic, natural forcing and unforced climate variability) act both locally near the coast and also in open ocean regions remote from the coast. This is because changes in sea level in shallow coastal areas are largely caused by addition or removal of mass from the open ocean, as coastal areas are too shallow for local steric effects to explain observed changes (Rietbroek et al., 2016). In other words, climate teleconnections involving the ocean communicate the response to forcing anomalies over large distances and between ocean basins. Therefore, a question most important for the current discussion is how open ocean processes set the sea level and ocean pressure at the boundary between the open ocean and the continental shelf-slope; and by which mechanisms mass from the open ocean is transferred across the continental slopes and into coastal regions, impacting coastal sea levels.

To set the scene, we lay out a kinematic framework, largely agnostic of dynamical processes, to guide our understanding of how these regions connect. Griffies and Greatbatch (2012) derive two such kinematic relationships from first principles, based on the conservation of mass, hydrostatic balance and some other standard assumptions, such as zero mass flux across the seafloor boundary.

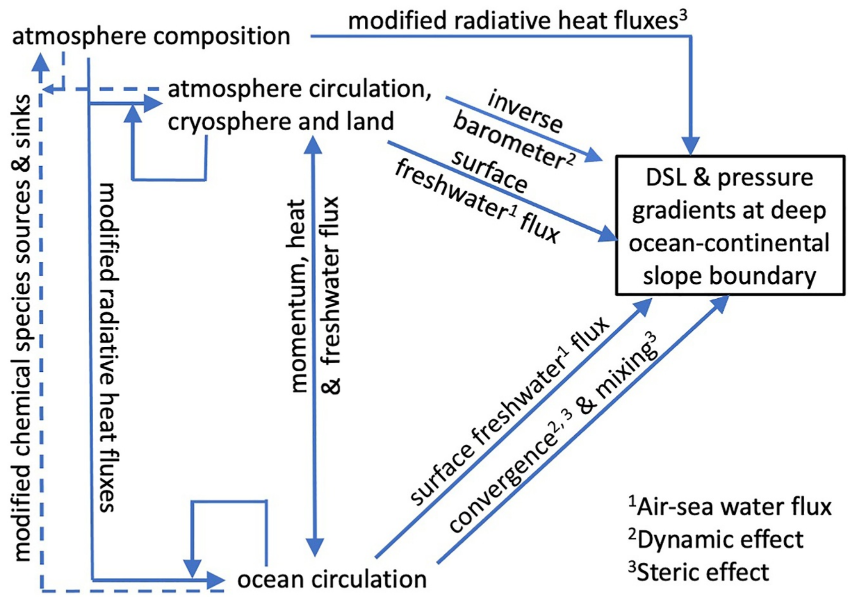

Figure 3. Causal network diagram for variability and secular trends of dynamic sea level (DSL) variability at the deep ocean-continental shelf boundaries.

In the simplest terms, Griffies and Greatbatch (2012) state, "… sea level experiences a positive tendency in those regions where mass locally increases and where the vertically averaged density decreases." This relates to their Equations 12 and 13, which provide two formulations to describe the same phenomenon, originating from the Lagrangian and Eulerian forms of mass conservation, respectively. They associate each of the two formulations with three general physical processes affecting DSL at a given location: (a) Boundary fluxes of water at the sea surface; (b) Dynamic effects; (c) Steric effects. The details of each are quite subtle, and we refer the reader to their paper for more details, but these general processes encompass: (a) mass or volume addition or removal related to precipitation, evaporation, river runoff, ice melt/formation; (b) convergence/divergence of mass or volume due to ocean currents, waves and mixing (including many scales, such as Meridional Overturning Circulation [MOC], gyres, tidal currents, internal waves, surface waves, mesoscale eddies, micro-scale turbulent diffusion, etc.); (c) changes to the local in-situ density contributing to the column-integrated volume, due to various processes such as "buoyancy fluxes at the ocean boundaries, convergence of buoyancy fluxes in the ocean interior, and processes associated with the equilibrium thermodynamics of the ocean as embodied by the equation of state."

One can imagine partitioning the ocean into volumes containing open ocean, continental shelf-slope, shallow shelf and coastal regions. In each region, because the kinematic sea level equations hold for the water column at each latitude-longitude location, we can imagine integrating them laterally and incorporating the effect of exchanges at lateral boundaries, from one region to another. Changes involving the open ocean therefore connect at the outer boundary of the continental shelf-slope via key variables. Conceptually, we can consider how various open ocean processes interact with this boundary (see schematic Figure 3).

The evolution of open ocean DSL change at the boundary with the shelf-slope can be viewed as a multi-stage process summarized as a causal network in Figure 3, where atmospheric composition (greenhouse gases, clouds, and aerosols), atmospheric circulation (e.g., the Jet Streams), cryosphere, land processes and ocean circulation (e.g., the AMOC) can all influence each other to produce a net effect on the DSL.

To summarize the left hand side of Figure 3, the deep ocean boundary condition to the slope and shelf regions, is sensitive to changes in atmosphere circulation/cryosphere/land processes (here viewed as a single climate system component), changes in ocean circulation, and changes in atmospheric composition. The three drivers, however, do not act independently: the composition of the atmosphere (greenhouse gases, aerosols etc.) modifies the radiative forcing which drives the ocean and atmosphere circulations; there are feedbacks between the ocean and atmosphere circulations and the atmospheric composition; and the atmosphere-cryosphere-land component interacts with the ocean via exchange of momentum and buoyancy (heat and freshwater). An additional complication is that all the individual climate system components (atmospheric composition, atmospheric circulation, ocean, cryosphere, land) have internal variability on a variety of timescales.

The right hand side of Figure 3 shows the processes by which the drivers change the deep ocean-slope-shelf boundary condition. Atmospheric composition changes modify the surface radiation balance and directly warm or cool the surface ocean and impact regional DSL by process (3). Changes in atmospheric circulation, and associated changes in sea level pressure, modify regional DSL via the IB effect, process (2). Changes in ocean circulation cause convergence/divergence of mass/volume and/or interior buoyancy fluxes which impact regional DSL via processes (2) and/or (3). Changes in mixing (e.g., associated with changing stratification) also contribute to regional DSL via process (3). Finally exchanges of buoyancy fluxes (heat and freshwater) between the atmosphere-cryosphere-land component and the ocean will impact regional DSL via steric effects, process (3) and freshwater exchange between the two additionally represents a regional addition or subtraction of oceanic mass, process (1). Changes in freshwater exchange (e.g., evaporation) can be initiated by either atmospheric changes (air temperature, windspeed) or oceanic changes (Sea Surface Temperature, SST) or a combination of both.

It should be noted that Figure 3 does not represent a global sea level budget, although the right hand side could be interpreted as a regional budget for any particular location on the deep ocean-slope-shelf boundary. The left hand side visualizes how changes can cascade through a regional climate system and the arrows represent interaction strengths which will vary from region to region.

Secular trends and changes in seasonal to interannual variability of regional DSL associated with anthropogenic forcing are characterized from the CMIP6 multimodel climate projection ensemble in Figure 4 (Table S1), which shows differences between 2080–2099 and 1993–2014 under the SSP585 warming scenario (see also Bulgin et al., 2023). Figure 4a shows that although global average DSL change is zero (because net oceanic mass is unchanged by ocean dynamics), secular trends occur regionally. It is notable that the models do not agree on the magnitude or even the sign of future changes in regional DSL over large parts of the global ocean (although they agree to a much greater extent on global steric and manometric sea level, not shown) and this has some implications for the use of CMIP models for downscaling (See Section 6). Figure 4 illustrates the fact that downscaling is only as good as the global models that feed into it and suggests that it is important to explore downscaling from a variety of different driving models. The main challenge, however, is to understand the physical mechanisms behind this pattern and to test its robustness to model complexity and resolution. Lyu et al. (2020) provide some insightful analysis on the processes such as the AMOC and wind stress curl which generate these future patterns of sea level change and of the role of model biases in causing variations of these patterns in different models. For example, they find that in models where the Equilibrium Climate Sensitivity increases substantially between CMIP5 and CMIP6, the DSL increase due to global warming in the North West Atlantic is also larger. Similarly models with a larger AMOC drop also experience larger DSL change in the subpolar North Atlantic. In general, the location of midlatitude westerly winds in the Southern Ocean, North Pacific and North Atlantic oceans and how they shift with climate change are important indicators of how much DSL change occurs in a given model. However, the reasons behind the shifts in wind stress and their relationship to the original model biases remain unclear. The relationship between changing windstress and DSL is better understood and related to the driving of the ocean circulation by windstress curl, however a more quantitative understanding has not yet been achieved.

One of the likely major circulation changes expected as a result of global warming is a reduction of the AMOC with estimates ranging from a 4%–55% reduction with respect to the present day, depending on model and scenario (Fox-Kemper et al., 2021). Additionally, the most recent IPCC report suggests that a complete and irreversible collapse cannot be ruled out, a shutdown being classed as very unlikely but with only medium confidence rather than high confidence as previously classed (Fox-Kemper et al., 2021). In the case of the subpolar north Atlantic the projected increase in sea level is known to be correlated to the AMOC decline (Bulgin et al., 2023; Little et al., 2019) and a natural question yet to be addressed is why we see an increase in sea level associated with a decrease in the AMOC. This could be because the salt transported northward by the AMOC is more important for setting the subpolar gyre density than the heat transport, so that the freshening associated with a reduced AMOC is greater than the cooling. Alternatively reduced heat loss to the atmosphere may be the cause of an increase in DSL rather than the AMOC (e.g., Bouttes et al., 2014). A relevant study in this context is that of Couldrey et al. (2021) which investigates potential reasons why different models predict different patterns of future change in DSL. They were able to determine that the variety of DSL responses is largely due to structural differences in the models rather than differences in surface fluxes experienced by the models. In the North

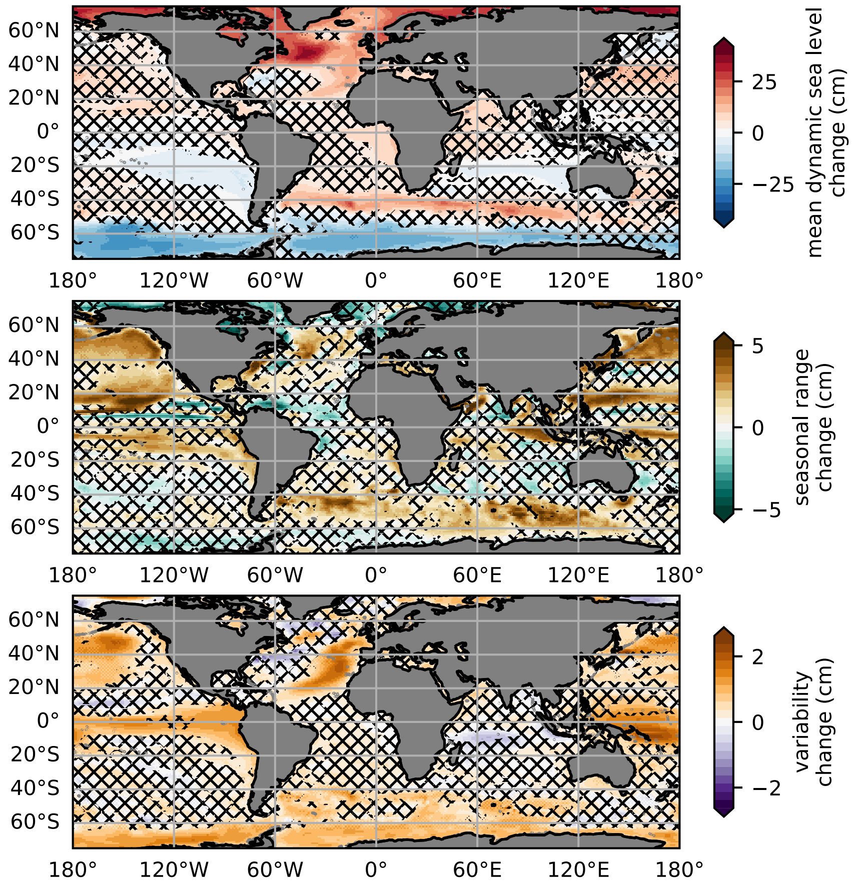

Figure 4. CMIP6 multimodel mean change between 2080 and 2099 under the SSP585 shared socioeconomic pathway and 1993–2014 from the historical experiments using 15 models (see Table S1 for details). Difference in 30-year mean dynamic sea level (DSL) (top panel); difference in mean seasonal cycle in DSL (middle panel) and difference in interannual variability of DSL (bottom panel). Prior to computing the changes in DSL the drift was removed from the DSL (zos variable) using piControl data in the same manner as in Bulgin et al., 2023. Cross-hatching indicates regions where changes are not significant at the 95% confidence level using a Kolmogorov-Smirnov test.

Atlantic the response of DSL to climate change was found to largely depend on the perturbed ocean circulation, which is very different between different models. As also highlighted by Couldrey et al. (2021) the Southern Ocean and the North Pacific are two other key regions where a thorough dynamical investigation of the response of DLS to climate change is lacking.

Whilst studies such as Bulgin et al. (2023) discuss secular trends in Atlantic DSL, the focus of the present paper is on seasonal to decadal variability. Figure 4b shows projected changes to the seasonal range in sea level, linked to change in density (Widlansky et al., 2020) and wind (Hermans et al., 2022). Many coastal areas are projected to see an increase in the seasonal range in DSL at the end of the twenty-first century including most of the western coastline of North and South America, East- and South East Asia, the western Indian Ocean and the coast of South West Africa. In addition, the Mediterranean and Red Seas are projected to experience increased seasonal range. In contrast, the southern Caribbean and the southern tip of India are projected to have reduced seasonal range, as are parts of Western Europe. While the magnitude of the trends may appear modest (±4 cm by the end of the century), it is still unclear what the potential socioeconomic impacts of such changes could be. Wahl et al. (2014) suggested that since the 1990s changes in the observed seasonal sea level cycle have almost doubled the risk of hurricane induced flooding for the eastern and north-eastern Gulf of Mexico coastlines. A recent study by Hermans et al. (2022) demonstrated that by 2100, with the SSP5–8.5 scenario, the CMIP6 models simulate an 8.4 cm (52%) increase in the difference between winter and summer mean sea level over the Northwest European Shelf, leading to potential changes in extreme sea levels in winter time (de Winter et al., 2013), and possible impacts on groundwater dynamics (Gonneea et al., 2013).

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Similarly, Figure 4c shows changes in interannual variability of DSL evaluated over the same 30 year periods. There is moderately enhanced interannual variability (order 1 cm) along much of the world coastline, notably in the eastern and western Equatorial Pacific but also all around the North Pacific, Western Europe, the western Indian Ocean and Antarctica. The only region with a significant reduction in interannual variability is the eastern Indian Ocean. The ensemble averaging used in this figure will mask larger changes in individual models.

In the Atlantic, an important activity would be to understand the relationship of DSL change (secular trends and variability) to the AMOC, the factors influencing the amplitude of projected reduction of the AMOC, and the relationship of changes in the AMOC with changes in the strength of the horizontal circulation. Whether the AMOC change is itself the dominant cause of sea level rise in the subpolar North Atlantic or whether both are caused by another driver (such as Arctic climate change) is still unclear. It would be very desirable to quantify projections of how DSL variability on longer timescales (up to decadal) will be affected by climate change and to improve our general understanding of the causes of such variability. Some work has already been done in this area, for example, Becker et al. (2023) used a large ensemble of simulations of a single climate model to remove the forced climate change signal and concentrate on the internal variability at different timescales. An important conclusion of that study is that the internal climate variability adds considerable uncertainty to projections of sea level change in the twenty-first century (up to 30 cm), with the uncertainty distributed in a spatially inhomogeneous manner. The focus of Becker et al. (2023) is largely statistical rather than on the dynamical process behind the internal climate variability contribution to DSL changes.

We argue that understanding the causes of DSL variability on seasonal to decadal timescales (as well as for secular trends) should involve a careful analysis of the heat and freshwater budgets in both models and observations, and of the impacts of changes on the density of the water column (or, equivalently, investigation of density and volume budgets). DSL changes are the result of convergence or divergence of seawater mass/volume and/or horizontal buoyancy fluxes, hence particular attention should be paid to understanding the origin and sources of convergence and divergence. In quasigeostrophic flow, for example, sources of divergence are the meridional variation of the Coriolis parameter (beta effect), advection, wind stress and bottom friction etc. From the point of view of driving processes, Ekman pumping is a well known source of convergence of volume, but mixing by eddies or smaller scale diabatic processes, for example, usually leads to a convergence or divergence of horizontal buoyancy flux. Whilst Figure 4a illustrates the impact of centennial climate change on DSL, interannual to multidecadal fluctuations in ocean circulation (and DSL) are partially associated with climate modes, for example, El Nino Southern Oscillation (ENSO), Interdecadal Pacific Oscillation (IPO), and NAO. Substantial work has been done on observed changes along the coast in all ocean basins (see for example the review by Han et al., 2019); with attribution of spatially uneven regional and coastal variability at interannual to multi-decadal timescales to internal climate variability, with a large fraction being associated with wind driven changes in ocean circulations due to ENSO in the Pacific and the NAO in Atlantic (Han et al., 2019). A particular strength of the Han et al. (2019) review is their separate consideration of the eastern and western boundaries of individual oceanic basins, recognizing that very different physical processes and drivers dominate in these very different geographical areas. In the Pacific, ENSO/IPO-related trade wind variability drives the well known sea level dipole between the west and east Pacific, and the associated Kelvin and Rossby wave activity spreads coherent variability along the eastern boundary where it combines with local forcing related to North Pacific climate modes. The western boundary of the Pacific is more influenced by wind-forced westward propagating Rossby waves generated in the ocean interior. This contrasts with the Atlantic where the NAO provides strong local control (via winds and air pressure) on DSL on timescales varying from intra-seasonal to decadal. The complication in the Atlantic is that the AMOC can also influence sea level on decadal to multidecadal timescales and relationship between DSL, the NAO, the AMOC and with external forcing is still far from fully understood.

Most studies have concentrated on statistical analysis to establish links between climate modes and sea level, but the challenge is to robustly identify the sea level signals at the deep ocean-slope-shelf boundary associated with these climate modes using both models and observations over the well observed period since the 1950s, to investigate if and how these modes will change in future projections and, crucially, to understand the ocean dynamics linking the climate modes to their sea level signatures. For example, coherent bottom-pressure modes potentially provide a way to dynamically relate the boundary conditions at the shelf-slope relevant to coastal DSL variability to the geostrophic component of the AMOC. Since the bottom pressure in these regions appears able to remove the "noisy" variability of mesoscale eddies (see Hughes et al. (2018) for a dynamical justification), they

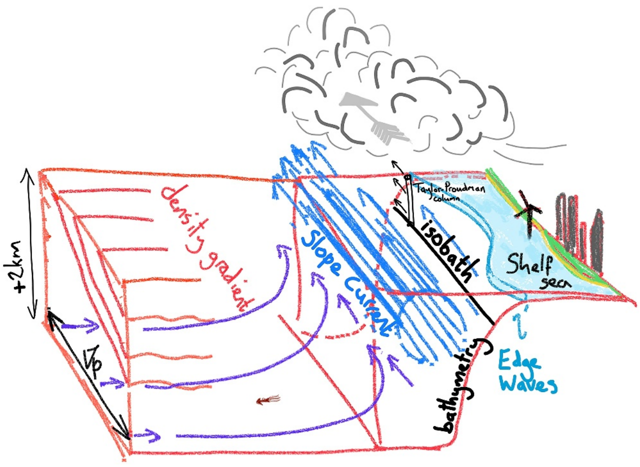

Figure 5. Schematic highlighting the physical processes acting at the shelf break. Significant drivers include the off-shelf along slope density gradient, Kelvin edge-waves and surface winds. These interact to maintain a geostrophic along-slope current, and across-slope transports. The sea surface dynamically adjusts in concert with these processes.

may also circumvent some of the problems related to attribution of AMOC variability and open ocean observations due to chaotic, intrinsic variability (Hirschi et al., 2013).

5. Ocean Shelf Exchange and Coastal Sea Level

Regional sea level is driven by layers of forcing that operate over different temporal and spatial scales (Fox-Kemper et al., 2021; Figure 1). Local drivers have a relatively large effect over short timescales and over potentially finer spatial scales, for example, tides over the course of a day, or winds over the synoptic to seasonal timescale. A fundamental question is: how well do projections capture the linear and nonlinear interactions between the large amplitude local sources of variability and the lower frequency deep ocean variability? Our current assessment of the open ocean impact on projected coastal sea level changes is based on the CMIP style models. These models typically lack a realistic representation of the tides, the complex bathymetry of the continental slope and shelf, and the finer scale processes occurring on the shelf (Holt et al., 2017). These deficiencies influence the representation of transports at the continental slope (Bryan et al., 2007) shelf sea circulation and mechanisms governing mass transport from the open ocean to the shelf (Wise et al., 2018; Wu, 2023) and are consequently associated with increased uncertainty in projections of sea level in coastal areas. Part of the solution to improving regional coastal sea level projections is ensuring climate models capture these interactions accurately. Another part of the solution is process studies that aim to develop a cause-and-effect understanding of the mechanisms driving coastal sea level on seasonal to decadal time scales. For example, although we know from observations that variability in open ocean steric sea level is statistically related with variability in coastal sea level in many locations (Dangendorf et al., 2021), the physical processes at work have not been adequately explained. Furthermore our ability to simulate some of these processes has been constrained by computational power, and our limited ability to simulate a large enough region at sufficiently fine scale and for long enough.

In preceding sections we have discussed processes associated with low and high frequency variability in the open ocean. A shelf break, where present, creates a barrier to the exchange of water masses and sea surface height anomalies between the deep ocean and the continental shelf seas. The shelf break marks the transition in bathymetry between the open ocean, which are typically a few kilometers deep, and the shelf seas, which are typically a few hundred meters deep or shallower. The transition occurs over relatively short length scales (10s of km) but have very long length scales (1,000s km) along the slope, giving rise to the characteristically steep bathymetric slopes which make submarine "islands" of the continental landmasses (Figure 5).

This rapidly varying bathymetric feature (depth, H) on a rotating planet (Coriolis parameter, f) prevents any unforced exchanges of watermasses across the break as planetary potential vorticity (f/H) must be conserved for large scale dynamics. Instead, open ocean height anomalies and open ocean geostrophic currents (having a vorticity and thickness) are qualitatively prevented from crossing onto the continental shelves and are heuristically deflected to follow isobaths (or f/H contours) and are manifest as along slope currents. In this way the shelf break acts as a barrier to "upper ocean weather" passing from the open oceans onto the shelves. Though this explains the leading order dynamics, not all motions are "unforced" and large-scale dynamical thinking does not always capture the small effects, which can be of fundamental importance in questions relating to sea level rise and variability. There is considerable uncertainty in the future projections regarding the role of cross shelf edge transport processes of the Northwest European Shelf (McCarthy et al., 2023); owing to resolution and shelf break process representation in models.

In a synthesis review of observational studies of the Northwest European shelf, Huthnance et al. (2022) suggest exchange transports of order several $m^2\ s^{-1}$, summing to ~10 Sv (1 Sv = $10^6\ m^3\ s^{-1}$) of exchange across the 5,000 km shelf edge between Biscay and north of Shetland, with significant spatial and temporal variation and associated balanced sea level gradients. In the following we consider some of these, locally acting, driving processes.

Ekman processes, characterized by a boundary stress driving an orthogonal volume transport, have two special effects at the shelf break. At the surface, stress is provided by wind and is such that along slope steady wind gives rise to local cross slope transport. Similarly, the along slope currents interact with the bed such that the bed exerts a drag on the fluid, which drives an across slope flow.

A useful scaling is the sea level change associated with depth-uniform currents in geostrophic balance: $\Delta\zeta = Qf/Hg$. So for the NW European shelf: slope current $Q \sim 1.5$ Sv, $H \sim 400$ m $\Delta\zeta \sim 5$ cm; North Sea circulation $Q \sim 0.3$ Sv, $H \sim 100$ m, $\Delta\zeta \sim 5$ cm; Rhine-Meuse outflow: $Q \sim 0.003$ Sv, $H \sim 10$ m $\Delta\zeta \sim 0.4$ cm (noting geostrophy is not the dominant dynamic balance at river outflows). These are all comparatively small values, so only very substantial changes in these currents would lead to significant sea level variability. Hence, the wave-like propagation of sea level variability is much more important than that associated with residual currents, and on open-shelves, this follows Kelvin-wave like physics. The key scales to resolve for this are the barotropic Rossby radius: $(gH)^{0.5}/\omega$ and the topographic scale: $H(\nabla H)^{-1}$. Both of these can be comfortably resolved with modest resolution coastal-ocean or high resolution global models in open-shelves. As the coast is approached, this becomes much more problematic as water depth shoals, topography is comparatively steep (ultimately O(1) of water depth) and friction introduces higher wave harmonics. This is compounded by complex coastlines introducing resonance and boundary layer effects (e.g., tidal eddies), typically at the scale of the tidal excursion (< a few kms).

At the shelf break barotropic tidal energy is converted to shorter baroclinic waves which result in local mixing and modification of the density and momentum profiles, though this conversion of energy does not represent a significant loss to the barotropic tidal wave field its impact on density modifies local horizontal pressure gradients across the shelf break, which in turn have an effect of balanced sea level. On scales shorter than the deformation radius, planetary geostrophic thinking is less relevant and the role of non-linear advection can be a significant momentum term. For example, in the proximity of shelf break canyons a balance between relative vorticity and friction processes might instead control the exchange across the shelf break and the concept of Peclet number regime may dominate (following Wise et al., 2018).

Though we can see how these processes may explain the conversion of open ocean sea level variability into coastal sea level variability be modulating the mass flux across the shelf break, without a closed budget, it is hard to discern the extent to which they may be canceled elsewhere along the slope or region, or how these processes would project onto future coastal sea level. For this we must rely on numerical simulations that have been robustly assessed. For example, within the complex shelf sea region of South East Asia, sea level rise in the low latitude South China Sea is the sum of largely canceling contributions from steric processes and mass redistribution (Thompson et al., 2023).

When numerical models are to be used to provide closed mass and momentum budgets challenges arise depending on their formulation. Most global GCMs do not have explicit tides, and therefore do not represent the component of circulation that arises from the non-linear advection of tides, nor do they have elevated bed stresses beneath the oscillatory tidal flow. Both processes modify the density structure of the global shelf seas, and are demonstrated as important for North West European Shelf circulation dynamics (Tinker et al., 2022). Neither can global GCMs, without tides, represent the interaction of tidal boundary layers on sea ice, which is found to significantly modulate the sea ice extent, by 15% over a decade (Luneva et al., 2015).

Similarly, the model vertical coordinates are typically chosen to increase the efficacy of certain processes: geopotential surface minimize horizontal pressure gradient errors; density coordinates minimize spurious mixing of water masses; terrain follow coordinates minimize bottom boundary layer errors. The ocean-shelf exchange contribution to sea level on the shelf will be mediated by the ability of the model to accurately represent the boundary layer processes whereby water masses can slide on and off the shelf in the vicinity of the shelf break. Not considering these processes in simulation design will adversely affect the efficacy of the cross-slope exchange. For example, with insufficient vertical resolution a simulation will not capture the depth varying current structure (e.g., Polton et al., 2013), or a simulation with geopotential coordinates (z-levels) will diffuse up and downslope flows (Wise et al., 2022). Slope steepness increases the "impermeability" of the f/H barrier at the shelf break. However coarse resolution models will typically misrepresent the bathymetry and so modify this control. However, slope steepness can cause other issues with terrain following coordinates through spurious horizontal pressure gradients and consequently drive spurious currents (Shchepetkin & McWilliams, 2003; Wise et al., 2022). These spurious currents flow along the shelf break and can drive exchange processes. As far we are

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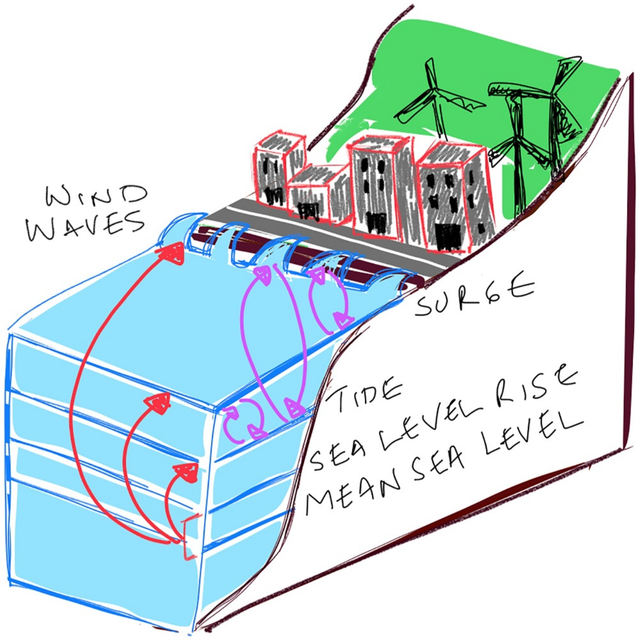

Figure 6. Schematic representation of main components of extreme sea levels: storm surge, waves, tide and mean sea level.

aware these processes have only been investigated for their impact on circulation and work is needed to quantify the impact on sea level.

6. Modeling the Impact of Sea Level Rise on Extreme Coastal Sea Level Events

Extreme coastal sea level events are driven by various mechanisms, spanning a wide range of time scales. The long-term decadal and seasonal variability of mean sea level is combined at the coast with the seasonal variability of freshwater discharges, the daily scale of weather-related wave and surge events, and the semidiurnal to diurnal scale of astronomical tidal oscillations. Event-scale extreme sea levels mainly occur in response to synoptic scale meteorological events. Examples include a series of major winter storms in 2013/2014 affecting the Atlantic coast of Europe (Masselink et al., 2016) and the 2017 Atlantic hurricane season (Rahmstorf, 2017; Valle-Levinson et al., 2020). These meteorological events can result in extreme sea levels arising from the combination of high astronomical tides, storm surges, waves, and extreme river flows.

The magnitude and frequency of extreme coastal sea levels is determined by local water depth and the presence/shape of the coastal boundary. The presence of the coast and shallow waters results in processes, such as tides, being considerably more complex than offshore, which in turn result in a coastal modification of the larger-scale sea level variability (Woodworth et al., 2019). Bathymetric and geometric features will strongly influence tidal and storm surge dynamics, and their interactions (Horsburgh & Wilson, 2007; Idier et al., 2012). As the depth of coastal waters increases in the future modulated by geomorphological change, coastal water level will be altered by interactions between sea level rise, tides, storm surges, and waves (Figure 6) (Idier et al., 2019). Tidal patterns over the continental shelves will change (Idier et al., 2017; Pickering et al., 2012, 2017), as well as in bays (Passeri et al., 2016) and estuaries (De Dominicis et al., 2020; Du et al., 2018; Holleman & Stacey, 2014). Storm surges can both amplify with sea level rise due to the decreased effect of bottom friction (Ali, 1999; Bilskie et al., 2016; Familkhalili & Talke, 2016; Liu & Huang, 2019) or diminish due to the reduction of the surface wind stress on the water column (Arns et al., 2015, 2017; Bilskie et al., 2016; De Dominicis et al., 2020; Shen et al., 2019). Ocean waves will break closer to the coast, with associated changes in wave setup and run-up (Chini et al., 2010; Rahmstorf, 2017) and amplified potential flooding impacts (Arns et al., 2017).

Currently, future extreme sea levels are calculated as a combination of individually modeled sea surface height associated with storm surges and waves, tide and sea level rise (IPCC, 2021), with a number of limitations, for example, the interaction between sea level rise and extreme sea surface height associated with storm surges, waves and tides not being taken into account (Jevrejeva et al., 2023; Tebaldi et al., 2021; Vousdoukas, Mentaschi, Voukouvalas, Bianchi, et al., 2018; Vousdoukas, Mentaschi, Voukouvalas, Verlaan, et al., 2018). Progress in the modeling of coupled coastal processes is urgently needed to predict how sea level rise will influence extreme sea level change at the coast and to ensure that design criteria for coastal protection are correctly specified, and hazard warning systems picks up potential disasters.

A correct representation of near coastal processes and their interactions with sea level rise requires high-resolution modeling, generally kilometer scale or up to 200–500 m (finer resolution might not be computationally feasible, and it would require non-hydrostatic approximation). This is needed to achieve a realistic and detailed representation of coastal geometry and bathymetry and resulting fine-scale physics, such as non-linear tidal components and tidal-eddies at headlands. High-resolution models often need to include wetting and drying schemes (O'Dea et al., 2020; Warner et al., 2013), particularly where tides are large. Ideally, morphological changes in bathymetry/coastal geometry should be also explicitly modeled, although highly challenging, it can be supported by a new generation of satellite observations. High-resolution models are very computationally expensive, due to time step limitations, and so tend to be restricted to small regional or local domains, and shorter runs. The different components (tides/storm surges, waves, rivers and sea level rise) are typically modeled separately and then often added together linearly. However, mean sea level, storm surge, tides and waves can result in non-linear interactions that can lead to greater (Hendry et al., 2019) or smaller (Arns et al., 2020) extreme sea level than the sum of individual components. Only some models include these, and it is not typical for a single model to contain all the nonlinear effects, for example, realistic global sea level rise interacting with tides, surge and waves (see Grayek et al. (2023) and Lewis et al. (2018) for examples of advanced systems).

A modeling framework for the robust quantification of the influence of sea level rise on extreme sea levels at local coastal sub-kilometric scale requires a nested downscaling approach to bridge scales from global to regional to local, with each nest receiving information representing the larger scale dynamics from the coarse model via open boundary conditions (Kourafalou et al., 2015). As discussed below, a single model encompassing global and sub-kilometer local scales is not yet practical. A possible approach would need to go from the IPCC-class global climate models (25–100 km), downscaled to a regional climate model ensemble (25–50 km), then used to force a regional kilometric scale coastal model (1–10 km), which will then provide boundaries to higher resolution fully coupled ocean-wave-river models (<km). An alternative modeling strategy is the use of unstructured grid hydrodynamical models and so reduce the need for multiple nestings. The variable resolution provides a bridge from 10s km resolution at the open boundaries (where they can directly get information from a global or regional climate model) to the sub-kilometric scale at the coast (De Dominicis et al., 2020).

To correctly reproduce extreme water levels at the coast, the sub-kilometric fully coupled ocean-wave-river models should be forced by "storm resolving" regional climate projections that are able to represent the intensities of tropical/extratropical cyclones (and their changes in intensity and frequency with future climate), for example, Euro-CORDEX (Outten & Sobolowski, 2021). It is important that storm resolving climate projections provide atmospheric forcing to the high-resolution ocean-wave-river models at the spatial (i.e., $\leq$10 km) and temporal resolution (i.e., at least hourly) needed to capture the peak of the winds driving the storm surge. Moreover, while the majority of regional climate projections are produced with atmospheric models only, that is, these models use prescribed lower boundary conditions (i.e., sea surface temperature), recent research indicated that in a coupled atmosphere–ocean model, the climate change signal is locally modified relative to the corresponding stand-alone atmosphere. This imposes some uncertainty on the widely used uncoupled future scenarios approach (Christensen et al., 2022; Gröger et al., 2021).

7. Development of Innovative Modeling Approaches for Simulation of Ocean Dynamics in the Coastal Ocean for Sea Level Projection

In this section we consider dynamical model development pathways that might improve the future projections of regional to local sea level variability, beyond the current state-of-the-art in the next 5–10 years. We can identify the current state-of-the-art at a global scale as the future climate projections from AOGCMs used in CMIP and HighResMIP (Haarsma et al., 2016) and downscaling of these using regional ocean models.

All aspects of ocean dynamics influence regional sea level and so model developments to improve the representation of this variability must be highly targeted to those components that are most likely to realize benefits in a cost-effective way in terms of human and computational resources. It is helpful to consider the familiar tri-axis of model resource allocation: resolution versus complexity versus simulation length. This is particularly challenging when considering the need to cross from the global to regional to local domain and the changes in scales and dynamical processes this transition must encompass, along-side the need to consider climatic timescales, and the multiple axes of uncertainty to be spanned. Hence, none of the axes of resource allocation can be substantially prioritized over the other two.

7.1. Resolution

At the global/ocean basin scale there is a need to accurately simulate both the distribution of heat and mass, and the ocean currents themselves. This directs us to eddying scales (e.g., ~1/10°), where boundary currents are reasonable well represented; without achieving this degree of fidelity in the global ocean (and particularly the ocean-margins), the translation of signals in sea level variability to regional scales is questionable. However, this immediately goes beyond what was achieved in CMIP6 and even much of HighResMIP, where the ocean resolutions are as fine as 0.25° (Haarsma et al., 2016). Notable emerging models are the HADGEM3-G3.1-HH with 1/12° ocean (Roberts et al., 2019) and GFDL CM2.6 with 1/10° ocean (Griffies et al., 2015). To illustrate the importance of resolution on sea level variability Figure 7 shows the sea surface height variability (monthly standard deviation over 20 years) for three comparable global NEMO model simulations at nominal 1°, ¼°, and 1/

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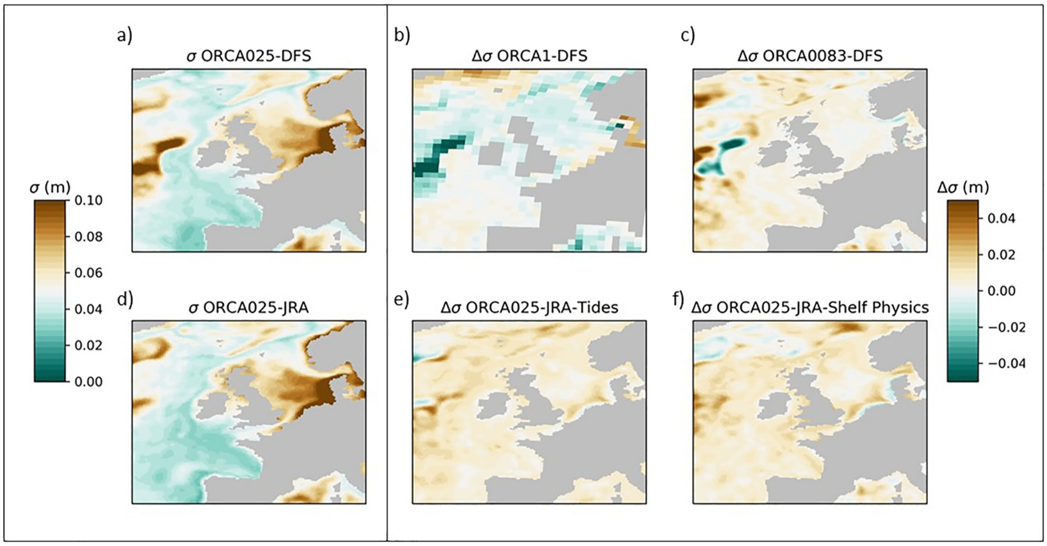

Figure 7. Exploring resolution and process representation effects on monthly sea level variability in global NEMO. Sea level variability is estimated from the standard deviation (σ) of model dynamics sea level using monthly output over 20-year. Top row shows 1/4° global (a) and then the difference from this in 1° and 1/12° global models (b, c). Bottom row shows a standard ¼° global run (d) and then the difference when: tides are added (ORCA025-JRA-Tides; (e) and when tides, multi-envelope coordinates and Generic Length Scale (GLS) mixing (a k-ε model following Luneva et al., 2019) are added (ORCA025-JRA-Shelf Physics; (f) The left color bar is for the left column and the right color bar is for the middle and right columns. Note: Configuration and forcing differ between simulations in top and bottom rows, so these are not directly comparable.

12° resolution, all with 75 partial step levels in the vertical. These show a marked decrease in variability in the NE Atlantic as resolution is coarsened from 1/4° to 1°, and a modest increase on refinement to 1/12°. At the regional scale it can be argued that process representation becomes as important as resolution. If barotropic processes dominate shelf-sea sea level variability, then these can be reasonably well represented by similar scales to the global high-resolution models (~9 km) in open shelf sea regions. Early results from a "shelf-enabled" 1/4° global NEMO model (Figure 7) including tides and hybrid terrain following—geopotential (S-Z) coordinates, show marked changes in sea level variability (generally increasing) as these features, aimed at improving shelf sea dynamics, are introduced.

As the coast is approached complex coastline and bathymetry, and non-linear dynamics (e.g., generating high tidal harmonics) mean much finer (km's and <km's) scales are required. In this regime any of current state-of-the-art global models become inadequate and other approaches are needed. There are three obvious avenues of development here: (i) regional downscaling; (ii) refining a quasi-uniform resolution structured global model; (iii) refining a multiscale global model. These are addressed in turn.

(i) Regional downscaling, whereby coastal-ocean model is run forced with a global ocean and a global atmospheric model, is by far the most straightforward option, so long as only a small number of regions are under consideration. Regional downscaling has been the main-stay of coastal-ocean modeling in research, climate, and operational oceanographic contexts for several decades. The advantages and pitfalls of configuring structured mesh approaches are described in detail by Polton et al. (2023), so will not be repeated here, only to say the initial nest grid can be shelf to ocean basin scale and multiple nests can achieve sub-kilometer scale local models. Alternatively, unstructured mesh coastal-ocean models (e.g., triangular grid) can achieve regional to local refinement in a single configuration. A key advantage of the regional approach is it de-couples the effort in developing and configuring the coastal-ocean from the global activity, so the regional model can be run many times more than the global parent, and potentially with modeling choices that would not be suitable for global simulations. A single global model configuration can support multiple nested coastal-ocean domains that were not conceived before the global simulation was run.

(ii) Refining a quasi-uniform resolution structured grid global model is an attractive option to reach the kilometric scales needed resolve closer-to-coast shelf sea processes. It also allows traceability to current state-of-the art configurations and builds on the many decades of development effort in those models. Notable efforts on this are the ECCO project (1/48° MITgcm; https://ecco-group.org/) and developments in the 1/36° global NEMO model (Bricaud, 2021). The challenge in terms of computation, storage and digital infrastructure is immense. There are also questions of how to treat the sub-mesoscale and sea-ice at these resolutions. Critically, within the development timescales considered here, even if these high-resolution global models could be integrated on climate timescales, it is not realistic to suppose this approach will achieve the sub-kilometer scale needed for local-coastal modeling (noted above). Hence, some element of nesting will still be needed, and whether there is an advantage of nesting directly from a very high resolution global to a sub-kilometer local model instead of using an intermediate regional step has yet to be demonstrated.

(iii) Refining a multiscale global model: After many decades of development, multi-scale global models based on triangular, for example, FESOM (Semmler et al., 2020), ICON (Jungclaus et al., 2022) and hexagonal (MPAS; Hoch et al., 2020) meshes have reached a degree of maturity that saw them participate in the CMIP process for the first time in Phase 6 (Semmler et al., 2020). Are these now the natural choice for investigating questions of regional-local sea level variability? The answer may well be "yes," but before we can be definitive, we must address the key question of where we can safely degrade resolution to allow sufficient refinement in coastal-ocean regions. Given our objective to explore the interaction of well-resolved open-ocean dynamics with the coastal-ocean, few areas available for degradation are apparent, maybe at gyre centers. So the multi-scale option then becomes one of refining from a base resolution of about 1/10° (as concluded by Holt et al. (2017)), and so will quickly push the computational cost into the same realms of the refined structured grids. Sophisticated grid refinement/degradation algorithms and limited areas of interests may ameliorate this, and control over this refinement is a significant advantage, set against the code maturity of the structured grid models and the flexibility of the nested approach. Another issue to bear in mind is, while these are attractive emerging options, changing global model in a large research or operational center is a once in a generation activity, with substantial impact of science and operational delivery.

7.2. Process Complexity

Tides are key dynamical processes, dominating high-frequency (a few hours) sea level variability, usually not explicitly represented in ocean GCMs. The simulation of lower frequency sea level variability (months to years) does not necessarily need to include tides, however bottom friction plays a key role in determining open-ocean to coastal ocean wave propagation and in most regions globally tides play a crucial role in setting this. Given the growing interest in full-physics global tidal models (see Arbic (2022) for a detailed review) it is natural to include tides in global models exploring sea level variability. It is worth noting accurate modeling of tides on a global scale requires additional model features, such as a treatment of self-attraction and loading and in some cases internal wave energy dissipation (Arbic, 2022). While tides do not necessarily impose additional stability time step constraints, recent experience with tides in NEMO (at ¼°) suggest a substantially reduced timestep is needed to maintain global water mass properties. At the current default timestep of 1,800 s, globally averaged ocean temperatures in a forced ocean simulation unrealistically increase over several decades. This is resolved by reducing the timestep to 600 s, presumably through a consequent reduction in spurious numerical vertical mixing. While this initial result deserves further investigation, as it stands, it is likely to prove highly problematic for the inclusion of tides in standard climate model configurations. This issue is likely to be ameliorated at higher resolutions, which require shorter timesteps anyway. Direct inclusion of tides also allows a direct comparison with sea level observations seamlessly across timescales.

Also important for modeling bottom friction is accurate representation of the benthic boundary layer, for example, using terrain following coordinates, which allow a smooth transition of coordinates over topography and also maintains the vertical resolution in shallow water. However, given the well-established issues with these in regions of steep topography hybrid (S-Z) approaches (Bruciaferri et al., 2018; Wise et al., 2022) are most likely the best way forward. Similarly vertical mixing schemes that include bottom boundary layer physics are important. All issues of friction become increasingly important as the coast is approached and the need for surface wave effects also arises.

7.3. Experiment Design and Uncertainty

In terms of exploring the dynamics of (natural) sea level variability, model experiments need to cover multiple cycles of the period of interest: 10 cycles is the canonical number for a well resolved signal. So 10-year simulations are required to explore seasonal variability, maybe 50 years to explore for NAO (with period ~5 years) and

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200 years for Atlantic Multidecadal variability or Pacific Decadal Oscillations (with period ~20 years). Of course, shorter simulations have their utility, accepting the different periods may not be separable, and shorter simulations are often all that are practical. But this sets the general scene—explorations of sea level variability require multi-annual to multi-decadal simulations. Shorter high-resolution simulations can be used for process understanding and to calibrate/assess longer, coarser ones. In the context of ocean model experiments forced by an observation constrained atmosphere (i.e., by a reanalysis), then a single realization is usually sufficient. The role of intrinsic ocean variability arising from eddies is interesting, but unlikely to be a first order control on coastal sea level variability (except possibly at coasts close to eddying boundary currents). In contrast, in coupled experiments, the dominant modes of variability need to be captured either through centennial scale control runs or initial condition ensembles.

When future climate experiments are to be conducted, considerations of uncertainty are paramount. Single realizations can explore process response and provide storylines of dynamically consistent change (Shepherd et al., 2018), but their utility is quickly exhausted in this context (where the nature of change is conceptually simple—rising sea level and increasing frequency of extremes). Hawkins and Sutton (2009) provide a useful framework for considering future climate uncertainty, separating scenario and model uncertainty in the context of natural variability. Climate models differ widely in their equilibrium climate sensitivity (Meehl et al., 2020) and so spanning this axis of uncertainty is as (or more) important than emissions scenario uncertainty. The question of natural variability dictates when a secular trend can be detected for example, against a 30-year mean (the World Meteorological Organization recommended baseline) and is a key determinant of experiment design. It makes end-of-century studies more straightforward than the, more readily useful, early- mid-century studies where natural variability is key. That said, approaches for this shorter time-horizon deserve substantial attention, as they match more closely to immediate societal needs (e.g., the policy timescales identified in the Introduction). Downscaling simulations add other layers of uncertainty arising from the different coastal ocean model choices, and exploring these is just as important as driving model and emissions uncertainty. At sub-kilometer scales, computational costs often limit the experiment design to timeslice or event based approaches, rather than multidecadal transient simulations.

Experiment design is central to any modeling activity that dictates the utility of the output to meet particular scientific or societal objectives. Hence, all development activities need to be seen in the context of the model experiments, and particular what is feasible to achieve a particular end, given expected compute, storage and human resource limitations. Given the multi-year lag between development and large scale application, a degree of foresight is needed on this resource landscape. Changing computer architectures and the ability of ocean models to exploit them makes this foresight challenging, and this has particular bearing on increased resolution and multi-scale global approaches. If current model configurations can maintain their efficiency (and this itself is a challenge), then expanding simulation length and ensemble numbers is more straightforward than changing models or refining global resolution; that is, this axis of resource allocation can most readily accommodate current expansions in computational resource. The requirement for decadal- multi-decadal simulations to span multiple axes of uncertainty articulated here tempers the ambitions of improved resolution, at least on these development timescales, and lends this work to favor process representation and ensemble size/simulation length.

8. Concluding Remarks

For the large number of adaptation users with diverse requirements, there is an urgent need to improve future sea level projections in coastal areas. Our current understanding of future sea level changes along the global coastline and impact of open ocean processes on coastal sea level changes is based on CMIP style climate models, which currently lack in the fine resolution and process representation to realistically simulate mechanisms governing heat and mass transport between the open ocean and shelf. This results in uncertainties in sea level projections near the coast. The extent to which open ocean dynamics affect coastal sea level and how this depends on time-space scales is one of the key puzzles we are currently grappling with in sea level research.

In this paper, we have provided some potential approaches to address this either through representing missing processes in CMIP style climate models or through regional/local downscaling, and so to advance simulations of future sea level variability near the coast. Improved simulations of sea level variability near the coast will lead to more explicit modeling of high-resolution processes of future flood hazards, in which local changes in tides, surges and waves can be resolved and combined with mean sea level changes.

We have highlighted several potential research avenues to improve simulations of sea level variability in coastal areas. In terms of computing we have now entered the exascale era. The peak performance of the largest high performance computing facilities has reached 1 exaflop (i.e., 10^{18} floating point operations per second) and disk storage capacities of 1 exabyte have become reality for the largest datacenters (Hoffmann et al., 2023). This presents us with immense opportunities. Running km scale (i.e., horizontal grid resolution between 1 and a few km) global coupled ocean-atmosphere models is within reach and several large projects have been working toward that goal (e). Apart from a better simulation of the delicate interplay between the open and coastal ocean, the increased resolution of these models will provide better simulations of extreme weather events impacting coastal regions and how these will change as the climate warms further. Challenges reside in the requirement for computer codes to become more efficient at running on many (up to millions) processors and in the exploitation of the vast amount of data this generation of models produces. The rapid advance in machine learning techniques we have been witnessing in recent years is opening further avenues for example, for running "hybrid" simulations where machine learning flanks "classical" modeling, as a tool to extract valuable information from the vast data sets, or as pragmatic (but black box like) forecasting systems (e.g., Bi et al., 2023; Sonnewald et al., 2021). This had led to ongoing discussions and considerations in the modeling community about the development of high-resolution global coastal ocean models (including the deep ocean); development of atmosphere-ocean coupled models and their specific applications for better understanding, quantification and prediction of future coastal flood hazards.

The key message from Section 4 is that our dynamical understanding of the processes that cause regional DSL change in the open ocean and crucially how these manifest at the all important deep-ocean-slope ocean boundaries is still incomplete. Thus, in addition to planning new high resolution simulations, application of machine learning techniques and new observational campaigns, more emphasis must be placed on elucidating the origin of local changes in water column pressure at the boundary between the deep ocean and the shallow shelf regions.

There are numerous open questions about the experimental design not discussed in our manuscript, for example, multi-model or initial conditions experiments and needs for global ensembles. There are several options to improve simulations by using nested sub-models, with challenging tasks for ensemble numbers, and how long the nested models need to run to get a sense of sea level changes, ranging from a decade to century.

Supporting the needs for more detailed sea level projections near the coast with a focus on impacts and adaptation and addressing knowledge gaps, discussed above, will require not only numerical simulations with an adequate spatial resolution and enhanced physics, but also related observations to improve the performance of high resolution regional and global ocean models in coastal areas. For decisions about adaptation options in coastal areas there is an increasing demand for precisely measuring present-day sea level rise at as many coastal sites as possible. For stakeholders responsible for coastal planning and risk assessment in coastal areas, availability of long-term sea level observations at coastal sites and interpretation of local sea level changes, identifying when and how the local sea level deviates from simulated sea level projections, are crucial for decisions about adaptation options. In addition to the scientific challenges discussed above, there is a crucial task to improve two-way communication and delivery of the required scientific information about future sea level changes between scientists and policy makers, coastal engineers and the public.

Data Availability Statement

All CMIP6 model data used available from the CMIP6 (Eyring et al., 2016) repository. The models and ensemble members used within this study are listed Table S1 in Supporting Information. Model data required to reproduce Figure 7 are available from Coward et al. (2024). Sea level data sets for Figure 2 are available from CMEMS (2023).

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