



Review article: Towards consistent estimation of coastal water levels combining satellite altimetry and hydrodynamic modelling

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Abstract. Coastal cities are increasingly exposed to flooding as sea level rises and as compound extremes involving tides, storm surge, waves, and river discharge act together. Reliable estimation of extreme coastal water levels is therefore fundamental to flood risk assessment, forecasting, and coastal management, yet it remains constrained by sparse in-situ networks and by the partial, scale-dependent representations that satellite altimetry and hydrodynamic models each provide. Over the past decade, advances in coastal altimetry and in regional-to-global hydrodynamic modelling have expanded the information available for coastal water-level estimation, but their combined use remains dominated by region-specific applications, and globally consistent methodologies are still emerging. Here we review approaches for combining satellite altimetry and hydrodynamic models across four interconnected domains: the detection of coastal sea-level and sea-state extremes from along-track altimetry; strategies for integrating altimetry with hydrodynamic models; vertical referencing and datum consistency; and validation and uncertainty characterisation, particularly in data-sparse settings. We argue that the central challenge is not how to merge two sources of information, but how to ensure that they represent commensurable quantities. No single integration strategy is universally optimal, and differences in process representation, sampling, and vertical reference must be treated explicitly rather than absorbed into residual error. While satellite altimetry does not resolve wave-driven processes at the shoreline and hydrodynamic models often approximate baroclinic and compound contributions, consistent vertical referencing and coherent propagation of uncertainty can render altimetry- and model-derived estimates comparable. Progress therefore depends less on combining datasets more widely than on defining when such combinations are physically meaningful, vertically consistent, uncertainty-aware, and transferable across coastal regimes, laying the foundation towards globally consistent estimation of coastal water levels.



1 Introduction

Coastal cities are increasingly exposed to flooding as a result of sea level rise and intense extreme events, and the growing influence of compound drivers such as storm surge, waves, river discharge, and rainfall (e.g. Green et al., 2025; Khanal et al., 2019; Ruan et al., 2024; and Xu et al., 2022a). Urban areas in particular are flood risk hotspots due to their concentration
35 of people, assets and critical infrastructure, and risk is likely to increase where, in addition to climate change, population growth and urbanization increases exposure (e.g. Wahl et al., 2015; Glavovic et al., 2022).

At the coast, extreme flooding usually occurs when high tide, storm surge, waves and mean sea-level anomalies act together (Vitousek et al., 2017), with flooding potential largely dictated by the magnitude of the coastal water level, defined here as the sea surface elevation relative to a geoid (i.e., a level surface). Coastal total water levels are the result of the combined
40 effects of tides, meteorologically forced variability (primarily due to atmospheric pressure and winds), density-driven (baroclinic/steric) variability, as well as wave-driven setup and runup at the shoreline (Idier et al., 2019). The relative contribution of these drivers to coastal water varies strongly by location, and non-linear interactions between them can modify water levels by several tens of centimetres (De Almeida et al., 2018). However, satellite altimetry does not resolve wave-driven setup and runup at the shoreline. Thus, for the purposes of this review, which focuses on the complementarity
45 between satellite altimetry and hydrodynamic modelling, the coast is defined as the coastal ocean seaward of the surf and swash zones, and coastal water levels do not reflect total water levels including wave setup, runup and swash.

While hydrodynamic models provide a physically consistent framework for estimating coastal water levels, their accuracy is constrained by various sources of uncertainty, and in practice, it remains difficult to calibrate and validate these numerical models in the absence of a comprehensive in-situ observation network with global coverage. Advances in satellite altimetry
50 over the past decade offer opportunities to reduce some of these uncertainties. These advances include enhanced retracking algorithms (e.g. Passaro et al., 2014), improved corrections for the wet tropospheric delay (e.g., Lázaro et al. 2020), and improved data editing (e.g., Birol et al. 2017). Together, they have resulted in several dedicated coastal altimetry products (e.g., Cancet et al., 2026, Peng et al., 2024, Schwatke et al., 2023; Cazenave et al., 2022, Birol et al., 2017) that have improved our understanding of sea level in the coastal zone.

55 Earlier work showed that altimetry can capture storm-surge signatures and complement the tide-gauge network (Antony et al., 2014), and that assimilating or integrating altimeter observations can reduce model errors in regional surge forecasts (Bajo et al., 2017; Asher et al., 2019). More recently, Guarneri et al. (2023) assimilated altimetry-derived low-frequency water levels to improve the low-frequency water level representation in a 2D tide-surge model. And in a subsequent study Guarneri et al. (2025) combined satellite altimetry with a two-dimensional hydrodynamic model by treating model-derived
60 tidal constituents as stochastic variables and updating them only when justified by altimetric precision, substantially improving tidal estimates and reducing residual water level variability over shallow parts of the northwest European continental shelf. In addition, altimetry derived empirical tide models have been shown to improve coastal hydrodynamic boundary conditions and water level skill (Hart-Davis et al., 2023), indicating that altimetry–model fusion approaches span a



continuum from loosely coupled correction frameworks to tightly coupled data assimilation and hybrid approaches that
65 modify model states or boundary conditions.

However, the combined use of satellite altimetry with high-resolution hydrodynamic models for coastal and total water level
estimation remains dominated by region-specific applications, with most studies focused on individual shelves, basins, or
estuarine systems using locally tailored data, assumptions, and workflows rather than globally consistent methodologies (e.g.
Rulent et al., 2020; Vignudelli et al., 2019; Caballero et al., 2020; Jahanmard et al., 2023). Reviews of coastal observing–
70 modelling systems consistently note that these efforts remain fragmented across regions and platforms, and that integrated
approaches applicable across diverse coastal regimes are still emerging rather than widely adopted (De Mey-Frémaux et al.,
2019; Melet et al., 2020; Ponte et al., 2019).

Towards developing globally consistent approaches of combining satellite altimetry and hydrodynamic models for
estimating coastal water levels and their extremes this review focuses on four interconnected domains that repeatedly
75 emerge across regions and applications: (i) the detection and characterisation of coastal sea-level and sea state extremes from
along-track altimetry; (ii) the use of altimetry derived sea level and wave information with hydrodynamic models; (iii)
vertical referencing and datum consistency across altimetry and model outputs; and (iv) validation strategies and uncertainty
characterisation for both altimetry-based and model-based coastal water level estimates, particularly in data sparse settings.

The review is structured as follows. Sect. 2 first outlines the physical processes governing extreme coastal water levels,
80 including their individual contributions and non-linear interactions. Sect. 3 then examines the capabilities and limitations of
satellite altimetry for detecting coastal extremes, with attention to sparse sampling and recent advances in coastal data
products. Sect. 4 provides an overview of hydrodynamic modelling approaches for coastal water levels, highlighting
representation gaps, baroclinic effects, and the role of regional downscaling. Building on these foundations, Sect. 5
synthesises strategies for combining satellite altimetry and hydrodynamic models and discusses key sources of inconsistency
85 and challenges during extreme events. Sect. 6 then argues that consistent vertical referencing, validation against independent
observations, and coherent uncertainty characterisation are cross-cutting prerequisites for rendering these estimates
commensurable. Finally, Sect. 7 presents a synthesis of advances, limitations, and priority directions for future research.

Textbox 1: Review scope and guardrails

This is a structured narrative review, not a systematic review or a benchmarking exercise. It synthesises conceptual and
methodological advances in combining satellite altimetry and hydrodynamic modelling to estimate coastal water levels and
their extremes, and does not aim to catalogue the literature exhaustively.

We define the coast as the coastal ocean seaward of the surf and swash zones. Coastal water levels therefore comprise tides,
meteorologically forced variability, and density-driven (baroclinic and steric) variability relative to a geoid; wave setup,
runup and swash are not resolved by altimetry and lie outside this scope, though they are noted where they affect
interpretation. Within this boundary the review addresses four domains: (i) detection of coastal sea-level and sea-state



extremes from along-track altimetry; (ii) integration of altimetry with hydrodynamic models; (iii) vertical referencing and datum consistency; and (iv) validation and uncertainty characterisation.

To limit the selection biases inherent to narrative synthesis, we apply a defined thematic scope, attend to the geographical and methodological balance of the cited literature, and note where coverage remains uneven: the evidence base is weighted towards the northwest European shelf and, secondarily, South and Southeast Asian deltas, with limited representation of other regions, particularly the Global South.

90 2 Physical processes governing extreme coastal water levels

2.1 Components of coastal water levels

Coastal water levels, seaward of the surf and swash zone, arise from the combined effects of multiple physical processes, including astronomical tides, meteorologically forced variability (due to atmospheric pressure and winds, including sea-state modulation of surface stress; Bonaduce et al., 2020), density-driven (baroclinic and steric) variability (which is also
95 modulated by wave-induced mixing; Bonaduce et al., 2024), as well as, in some settings, freshwater (buoyancy) inputs from rivers, which modifies shelf density structure (Pugh and Woodworth, 2014; Woodworth et al., 2019). These processes act at different spatial and temporal scales, and interact non-linearly, such that their relative importance for coastal flooding varies strongly between regions and events (Idier et al., 2019; Kirezci et al., 2020; Pugh and Woodworth, 2014; Woodworth et al., 2019). Consequently, the total water level relevant for flooding cannot be interpreted from offshore sea surface height alone
100 but must be understood together with the chain of processes linking offshore forcing, nearshore transformation, and shoreline response (Fig. 1; Pugh and Woodworth, 2014; de Silva et al., 2020). Collectively, these processes span a wide range of spatial and temporal scales, from seconds and metres for wave processes to decades and basin scales for large-scale ocean circulation and climate variability (Woodworth et al., 2019).

The time-averaged component of coastal water level is associated with density-driven (baroclinic) processes and large-scale
105 ocean circulation and is commonly expressed as mean dynamic topography (MDT) when referenced to a geoid (Woodworth et al., 2019). This component represents the mean offshore baroclinic water level relative to the equipotential reference surface and can reach magnitudes of up to ~1.5 meters, exerting a first-order control on spatial distribution of coastal water levels. Seasonal to interannual variations in this component arise from winds, atmospheric pressure, steric effects, and baroclinic circulation, while long-term sea-level rise shifts the entire distribution of coastal water levels upward. This shift
110 lowers the threshold at which tides, surge, or waves produce flooding, leading to a disproportionate increase in the frequency of extreme and high tide events, even for relatively modest increases in mean sea level (Vitousek et al., 2017; Taherkhani et al., 2020). Sea-level rise increases the frequency of high-tide and nuisance flooding and elevates the probability that extreme water levels exceed impact-relevant thresholds, with non-linear interactions between tides, surge and mean sea level further amplifying these extremes, especially in shallow and estuarine settings (Idier et al., 2019; Serafin et al., 2017).

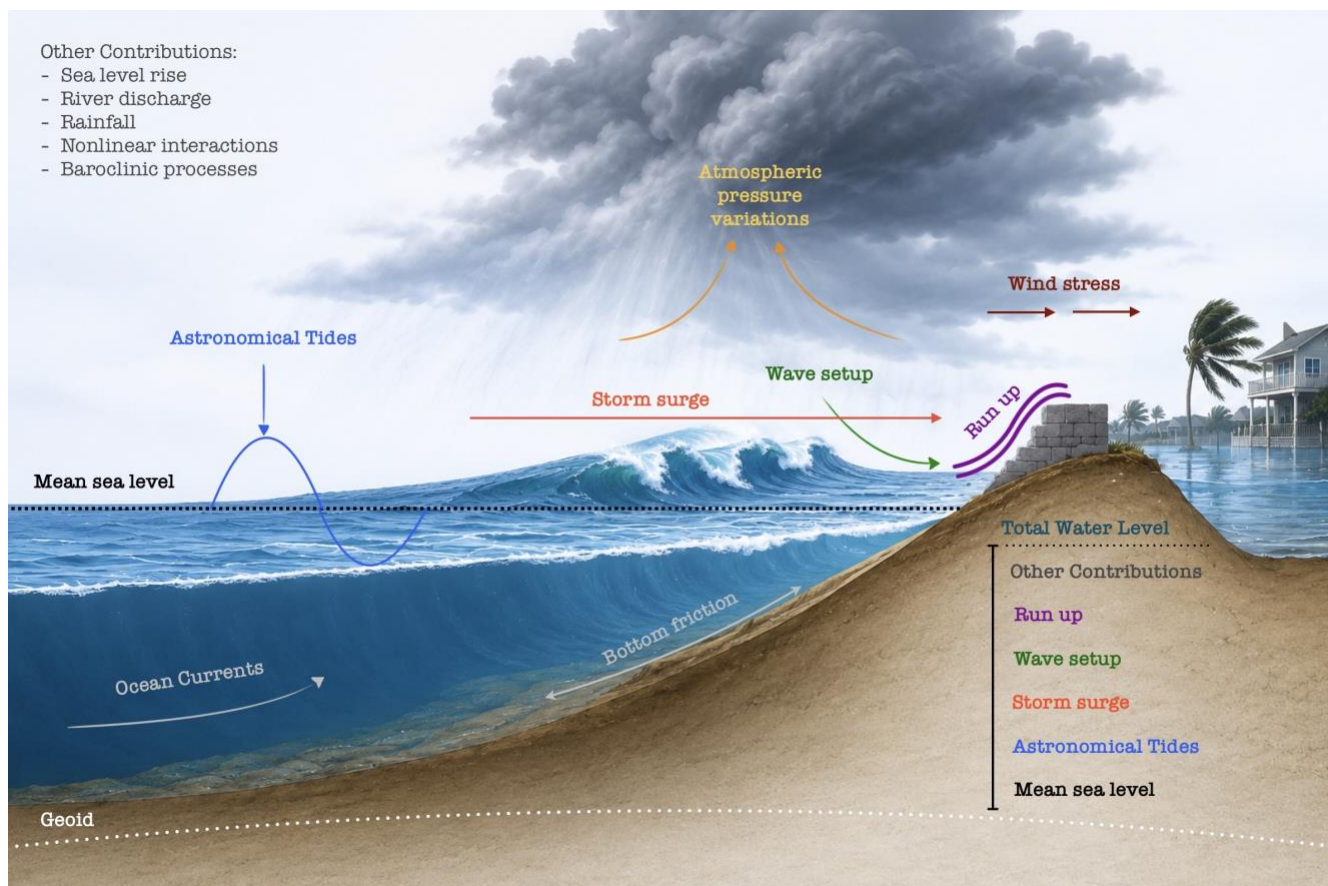


Figure 1. Conceptual schematic illustrating the processes contributing to coastal total water levels, including mean sea level, tides, meteorological surge, and wave driven setup and runup, and their evolution from offshore to the shoreline. The background graphic was generated using ChatGPT, the text and labels were added by the authors.

Astronomical tides are a major predictable contributor to coastal water level variability and strongly modulate flood risk, with highest impacts occurring when storm surge or energetic wave conditions coincide with high tide; in meso- to macro-tidal environments, tides often dominate this variability (Idier et al., 2019). Beyond their deterministic role, changes in tidal characteristics and tidal anomalies have been shown to significantly influence high tide flooding frequencies, in some regions contributing as much as, or more than, changes in storm surge magnitude (Li et al., 2021; Li et al., 2022; Hague & Talke, 2024).

Meteorological storm surge, driven by wind stress and atmospheric pressure gradients, is a dominant contributor to extreme coastal water levels during storms and often governs the magnitude of episodic coastal flooding. However, surge interacts non-linearly with tides through depth dependent friction and estuarine geometry, modifying both the timing and amplitude of extreme water levels and shaping local inundation patterns, particularly in estuaries and semi enclosed basins (Idier et al., 2019; Arns et al., 2020).



This review will focus on ocean-driven processes contributing to extreme coastal water levels. These include density-driven (baroclinic) variability, tides, and meteorologically forced variability.

2.2 Non-linear interactions and compound effects

Importantly, coastal water-level components do not combine linearly, and their interactions can alter both the magnitude and timing of extremes. For example, tide–surge interaction arises through advection, shallow-water effects and non-linear bottom friction, and can either amplify or attenuate surge depending on local depth, geometry and phase (Wolf, 1978; Flather, 2001; Zhang et al., 2010; Idier et al., 2012). Along the UK coast, these interactions have been observed to modify surge peaks by several tens of centimetres (Horsburgh and Wilson, 2007), while in shallow deltaic environments in the Bay of Bengal they can reach ~0.6 m (Johns et al., 1985; Krien et al., 2017). Comparable magnitudes have since been reported across a wide range of estuaries and deltas, indicating that tide–surge nonlinearity is pervasive rather than site-specific (Idier et al., 2019; Costa et al., 2023; Guo et al., 2025).

Wave-driven contributions are similarly state-dependent and can interact through tides through nearshore wave transformation and breaking (Pedreros et al., 2018), but these effects primarily occur close to the shoreline and are not directly resolved in the offshore water level estimates considered here.

Mean sea-level rise can also modify tides and surges by changing water depth and frictional regimes, thereby altering the strength of the interactions described above. Modelling studies have demonstrated that accounting for interactions with changes in mean sea level can produce amplified tidal ranges and higher extremes relative to approaches that treat mean sea level change as a simple offset (Arns et al., 2015; Idier et al., 2017). Recent analyses likewise indicate that adding sea-level rise linearly to present-day storm tides can underestimate future extreme water levels by ~0.1–0.2 m and lead to two- to fourfold underestimation of extreme-event frequency in some regions, consistent with the view that sea-level rise modifies the full distribution of extremes rather than acting as a uniform shift (Idier et al., 2019; Moftakhari et al., 2024; Arns et al., 2017). Collectively, these examples illustrate why linear superposition is inadequate under extreme conditions: both the amplitude and phase of individual contributions depend on the evolving state of the coastal system. In coastal lagoons, maximum water levels can rise faster than sea-level rise (Lorenz et al., 2023).

Beyond direct physical coupling, extreme coastal water levels are also shaped by the co-occurrence and statistical dependence of different drivers, even where local hydrodynamic interactions are weak. Global analyses show that extreme storm surges and wind waves frequently occur concurrently due to shared atmospheric forcing; Marcos et al. (2019) estimated that such dependence affects ~55% of the world's coastlines. Accounting for this dependence increases estimated extreme water levels and reduces return periods relative to independence assumptions, in some regions by a factor of two or more. Comparable dependence structures have been identified for surge–river, surge–precipitation and multi-driver compound flooding in deltas and estuaries, where joint probabilities differ markedly from those obtained under independence assumptions (Couasnon et al., 2020; Wu et al., 2024).



Recent evidence further suggests that the dependence structure itself may evolve. Radfar et al. (2026) identified significant co-variability among major tidal harmonics at a substantial fraction of long-record tide-gauge stations, linked to basin geometry, non-linear shallow-water processes and large-scale climate variability such as ENSO. Together with evidence that tidal statistics and non-tidal residuals co-vary with mean sea level at many locations, these findings suggest that the dependence structure governing extreme coastal water levels is not strictly stationary under climate change (Moftakhari et al., 2024).

In summary, interactions among mean sea level, tides, storm surges and waves (and, in estuarine systems, river discharge and rainfall) can contribute several tens of centimetres (and in some cases close to a metre) to extreme coastal water levels. Approaches that assume independence or linear additivity of tides, surges, waves, river discharge and mean sea level change can therefore systematically underestimate the frequency and severity of extremes, with substantial implications for coastal flood projections and impact assessments (e.g., Horsburgh and Wilson, 2007; Krien et al., 2017; Pedreros et al., 2018; Arns et al., 2015; Xiao et al., 2021; Du et al., 2024).

3 Detecting coastal extremes from satellite altimetry

3.1 What altimetry can and cannot observe

Sea level extremes in coastal regions can be identified using remote sensing, particularly through sea level measurements obtained from satellite altimetry. Altimetry products typically provide the SSH and its variations referenced to a long-term mean sea surface, i.e. the Sea Level Anomalies (SLA). Moreover, they include the estimation of the tidal height from a tidal model and the atmospheric pressure contribution to the sea level as a set of geophysical adjustments, that are provided separately. This enables, in principle, the consistent separation and recombination of total water level components when analysing extreme events. These correction terms are important when interpreting SSH or SLA in the coastal zone, as they allow the user to reintroduce or remove individual physical contributions consistently across different missions.

However, satellite altimetry does not resolve nearshore processes associated with wave breaking, such as wave setup, runup or swash. As a result, wave-driven contributions must be inferred from complementary datasets such as altimetry-derived significant wave heights that are translated nearshore with empirical formulas or hydrodynamic models (Dodet et al., 2020).

3.2 Extreme detection under sparse sampling

Historically, the study of extreme sea levels and sea states using satellite altimetry has been hampered by two main issues: (1) the quality of data in the coastal zone, and (2) the limited temporal sampling of altimetry missions (Benveniste et al., 2019). Recent studies have demonstrated that combining satellite altimetry with in-situ data and model simulations can help mitigate these limitations and have the potential to improve our ability to use remote sensing for studying coastal sea levels and sea states (Cavaleri et al., 2021).



Previous studies have explored approaches to identifying extreme sea levels using altimetry-only sea-level records, without reliance on ancillary data sources: the peak-over-threshold method, which identifies events exceeding a predefined magnitude (Andersen et al., 2015) and the monthly maxima surge water levels approach (Bij de Vaate et al., 2024). The appropriateness and accuracy of these altimetry only approaches differ: monthly maxima methods tend to provide more robust and internally consistent estimates under sparse sampling, with demonstrated large-scale agreement with tide gauge derived extremes (Lobeto and Menéndez, 2024; De Vaate et al., 2024), whereas peak over threshold methods are more sensitive to sampling gaps and threshold selection and therefore less reliable when applied solely to altimetry without ancillary information (Collings et al., 2025; Vignudelli et al., 2019). Finally, concerning validation, Antony et al. (2014) and Ji et al. (2019) conducted the first dedicated studies of coastal altimetry data against tide gauges in the Bay of Bengal and along the coast of China for extreme events. They found that, on average, 45% (Bay of Bengal) and 26% (coast of China) of surge events were captured by at least one altimeter (though typically not coinciding with the timing of peak surge), with water level differences of about 10–20 cm.

3.3 Advances in coastal altimetry

Altimetry measurements become increasingly degraded toward the coast, with significant impacts typically occurring within tens of kilometres from land (Birol et al., 2025). To address this, several institutions have reprocessed historical altimeter time series using dedicated coastal retracking, geophysical corrections and postprocessing techniques. These efforts aim to improve radar waveform fitting in complex coastal environments and to refine geophysical corrections applied to the raw range measurements from which sea level and sea state estimates are derived. Notable examples include the Adaptive Leading Edge Subwaveform retracker (ALES; Passaro et al., 2014) and the XTRACK processing system (Birol et al., 2021), which have been integrated into broader initiatives such as ESA’s Sea Level Climate Change Initiative.

One outcome of these developments is the concept of “virtual tide gauges”, defined as the coastal-proximal points along altimeter ground tracks where reliable sea-level observations can be retrieved (Cazenave et al., 2022). Virtual tide gauges have substantially expanded the spatial coverage of coastal sea-level observations over multiple decades, extending several kilometres closer to the shoreline than previously possible. Nevertheless, their utility for extreme-event analysis remains constrained by satellite repeat cycles and the inherently sparse temporal sampling of along-track altimetry.

In parallel, the ESA Sea State Climate Change Initiative (ESA SS_cci) has developed a multi-mission dataset providing globally cross-calibrated significant wave heights to study trends and variability in the wave climate (Dodet et al, 2020). This dataset is based on the WHALES algorithm (Passaro et al., 2026), an improved version of ALES dedicated to estimating the sea state, optimising the derivation of wave height, which has shown significant improvements in coastal data quality and coverage (Schlembach et al., 2020). Recent studies demonstrated that this dataset can be used to analyze extreme sea states in the open ocean, suggesting strong potential for its application to coastal extremes (De Carlo and Ardhuin, 2024).



225 Despite these advances, the literature on observing coastal extremes using satellite altimetry is limited and mostly consists of regional case studies. Several early and recent studies nevertheless show how altimetry can contribute to extreme-event analysis: along-track observations can capture storm-surge signatures (e.g., Scharroo et al., 2011), altimetry-derived water levels can support hydrodynamic modelling and assimilation (Bajo et al., 2017), and conventional altimetry can be combined with tide gauges for coastal extreme-value analysis (Lobeto et al., 2018). However, these applications remain largely regional and often depend on ancillary information such as exposure, shelf width, bathymetry, hydrodynamic reanalyses, or in-situ observations rather than on altimetry alone.

Looking ahead, more recently, the advent of wide-swath altimetry is opening new possibilities to improve our understanding of the spatial footprint of storm surges and to close the observational gaps with tide gauges (Vega-Gimenez et al., 2025). While SWOT, which carries the first wide-swath altimeter, is not intended to provide an operational framework, it offers an invaluable dataset to prepare for an era of near-global ocean coverage and improved temporal resolution, with the planned launch of two wide-swath altimeters by the European Space Agency in the 2030s (the Sentinel-3 New Generation Topography constellation).

Based on the existing literature on estimating coastal water levels from altimetry, several gaps remain. First, the use of retracked sea level data at high-resolution (20 Hz) has not been fully exploited. Many studies rely on low-resolution data (1 Hz) or on high-resolution products not optimized for the coastal zone. This significantly limits the ability to observe the typical sea level gradient expected near the shelf break, particularly when the shelf break is located close to the coast.

In addition, the integration of ancillary data, such as hydrodynamic reanalyses and tide gauge observations, can enhance the identification of extreme sea level events. Reanalysis products provide valuable insight into the occurrence of such events (Muis et al., 2020), while the validation of altimetry-derived sea level measurements requires comparison with tide gauge records.

Second, the use of high-resolution data is often constrained by the presence of outliers, particularly in coastal regions. Nevertheless, outlier analysis can be performed on along-track data, as most outliers typically manifest as unrealistic sea level gradients. These are distinguishable from the characteristic rise in sea level observed over several consecutive along-track points, which has been shown to indicate storm surges detected by altimetry (see, for example, Fig. 4 in Han et al., 2017).

Third, while tide gauge data are often located in sheltered areas, the use of “virtual stations” potentially allows us to estimate the contribution of wave height to the water level impacting the coast, i.e. wave setup. The influence of wave setup on coastal altimetry records was tentatively explored by Melet et al. (2020), but its contribution to individual extreme events has yet to be fully investigated. For this purpose, improved estimates of coastal sea level and sea state can be combined, using significant wave height to empirically estimate wave setup.



4 Hydrodynamic modelling of coastal water levels: from regional models to global modelling frameworks

4.1 Modelling approaches

Coastal water levels are most commonly estimated using regional or global hydrodynamic models that resolve tides, storm surges, their non-linear interactions and other contributions (Horsburg and de Vries, 2011). These physics-based models solve the shallow water equations either in a depth-averaged (2D) or three-dimensional (3D) configuration to obtain spatially-resolved coastal water level estimates.

The choice between 2D and 3D model configurations reflects a fundamental trade off between physical realism and computational efficiency. Depth averaged models are attractive due to their relatively low computational cost and numerical robustness, which makes them well-suited for operational forecasting and decadal simulations (e.g. Muis et al., 2020). Three dimensional models, by contrast, explicitly represent baroclinic processes such as stratification, density gradients and associated circulation, which can significantly influence mean and seasonal water levels, tidal propagation, and surge dynamics, depending on the region (Kodaira et al., 2016; Müller et al., 2014; Opel et al., 2024). However, their higher computational demands and more complex boundary conditions limit their applicability. Consequently, continental to global-scale hydrodynamic models used in coastal risk assessments and operational forecasting applications rely on barotropic (depth-averaged) formulations that simulate wind- and pressure-forced water levels (Muis et al., 2020; 2023; Vousdoukas et al., 2018). Examples of large-scale 3D models do exist but at the trade-off of lower horizontal resolution (e.g. Irazoqui Apecechea et al., 2025; Wang et al., 2022a).

Storm surge simulations require near surface wind and mean sea level pressure fields, typically obtained from global atmospheric reanalyses such as ERA5 (Hersbach et al., 2020) or operational forecast systems such as IFS (Roberts et al., 2018). For climate change assessments, outputs from global climate models, for example CMIP6 (Eyring et al., 2016) are often used. Model skill is highly sensitive to the spatial and temporal resolution of these forcings, and while most climate models are relatively low resolution, the availability of high resolution climate models is increasing (Dullaart et al., 2020). High spatial resolution of the weather and climate model data that is used as hydrodynamic model forcing is especially crucial for regions affected by tropical cyclones, characterized by small spatial scales and steep pressure gradients (Dulac et al., 2022).

Tidal forcing can be imposed either through tide-generating potentials and by prescribing boundary water levels derived from tidal constituents, often obtained from global tide models, including those that assimilate altimetry data (Lyard et al., 2021; Hart-Davis et al., 2021). Coupled tide-surge models explicitly represent non-linear interactions arising from depth-dependent bottom friction, advection, and water level dependent propagation speeds (Idier et al., 2012; Zhang et al., 2010). These interactions can substantially modulate extreme water levels (Arns et al., 2020), particularly in shallow regions with large tidal ranges. For regional system such as the Dutch Continental Shelf Model, improvements in tidal boundary conditions obtained from altimetry have been shown to enhance overall model performance (Hart-Davis et al., 2023).



Beyond tide–surge dynamics, several additional physical processes can contribute to coastal water levels but are not routinely resolved in large scale hydrodynamic models. Coastal hydrodynamic models typically do not explicitly resolve
290 ocean wave effects, which can contribute to coastal water levels through wave setup and wave runup, particularly during extreme events and along coasts with narrow continental shelves (Parker et al., 2023). Wave contributions can be represented either through linear addition of empirically derived wave setup based on wave model output, or through direct coupling between hydrodynamic and wave models. Several global studies have adopted simplified parameterisations of wave setup (e.g. Almar et al., 2021; Kirezci et al., 2020), but these approaches are associated with considerable uncertainty. Coupled
295 ocean-wave simulations can provide more accurate estimates of water levels (Bonaduce et al., 2020) but require a dedicated coupled wave model of a similar spatial scale to the hydrodynamic ocean model (Chaigneau et al., 2024a). Process based wave models that efficiently model wave setup based on offshore wave conditions at large scales are also emerging (Leijnse et al., 2024; Roelvink et al., 2025).

Another process that is generally not included in large-scale coastal hydrodynamic models is the effect of river discharge and
300 rainfall. Interactions between fluvial inflow and coastal water levels can be particularly important in deltas and estuaries, where compound effects may significantly amplify extreme water levels (Ikeuchi et al., 2017; Eilander et al., 2020).

From regional to global scales hydrodynamic models are widely used in operational forecasting, coastal hazard assessments and scenario studies, as they allow for detailed representation of bathymetry and coastlines, as well as integration of region-specific datasets. Such models are typically designed to resolve the dominant processes in a given region at high spatial
305 resolution. Numerous regional models exist, particularly in regions where storm surges have historically posed major risks, such as the United States, Northwestern Europe, Australia, India, and Bangladesh among others (Horsburg and de Vries, 2011). At the same time, global climate impact assessments require spatially consistent estimates of coastal water level variability. In addition, many low-income regions facing rapidly increasing coastal flood risk urgently require reliable information at locations not covered by regional models. While regional models remain indispensable for detailed local
310 analysis, their limited scalability and spatial coverage motivate the development of global hydrodynamic modelling approaches that provide a coherent framework across diverse coastal regimes. Such models can support national and international decision making related to climate adaptation and disaster risk reduction (Ward et al., 2018; Ward et al., 2020).

Whereas previously the modelling of coastal water levels at continental to global-scale was limited by the computational costs and lack of global input data, recent advances in numerical methods, computational resources, and global datasets have
315 enabled the development of continental to global scale hydrodynamic models suitable for large scale risk assessments under present and future climate conditions (e.g. Muis et al., 2016, 2020, 2023; Vousdoukas et al., 2016, 2018; Wang et al, 2025; Irazoqui Apecechea et al., 2025; Shirmura et al., 2022; Mentaschi et al., 2023). A key enabler has been the adoption of unstructured grids with spatially varying resolution, allowing kilometre scale resolution near the coast while maintaining coarser resolution offshore (Kernkamp et al., 2011). Examples of global models simulating tides and storm surge include
320 GTSM (Wang et al., 2022), NEMO-based configurations (Wang et al., 2023) and global ADCIRC applications (Pringle et al., 2020). Combined with high quality atmospheric reanalyses and tidal forcing, these models can now generate multi



decadal, globally complete coastal water level time series and can even be integrated in operational forecasting systems (Bernier et al., 2024).

Despite these advances, limitations persist near the coast. In some regions, model resolution remains insufficient to resolve
325 complex coastlines, semi-enclosed bays, barrier islands, and estuaries. Local grid refinement, dynamic downscaling, or sub
grid parameterisations can improve accuracy in such settings (Benito et al., 2025; Woodruff et al., 2023). In addition, the
quality of global bathymetry datasets -typically derived from GEBCO or ETOPO -limits the representation of nearshore
morphology, estuarine channels, and narrow inlets that strongly influence surge propagation and tidal amplification (Idier et
al., 2019; Rasquin et al., 2020; Muis et al., 2020). Errors in bathymetry and coastline geometry often lead to underestimation
330 or misrepresentation of local surge extremes, particularly in funnel-shaped estuaries or deltaic systems (Arns et al., 2020;
Orton et al., 2016). Model performance is further influenced by parameterisations of bottom friction and air–sea momentum
exchange, especially under extreme wind conditions such as tropical cyclones (e.g. Ozkan et al., 2025; Lin and Chavas et al.,
2012).

To mitigate these limitations, both dynamical and statistical downscaling approaches are applied. Dynamic downscaling uses
335 global model output as boundary conditions for high-resolution regional models, enabling refined bathymetry, coastline
geometry, and forcing data to be incorporated. Such nested frameworks have been shown to substantially improve the
simulation of extreme coastal water levels (Benito et al., 2025; Trošelj et al., 2021; Irazoqui Apecechea et al., 2025).
Alternatively, statistical downscaling and bias correction methods based on tide gauge observations, including machine
learning methods, can reduce systematic errors in large scale models (Li et al., 2026; Irazoqui Apecechea et al., 2025; Parker
340 et al., 2023; Cerrone et al., 2025). However, the effectiveness of these approaches remains constrained in many regions by
the sparse availability of long term in situ observations, particularly in the Global South (Haigh et al., 2022).

4.2 Baroclinic Processes and Mean Dynamic Topography

Depth-averaged tide-surge hydrodynamic models do not resolve the density-driven (baroclinic) processes associated with
temperature and salinity gradients and ocean circulation. These processes contribute to both the mean and low-frequency
345 variability of coastal water levels and can interact non-linearly with tides and storm surges, thus influencing the magnitude
and timing of extreme water levels, particularly in regions affected by strong steric variability or energetic boundary currents
(Camargo et al., 2025). The inclusion of baroclinic corrections has shown to improve performance in regional (e.g. Slobbe
et al., 2013; Zijl et al., 2022; Ye et al., 2020; Chaigneau et al., 2024b) and global hydrodynamic models (Wang et al., 2022b;
Wang and Bernier, 2025; Ye et al., 2020).

350 Low-frequency baroclinic water level changes manifest as seasonal fluctuations driven by variations in temperature and
salinity, as well as by large-scale ocean circulation. These signals can be reasonably approximated by annual and semi-
annual periodic components, although their amplitude and phase can exhibit considerable interannual variability depending
on the region (Vinogradov et al., 2008; Tsimplis & Woodworth, 1994; Plag & Tsimplis, 1999). In a depth-averaged regional
model, such low-frequency variability can be partially represented via boundary conditions informed by three-dimensional



355 ocean reanalysis datasets, such as GLORYS (Jean-Michel et al., 2021). However, the relatively coarse spatial resolution (~10
km) of these global products and the challenges associated with capturing non-linear interactions limit their direct
applicability. Where available, regional 3D models can provide a more consistent source of information on low-frequency
baroclinic water level variability, but these are complex to set up and require a comprehensive in situ observation network
for calibration and validation, not always available, particularly in the Global South. Satellite altimetry offers a promising
360 means of closing this gap, provided that the model configuration to include the data is designed in such a way that physical
processes represented by the data are included in such a way that they do not contribute more than once (double-counting) to
modelling coastal water level components.

Another manifestation of baroclinic processes is the mean dynamic topography (MDT), defined as the difference between
the mean sea surface and the geoid. MDT represents the time averaged baroclinic water level relative to an equipotential
365 reference surface and can reach amplitudes in the order of 1 metre (Jousset et al., 2026). In addition to its physical relevance,
MDT plays a crucial role in ensuring consistency between modelled coastal water levels and topographic data used for flood
modelling. Because hydrodynamic models operate relative to an internal reference surface, explicit consideration of MDT is
needed to harmonize the vertical reference of the model output with that of the geoid referenced digital elevation models,
thus avoiding systematic vertical offsets.

370 Various practical approaches have been proposed to account for the missing baroclinic processes in 2D hydrodynamic
models, including post-processing corrections, adjustments to atmospheric forcing, simplified coupling with ocean reanalysis
products and nudging approaches, each with specific assumptions and limitations. The simplest method is using post-
processing corrections to account for the MDT, this method has been widely applied in global studies (e.g. Kirezci et al.,
2020) and assumes that (i) MDT represents the mean baroclinic water level and (ii) this contribution can be linearly added to
375 tide and surge. Muis et al. (2018) has combined the results of a global barotropic model with steric water levels to account
for variations in water density. While the linear addition in post-processing generally performs well in deep water, it may
produce less accurate estimates of water levels in shallow regions, where the changes in mean water level have a stronger
influence on tidal propagation and storm surges.

To address the dynamic influence of baroclinicity on tide–surge propagation, forcing level adjustments have been proposed
380 in which processes not resolved by depth-averaged models are introduced as an equivalent pseudo atmospheric pressure
added to the meteorological forcing. Asher et al. (2019) show that low-frequency, large-scale contributions, including
baroclinic processes, steric variability, and far-field atmospheric forcing, can be incorporated into a barotropic surge model
in this way, substantially reducing water-level residuals. A more physically complete approach is the dynamical inclusion of
baroclinic effects, as described by Slobbe et al. (2013). In this method, depth averaged baroclinic pressure gradients are
385 computed diagnostically from temperature and salinity fields obtained from a 3D model and included in the momentum
equations under the Boussinesq approximation. While this approach better represents baroclinic physics, it requires
consistent 3D forcing and careful treatment of boundary conditions. Wang et al. (2022b; 2025) have addressed the gap in
baroclinic processes representation by nudging the temperature and salinity fields based on ocean reanalysis and including



simplified vertical layers to a barotropic model. In all cases, isolating the baroclinic signal remains challenging, and
390 inconsistencies between models, observations, and reference surfaces can be implicitly absorbed into the applied corrections.
Overall, the omission or simplified treatment of baroclinic processes and MDT remains a key limitation of depth averaged
coastal hydrodynamic models, particularly for applications requiring accurate estimates of absolute water levels and
extremes. Addressing these limitations is essential both for improving the physical realism of large scale coastal water level
simulations and for establishing a consistent vertical reference framework when integrating hydrodynamic models with flood
395 hazard and impact models. Satellite altimetry data has the potential to fill this gap as it is particularly well-suited for
quantifying low-frequency water level changes and defining vertical references. The methodological implications of
combining hydrodynamic models with satellite altimetry to increase modelled water level accuracy are discussed in more
detail in the following sections.

5 Strategies for combining satellite altimetry and hydrodynamic models

400 Satellite altimetry and hydrodynamic models can be combined in several ways to estimate coastal water levels. The choice of
approach depends on the dominant drivers, observational coverage, and the processes resolved by the model. Because
coastal environments vary strongly in these characteristics, no single approach is universally optimal. Existing methods
therefore form a continuum from diagnostic comparison to more tightly coupled integration frameworks. These approaches
share a common logic: fusion is most usefully understood as supplying the processes a model cannot itself resolve, subject to
405 the observation and the model representing the same processes on the same vertical reference (see Sect. 6).

5.1 Classes of approaches

Approaches for combining satellite altimetry observations with hydrodynamic models can be grouped into four conceptual
classes according to how altimetry information is used within the modelling system. These classes distinguish between
diagnostic use, boundary-condition or forcing constraints, data assimilation, and hybrid or stochastic approaches. How
410 satellite altimetry is combined with hydrodynamic models depends on data availability, computational cost, implementation
complexity, and the degree to which altimetry observations are representative of the coastal processes resolved by the model
(Rulent et al., 2020; Vignudelli & Biasio, 2021; Schumann et al., 2022; Schumann & Neal, 2021).

Validation and diagnostic use represents the least coupled and complex class. Here, satellite altimetry-derived water levels
are compared with model outputs to assess skill, identify systematic biases, and support model calibration. This approach
415 does not require modification of the hydrodynamic model and remains diagnostic, as it does not directly improve forecasts or
reanalyses in real time (Schumann et al., 2022; Tarpanelli et al., 2026). In coastal and estuarine settings, satellite altimetry
has been used to evaluate modelled sea-level variability and event-scale water-level anomalies, particularly offshore or near
estuary mouths (Diouf et al., 2025).



Boundary-condition and forcing enhancement uses satellite altimetry-derived information to constrain model inputs rather than outputs. In coastal applications, satellite altimetry has been used to inform open-boundary water levels and tidal constituents (Lyard et al., 2021; Hart-Davis et al., 2021). By acting at the boundaries, this approach can improve the large-scale consistency of simulated water levels while avoiding direct intervention in internal model dynamics, as demonstrated in studies showing improved boundary conditions and model skill when incorporating altimetry-derived information (Hart-Davis et al., 2023).

In data assimilation, satellite altimetry observations are used to update model states or parameters during model integration, typically using sequential or variational methods (e.g. Evensen, 1994; Le Dimet & Talagrand, 1986). These approaches aim to reduce forecast or hindcast errors but require explicit treatment of observation and model uncertainties and are more demanding in terms of implementation and computational cost (Stanev et al., 2016; Wilkin et al., 2022). Coastal applications demonstrate the potential of this approach. For example, Guarneri et al. (2023) assimilated altimetry-derived low-frequency water levels into a two-dimensional tide–surge model, demonstrating that this approach can substantially improve the representation of low-frequency variability when compared with tide-gauge observations. However, assimilation performance depends strongly on spatial representativeness and sampling, particularly in coastal regions where dynamics are complex and errors are less homogeneous (Edwards et al., 2024; Schumann et al., 2022).

Hybrid and stochastic approaches use satellite altimetry-derived information to adjust specific components of the hydrodynamic model or its outputs, rather than updating the full model state through assimilation. These methods focus on particular elements of the coastal water-level signal, such as tidal constituents or residual water levels, and typically represent uncertainty through stochastic or statistical formulations applied to these components. For example, Guarneri et al. (2025) apply stochastic refinement of tidal or water-level components using altimetry data without modifying the model state during integration. A related approach is residual-field correction, in which differences between model outputs and observations are modelled statistically and applied as spatially and temporally varying corrections to improve water-level estimates (Wang & Babovic, 2014). More broadly, hybrid strategies include stochastic forcing or generator frameworks, in which synthetic ensembles of sea-level or surge drivers are used to force hydrodynamic models or their surrogates, enabling improved characterisation of coastal water-level variability, particularly in data-sparse or compound-event settings (Wang et al., 2024).

5.2 Sources of inconsistency

Satellite altimetry, in situ observations, and hydrodynamic models do not represent coastal water levels in the same way. Differences between these systems arise from several distinct sources: (i) process mismatch, where observations and models do not resolve the same physical contributions; (ii) representativeness mismatch, due to differences in spatial and temporal sampling; and (iii) spatial leakage and signal mixing, arising from processing and mapping of observations. Figure 2 provides a conceptual illustration of the scale-dependent sampling of coastal water levels by different observing systems and models.

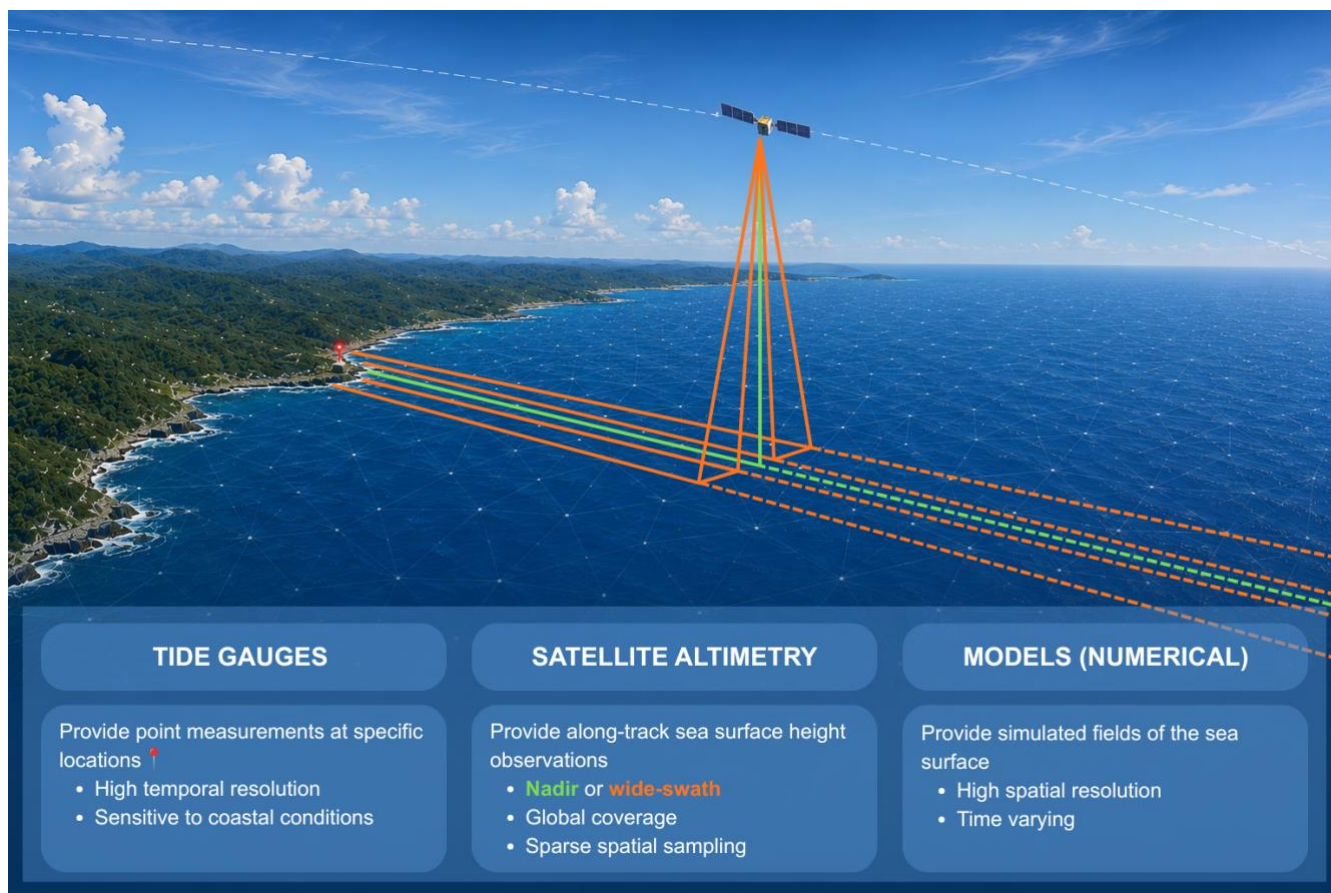


Figure 2. Conceptual illustration of scale-dependent sampling of coastal water levels by tide gauges, satellite altimetry, and hydrodynamic models, highlighting representativeness differences that affect comparison and integration. The background was generated using ChatGPT, the text and labels were added by the authors.

Satellite altimetry can capture tides, mean sea-level variability, and storm surge, but does not resolve nearshore wave-driven processes including wave setup, runup, and swash (Vignudelli et al., 2011; Apotsos et al., 2007; Holman, 1986; Dodet et al., 2020). In contrast, tide gauges sample total water levels at fixed coastal locations, reflecting the combined influence of all contributing components for that location, while hydrodynamic models represent these processes to varying degrees depending on their formulation, assumptions, resolution, and included physics. In addition, these systems sample coastal water levels at different spatial and temporal scales, with point measurements, spatially averaged observations, and grid-based model fields representing different space–time quantities (Schutgens et al., 2017; Rulent et al., 2020; Cipollini et al., 2016). None of these systems therefore captures the full coastal water-level signal at all relevant scales; instead, each provides a scale-filtered and process-dependent representation of the underlying dynamics (Rulent et al., 2020; Azevedo Correia de Souza et al., 2023; Guarneri et al., 2025).

In coastal environments, this representativeness mismatch manifests primarily through spatial and temporal sampling differences. Spatially, small offsets between observation and model locations, or differences between point measurements



and grid-cell averages, can lead to discrepancies of several decimetres that reflect unresolved variability rather than measurement uncertainty (Schutgens et al., 2017; Rulent et al., 2020; Oelsmann et al., 2021; Afrasteh et al., 2022; Azevedo
470 Correia de Souza et al., 2023; Guarneri et al., 2025). These discrepancies are particularly pronounced in regions with strong spatial gradients in water level components (e.g., estuaries, shelf breaks, and shallow coastal systems), where variability is not resolved by the effective sampling scale of the observation or the model. Temporally, intermittent sampling can miss short-lived peaks or distort estimates of extremes when observations do not coincide with maximum water levels (Rulent et al., 2020; Ray et al., 2021). This effect is compounded when models rely on sub-grid parameterisations or do not fully
475 resolve relevant processes, such that differences between observed and modelled water levels reflect both scale and process mismatch. Representativeness mismatch should therefore be treated as a structural component of coastal water-level comparison rather than a residual that can be removed through processing (Oelsmann et al., 2021; Mostafavi et al., 2023). Spatial leakage and signal mixing arise from the processing of altimetry data. Mapping and filtering procedures can redistribute variability and smooth coastal gradients, while imperfect corrections can propagate into gridded products,
480 contaminating nearshore signals (Taburet et al., 2019; Zaron & Ray, 2018). These effects are distinct from sampling differences and can introduce apparent inconsistencies unrelated to physical processes. In practice, spatial leakage is often introduced during the mapping stage, where interpolation and smoothing redistribute variability and damp sharp coastal gradients, transferring offshore signals into the coastal zone (Taburet et al., 2019). Additional signal mixing can arise when imperfect tidal or high-frequency corrections propagate into gridded products,
485 contaminating sea-level anomaly fields, particularly near the coast (Zaron & Ray, 2018). As a result, apparent differences between observations and models may reflect processing artefacts rather than physical inconsistencies. These effects are generally small offshore but can become substantial in coastal regions where gradients are strong. Careful treatment is therefore required in model–data fusion and intercomparison, including appropriate collocation, filtering, and product selection, and assimilation frameworks must account for mapping and correction errors to avoid introducing spurious
490 variability into the model state (Taburet et al., 2019; Zaron & Ray, 2018) or use the along-track data directly. These sources of inconsistency have direct implications for model–data comparison and integration. Meaningful comparison requires ensuring commensurability in terms of represented processes, spatial and temporal scales, and vertical reference surfaces. Without this, apparent differences may be misinterpreted as model error. In integration frameworks, these effects must be accounted for explicitly to avoid introducing spurious variability.

495 **5.3 Integration during extreme events**

During extreme events, combining satellite altimetry and hydrodynamic models becomes particularly challenging due to sparse sampling and strong temporal variability. There are three main challenges to EO–model integration during extremes: (i) temporal alignment of observations and model output, (ii) sampling of the event evolution, and (iii) attribution of the observed signal to the relevant physical processes.



Temporal alignment is critical because extreme water level peaks depend on the timing of tides, surge, and waves (Sect. 2). For useful integration, simulation output times need to match observation times because differences in timing can lead to large apparent discrepancies, even when magnitudes are consistent (Ji & Li, 2020; Srinivasan & Tsonetos, 2023). Apparent mismatches between observations and model output may reflect timing misalignment rather than deficiencies in the simulated dynamics. Integration approaches that rely on event-scale information are therefore only effective when observations constrain the evolving phase of the event, rather than background conditions (Slater et al., 2020; Umgiesser et al., 2022).

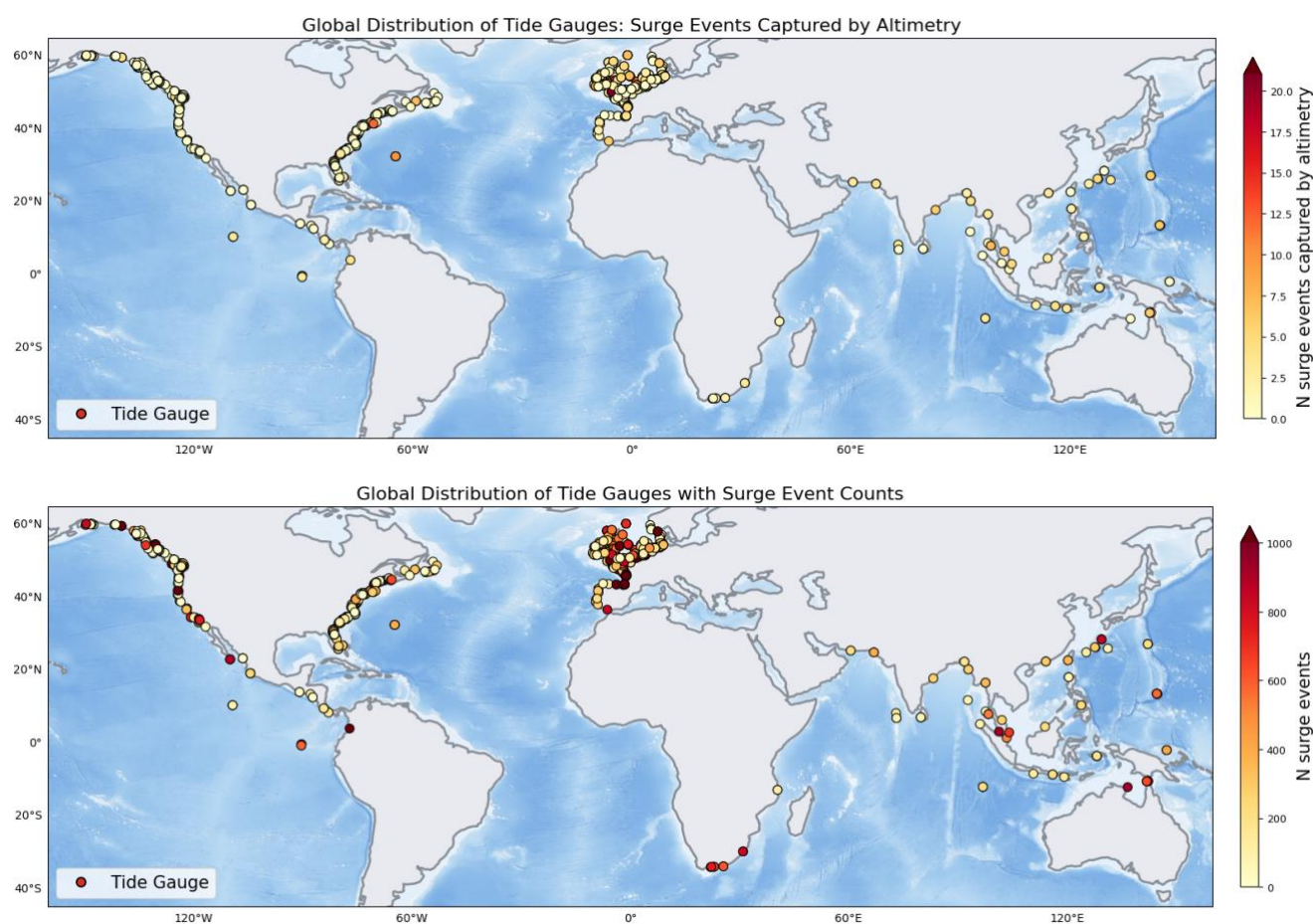


Figure 3. Event-scale sampling of coastal extremes by satellite altimetry (from Johnson et al., 2026). Spatial distribution of tide gauge identified extreme events coinciding with altimeter overpasses and the corresponding differences, illustrating the heterogeneous and episodic sampling of extremes rather than measurement accuracy. The upper panel depicts the distribution of tide gauges located within altimetry data regions with the number of surge events occurring during an altimetry overpass. The lower panel details the gauge distribution with the number of surge events per location computed from the tide gauge surge series.

Event sampling concerns whether the event is observed at all. Since satellite altimetry provides intermittent observations along discrete ground tracks (Sect. 3), extreme coastal water-level events may not be sampled at their peak or may not be sampled at all. This can lead to biases in event-based validation and distortions in extreme-value estimates when unobserved



peaks are implicitly treated as model error (Ji & Li, 2020; Srinivasan & Tsonos, 2023). Events are often only partially sampled, for example offshore or during either the rising or falling limb, such that model–observation differences reflect sampling geometry rather than deficiencies in the simulated dynamics (Slater et al., 2020). Figure 3 illustrates these constraints, showing that coincidence between altimeter overpasses and extreme coastal events is spatially uneven and often sparse.

Process attribution concerns which physical drivers are represented in the combined observation–model signal. For example, satellite altimetry primarily reflects sea-level contributions to water level while wave-driven processes remain unresolved (Sect. 3), and models represent these processes to varying degrees depending on their formulation (Sect. 4) (Zhang et al., 2021; Xu et al., 2022b). As a result, agreement or mismatch between observations and models may reflect differences in the processes being represented rather than the full water-level signal. Consequently, integration during extremes must be interpreted in terms of which drivers are effectively constrained by the available observations (Sun et al., 2024; Umgiesser et al., 2022).

These challenges highlight that integration during extremes depends not only on data availability but on careful consideration of timing, sampling, and process representation.

The strategies described above are necessary but not sufficient for consistent estimation of extreme coastal water levels. Their outputs are only meaningful when satellite altimetry and model results are expressed relative to a consistent vertical reference, validated against independent observations, and accompanied by a coherent characterisation of their uncertainties. These cross-cutting requirements are addressed in the following section.

6 Ensuring commensurability: vertical referencing, validation, and uncertainty

Consistent estimation of extreme coastal water levels requires that satellite altimetry and model outputs be not only combined but rendered commensurable. Three requirements cut across the integration strategies of Sect. 5 and the observing and modelling systems of Sect.s 3 and 4: a consistent vertical reference surface, validation against independent observations, and a coherent treatment of uncertainty. Each is considered in turn below.

6.1 Why vertical referencing is a cross-cutting problem

An additional prerequisite for integrating EO- and modelling-derived extreme coastal water levels is that both are expressed relative to a consistent, well-defined vertical reference surface. Otherwise, differences exceeding several decimetres may arise, directly contaminating estimates of extreme water levels and flood depths.

The model-derived coastal water levels are referenced to the model’s internal reference surface. This surface has often been identified as mean sea level (e.g., Mouthaan et al., 1994; Heemink et al., 2002; Iliffe et al., 2007; Dodd et al., 2010). However, as noted by Hughes and Bingham (2008) and Slobbe et al. (2013), the interpretation that a model’s internal reference surface represents mean sea level is incorrect. This follows directly from the fact that the dynamics of such models



typically assume zero horizontal gravity components, implying that the model's vertical reference surface is an equipotential surface of the Earth's gravity field (a so-called geopotential surface, or level surface) – a surface that is characterized by constant gravity potential. In contrast, the mean sea level is not an equipotential surface because of mean dynamic topography.

The internal reference surface is therefore the same type of surface as the geoid, which, alongside ellipsoids, is commonly used to express elevations on land and water levels offshore (see Hofmann-Wellenhof and Moritz (2005) for a comprehensive introduction and Meyer et al. (2006) for a concise overview). The geoid, however, is merely one of an infinite number of possible geopotential surfaces, each of which is characterized by its own value of gravity potential. In practice, the specific geopotential surface selected as the vertical reference surface varies between countries and regions. In global applications, the equipotential surface that best fits global mean sea level is typically selected (see Sánchez et al. (2016) for details).

6.2 Vertical referencing workflow

The sequence of steps required to replace the geopotential surface corresponding to the model's reference surface with the one described by the geoid model is referred to as 'vertical referencing'. At a minimum, these steps include (i) expressing the model bathymetry relative to the chosen geoid model, and (ii) prescribing water levels along the open-ocean boundaries relative to the same geoid model. It may also be necessary to express the overflow heights of special hydrodynamic features (such as barriers, weirs, and sluices) relative to the geoid. These practical implications for hydrodynamic modelling were explicitly discussed by Slobbe et al. (2013).

The water levels prescribed as open boundary conditions should be total water levels. However, these refer to a geopotential surface that does not necessarily coincide with the one described by the chosen geoid model. The difference in gravity potential results in a geometric offset that can be assumed to be spatially constant for regional and local models (see Slobbe et al., 2013). Therefore, the required datum shift can be computed from the differences between observation- and model-derived mean water levels over an arbitrary part of the model domain. The use of mean water levels is not strictly required for estimating the datum shift, but it reduces the influence of random and short-term variations, thereby providing a more robust estimate of the offset. Regions prone to errors in either of these estimates—such as coastal zones and areas along the open model boundaries—can be excluded from this analysis.

Vertical referencing model bathymetry presents additional challenges. The main challenges are that (i) bathymetry is typically adjusted during model calibration and (ii) the vertical datum of the bathymetry is often unknown. Consequently, it is frequently unclear how the bathymetry should be transformed consistently. Assuming that the model bathymetry is referenced to mean sea level, Slobbe et al. (2013) found that, for the Wadden Sea, vertically transforming the bathymetry to the geoid had a significant impact (>6 cm) only in the intertidal regions. On average, however, the effect was negligible, with a mean impact on model-derived mean water levels of 0.01 cm. It should be noted, however, that modifying the bathymetry generally requires recalibration of the hydrodynamic model.



6.3 Uncertainty in vertical referencing

6.3.1 Uncertainty in the datum shift

Any error in the estimated datum shift propagates one-to-one into the model-derived (extreme) water levels. Systematic errors in the datum shift may originate from several sources. These include systematic errors in the observation-derived and model-derived mean water levels, as well as errors inherited from the geoid model to which the observation-derived water levels are referenced. A third source consists of inconsistencies between the observation-derived and model-derived mean water levels that are unrelated to differences in vertical reference. Examples of such inconsistencies are discussed in Sect. 5.2. The impact of these errors and inconsistencies depends partly on the spatial domain over which the datum shift is estimated. If the domain chosen is too small, the estimate may become sensitive to local errors and representativeness issues. A detailed error budget for the model-derived and observation-derived water levels is beyond the scope of this review. Instead, the discussion below focuses on one of the key contributors to vertical-referencing uncertainty: the accuracy of contemporary geoid models.

6.3.2 Uncertainty in geoid models

Over the ocean, modern geoid models rely predominantly on satellite-altimetry-derived gravity information (e.g., Louis et al., 2010; Andersen, 2013). The spatial coverage and sampling density of altimetry-derived gravity field information over open ocean have improved substantially over recent decades through the accumulation of geodetic mission phases (e.g., Sandwell et al., 2021). Furthermore, unlike conventional nadir altimeters, which provide gravity-sensitive observations primarily in the along-track direction, SWOT's swath altimetry enables the recovery of both along- and cross-track geoid gradients (or deflections of the vertical), thereby providing access to the full gravity field signal (e.g., Li et al., 2025; Zhu et al., 2025).

Nevertheless, altimetry-derived gravity field functionals remain less reliable in shallow-water and coastal regions (e.g., Andersen and Knudsen, 2000; Annan and Wan, 2021), mainly due to the reduced quality of altimetry data in coastal regions (Vignudelli et al., 2011) and uncertainties in the dynamic topography corrections (e.g., Slobbe and Klees, 2014). As a result, the quality of geoid models generally deteriorates towards the coast.

In some regions, altimetry-derived gravity information is supplemented by shipborne gravimetry data. Although these measurements may provide valuable short-wavelength information, many datasets were acquired prior to the widespread availability of GNSS positioning and may therefore contain systematic errors (Wessel and Watts, 1988). Moreover, their spatial coverage is often highly inhomogeneous (e.g., Watts et al., 2020), with dense observations in offshore exploration areas and large gaps elsewhere. Such sampling characteristics complicate the consistent recovery of coastal gravity signals.

The uncertainty of a geoid model is commonly interpreted as the combination of omission and commission errors (e.g., Losch et al., 2002). Omission errors arise because the available gravity observations do not fully resolve the short-



wavelength structure of the gravity field. Commission errors originate from measurement noise and systematic errors in gravity observations and gravity field models used for geoid determination.

The distinction between omission and commission errors is particularly relevant in coastal applications. Over the open ocean, gravity-field gradients are generally smooth and omission errors tend to remain limited, except near major bathymetric features such as continental shelf breaks, ocean trenches, and seamount chains. Along coastlines, however, both omission and commission errors typically increase because the gravity field varies more rapidly and because observation density and quality often deteriorate. Consequently, the uncertainty of a geoid model is inherently spatially variable and depends strongly on the density, distribution, and quality of the gravity observations available in a particular region. Farahani et al. (2017) provide empirical relationships that quantify the commission and omission errors as a function of data spacing and measurement precision.

6.4 Validation

For modelled and altimetry-derived sea-level and sea-state products, validation strategies generally rely on comparison with records from tide-gauges and buoys, using collocated time series and common geophysical corrections to ensure consistency (e.g., Cazenave et al., 2022; Dodet et al., 2020). Such validation is essential not only for establishing the standalone performance of EO products, but also for determining their suitability for constraining hydrodynamic model boundary conditions, assessing model skill across diverse coastal environments, and exposing uncertainties in observational and modelling datasets.

For EO sea-level products derived from satellite altimetry, validation generally relies on comparisons with tide-gauge observations located as close as possible to the altimetry track. The evaluation is typically based on standard statistical metrics, such as the correlation coefficient, RMSE, and trend differences, and is meant to quantify the agreement between altimetry and in-situ measurements. In this context, ensuring consistency between tide-gauge and altimetry datasets in terms of geophysical components (tidal height, atmospheric contribution to the sea level) and reference surfaces is crucial, as discrepancies can introduce systematic centimeter-scale offsets in the coastal zone (e.g., Cazenave et al., 2022). In addition, at finer spatial scales, complementary validation approaches, such combining tide gauges with video monitoring systems, have been employed to investigate the influence of wave-related processes on altimetry-derived sea-level estimates (Abessolo et al., 2023).

The commonly used metrics (e.g, correlation coefficient, RMSE, mean bias) are well suited in data-rich environments, such as the North Sea, where validation consists of pointwise comparisons with in-situ observations. It should be noted, though, that the performance metrics are generally selected according to the characteristics of available in-situ data. As such, in data-sparse estuarine and deltaic settings, validation typically relies on multi-source consistency checks. This involves comparing models, EO, and available in-situ measurements during overlapping periods (e.g., Diouf et al., 2025), or for documented extreme events, such as Cyclone Idai (e.g., Probst and Annunziato, 2019).



6.5 Uncertainty sources

645 Quantifying uncertainties in coastal water level estimates is important for interpreting EO products, assessing hydrodynamic model skill, and evaluating the robustness of extreme water-level statistics. Previous work has shown that uncertainties arise from multiple sources, including observational errors in satellite altimetry and in-situ observations, model structural and parametric choices, meteorological and oceanic forcing, and statistical estimation of extremes. Comprehensive coastal impact assessments therefore distinguish between different types of uncertainty (e.g., measurement, model, scenario, and sampling uncertainty) and aim to quantify their relative contributions to projected changes in sea level and extreme water levels (e.g., van de Wal et al., 2019).

For EO-based coastal sea-level products, uncertainty might result from instrumental noise, retracking choices, geophysical corrections, orbit errors, and inter-mission biases (e.g., ESA, 2019). Within this context, in a recent round-robin analysis of multiple retracking and correction algorithms, Birol et al. (2025) show how the dispersion among solutions, and thus the uncertainty, increases toward the coast, and they validate the resulting sea-level anomalies against tide-gauge records, quantifying the uncertainty associated with each component.

For altimetry-derived significant wave height, uncertainty quantification commonly relies on a combination of direct buoy-satellite comparisons and triple-collocation analyses. These methods allow the partitioning of random errors among altimeters, buoys, and numerical wave models, and they provide variance estimates that depend on sea-state conditions and, in some studies, proximity to the coast (Caires and Sterl, 2003; Wang et al., 2014; Dodet et al., 2022). In light of that, the development of a multi-mission significant wave height climate data record is recommended to include a systematic error characterisation and inter-mission consistency assessments, as done, for example, within the ESA Sea-State CCI project (Dodet et al., 2020).

Uncertainty quantification is equally important in hydrodynamic modelling of coastal water levels. Process-based models of tides and surge are sensitive to wind and pressure forcing, bottom friction, bathymetry, and open-boundary conditions; ensemble and sensitivity studies show that different plausible configurations can lead to centimetre- to decimetre-scale differences in simulated coastal water levels and extremes (e.g., Lyddon et al., 2020). A variance-based global sensitivity analysis has been used to decompose the contribution of different inputs, such as sea-level rise, astronomical tide, and surge, to variability in extreme coastal water levels, providing a quantitative ranking of key drivers and highlighting which parameters and forcings require tighter constraints (Dalinghaus et al., 2025).

Based on these studies, it follows that robust coastal water-level estimation requires (i) explicit error budgets and validation-based uncertainty estimates for EO sea-level and sea-state products, including their degradation near the coast, and (ii) ensemble or sensitivity-based assessments of hydrodynamic model uncertainty associated with forcings, parameterisations, and boundary conditions.



675 7 Synthesis: advances, limitations, and future directions

The central challenge in combining satellite altimetry and hydrodynamic modelling is not simply how to merge two sources of coastal water-level information, but how to ensure that they represent commensurable quantities. Extreme coastal water levels arise from interacting processes that operate across a wide range of spatial and temporal scales, while satellite altimetry and hydrodynamic models each provide only partial, scale-dependent representations of the total signal. As a result, integration is only meaningful when differences in process representation, sampling, and vertical reference are treated explicitly rather than absorbed into residual error.

Over the past decade, treatment of coastal water levels has evolved from linear superposition of components towards a more integrated understanding of non-linear interactions and compound effects involving tides, atmospheric pressure and winds, baroclinic and steric variability, and wave-driven processes. In parallel, improved retracking algorithms and geophysical corrections have extended altimetry closer to the coast, while global and regional hydrodynamic modelling frameworks have improved through unstructured grids, coherent large-scale boundary conditions, and downscaling approaches, as reviewed in Sect.s 2–4. These advances have expanded the information available for coastal water-level estimation, but they do not by themselves ensure that the resulting products are mutually comparable.

Advances in satellite altimetry and hydrodynamic modelling have supported a growing range of EO–model integration strategies, spanning diagnostic comparison, boundary-condition constraints, data assimilation, and hybrid approaches, as reviewed in Sect. 5. No single integration strategy is universally optimal. Suitability depends on the dominant processes, the spatial and temporal scales at which they operate, the extent to which those processes are resolved by the observing and modelling systems, and the availability of validation data.

Several barriers therefore continue to limit consistent estimation of extreme coastal water levels at regional to global scales. Satellite altimetry does not resolve wave-driven processes at the shoreline, while hydrodynamic models often omit or approximate wave effects, baroclinic contributions, and compound river–coastal interactions. Sparse along-track sampling, spatial offsets, and scale mismatches further complicate event-scale interpretation. Bathymetric uncertainty, complex coastline geometry, inconsistent vertical references, and fragmented treatment of observational, model, and statistical uncertainty remain major sources of non-comparability, as reviewed in Sect.s 3–6.

Future progress requires a shift from combining datasets towards ensuring their commensurability. The meaningful fusion of satellite altimetry and hydrodynamic models rests on two conditions: the observation and the model must represent the same processes, and both must share the same vertical reference. Consistent vertical referencing should therefore be treated as a prerequisite rather than a post-processing step, and uncertainty frameworks need to propagate measurement error, model uncertainty, representativeness differences, and sampling limitations consistently from observations through modelling to extreme-value estimation. Both requirements, together with validation against independent observations, are addressed in Sect. 6.



Within this constraint, fusion can be understood as supplying the processes a model cannot itself resolve. Where a three-dimensional model represents these processes internally, altimetry could be used to constrain the event-scale state; where a depth-averaged model omits baroclinic, low-frequency, and mean dynamic topography contributions, fusion serves to reintroduce them. These approaches are not mutually exclusive: once a depth-averaged model has been rendered process- and datum-commensurate, data assimilation and hybrid methods can be layered upon it to refine extremes, provided the resulting uncertainty is made explicit. The priority is therefore not only to combine satellite altimetry and hydrodynamic models more widely, but to define when such combinations are physically meaningful, vertically consistent, uncertainty-aware, transferable across coastal regimes, and fit for purpose.

715 **Code and data availability**

No new datasets or software code were generated or analysed for this article. This manuscript is a narrative review based on previously published literature, datasets, and model products cited throughout the text. Accordingly, there are no author-generated data or code files to deposit in a public repository.

Author contributions

720 Björn Backeberg, Jemma Johnson, Natalia Aleksandrova, Cornelis Slobbe, Fabio Mangini, Marcello Passaro, Sanne Muis, Pavel Ditmar, Antonio Bonaduce, Gundula Winter, and Michael Hart-Davis contributed to the conceptualisation, writing of the original draft, review, and editing of the manuscript. Jemma Johnson and Michael Hart-Davis prepared the visualisations. All authors read and approved the final manuscript.

Competing interests

725 The authors declare that they have no conflict of interest.

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References

- Abessolo, G. O., Birol, F., Almar, R., Léger, F., Bergsma, E., Brodie, K., and Holman, R.: Wave influence on altimetry sea level at the coast, *Coastal Engineering*, 180, 104275, <https://doi.org/10.1016/j.coastaleng.2022.104275>, 2023.
- Afrasteh, Y., Slobbe, D., Verlaan, M., Klees, R., Guarneri, H., Keyzer, L., Pietrzak, J., Sacher, M., Snellen, M., and Zijl, F.: An empirical noise model for the benefit of model-based hydrodynamic leveling, *Journal of Geodesy*, 97, <https://doi.org/10.1007/s00190-022-01694-x>, 2022.
- Andersen, O. B.: Marine Gravity and Geoid from Satellite Altimetry, in: *Geoid Determination, Lecture Notes in Earth System Sciences*, edited by: Sansò, F. and Sideris, M., Springer, Berlin, Heidelberg, 110, https://doi.org/10.1007/978-3-540-74700-0_9, 2013.
- Andersen, O. B., Cheng, Y., Deng, X., Steward, M., and Gharineiat, Z.: Using satellite altimetry and tide gauges for storm surge warning, *Proceedings of HP2/HP3, IAHS Publication*, 365, 28–34, <https://doi.org/10.5194/piahs-365-28-2015>, 2015.
- Andersen, O. B. and Knudsen, P.: The role of satellite altimetry in gravity field modelling in coastal areas, *Physics and Chemistry of the Earth, Part A: Solid Earth and Geodesy*, 25(1), 17–24, [https://doi.org/10.1016/S1464-1895\(00\)00004-1](https://doi.org/10.1016/S1464-1895(00)00004-1), 2000.
- Annan, R. F. and Wan, X.: Recovering Marine Gravity Over the Gulf of Guinea From Multi-Satellite Sea Surface Heights, *Front. Earth Sci.*, 9, 700873, <https://doi.org/10.3389/feart.2021.700873>, 2021.



- Antony, C., Testut, L., and Unnikrishnan, A. S.: Observing storm surges in the Bay of Bengal from satellite altimetry, *Estuarine, Coastal and Shelf Science*, 151, 131–140, <https://doi.org/10.1016/j.ecss.2014.09.012>, 2014.
- Arns, A., Dangendorf, S., Jensen, J. et al.: Sea-level rise induced amplification of coastal protection design heights, *Sci Rep*, 7, 4017, <https://doi.org/10.1038/srep40171>, 2017.
- <https://doi.org/10.1029/2006JC003549>
- Arns, A., Wahl, T., Dangendorf, S., and Jensen, J.: The impact of sea level rise on storm surge water levels in the northern part of the German Bight, *Coastal Engineering*, 96, 118–131, <https://doi.org/10.1016/j.coastaleng.2014.12.002>, 2015.
- Arns, A., Wahl, T., Wolff, C. et al.: Non-linear interaction modulates global extreme sea levels, coastal flood exposure, and impacts, *Nat Commun*, 11, 1918, <https://doi.org/10.1038/s41467-020-15752-5>, 2020.
- Asher, T. G., Luettich, R. A., Jr., Fleming, J. G., and Blanton, B. O.: Low frequency water level correction in storm surge models using data assimilation, *Ocean Modelling*, 144, 101483, <https://doi.org/10.1016/j.ocemod.2019.101483>, 2019.
- Azevedo Correia de Souza, J. M., Suanda, S. H., Couto, P. P., Smith, R. O., Kerry, C., and Roughan, M.: Moana Ocean Hindcast – a >25-year simulation for New Zealand waters using the Regional Ocean Modeling System (ROMS) v3.9 model, *Geosci. Model Dev.*, 16, 211–231, <https://doi.org/10.5194/gmd-16-211-2023>, 2023.
- Bajo, M., De Biasio, G., Vignudelli, S., and Zecchetto, S.: Impact of using scatterometer and altimeter data on storm surge forecasting, *Ocean Modelling*, 118, 14–24, <https://doi.org/10.1016/j.ocemod.2017.03.014>, 2017.
- Benito, I., Aerts, J. C. J. H., Ward, P. J., Eilander, D., and Muis, S.: A multiscale modelling framework of coastal flooding events for global to local flood hazard assessments, *Nat. Hazards Earth Syst. Sci.*, 25, 2287–2315, <https://doi.org/10.5194/nhess-25-2287-2025>, 2025.
- Benveniste, J., Cazenave, A., Vignudelli, S., Fenoglio-Marc, L., Shah, R., Almar, R., Andersen, O., Birol, F., Bonnefond, P., Bouffard, J., Calafat, F., Cardellach, E., Cipollini, P., Le Cozannet, G., Dufau, C., Fernandes, M. J., Frappart, F., Garrison, J., Gommenginger, C., Han, G., Hoyer, J. L., Kourafalou, V., Leuliette, E., Li, Z., Loisel, H., Madsen, K. S., Marcos, M., Melet, A., Meyssignac, B., Pascual, A., Passaro, M., Ribó, S., Scharroo, R., Song, Y. T., Speich, S., Wilkin, J., Woodworth, P., and Wöppelmann, G.: Requirements for a coastal hazards observing system, *Frontiers in Marine Science*, 6, 348, <https://doi.org/10.3389/fmars.2019.00348>, 2019.
- Bernier, N. B. et al.: Storm surges and extreme sea levels: Review, establishment of model intercomparison and coordination of surge climate projection efforts (SurgeMIP), *Weather and Climate Extremes*, 45, <https://doi.org/10.1016/j.wace.2024.100689>, 2024.
- Bij de Vaate, I., Slobbe, D. C., and Verlaan, M.: Mapping the spatiotemporal variability in global storm surge water levels using satellite radar altimetry, *Ocean Dynamics*, 74(3), 169–182, <https://doi.org/10.1007/s10236-023-01596-2>, 2024.
- Birol, F., Bignalet-Cazalet, F., Cancet, M., Daguze, J., Fkaier, W., Fouchet, E., Léger, F., Maraldi, C., Niño, F., Pujol, M., and Tran, N.: Understanding uncertainties in the satellite altimeter measurement of coastal sea level: Insights from a round-robin analysis, *Ocean Science*, 21, 133–155, <https://doi.org/10.5194/os-21-133-2025>, 2025.



- Birol, F., Fuller, N., Lyard, F., Cancet, M., Niño, F., Delebecque, C., Fleury, S., Toubanc, F., Melet, A., Saraceno, M., and Léger, F.: Coastal applications from nadir altimetry: Example of the X-TRACK regional products, *Advances in Space Research*, 59(4), 936–953, <https://doi.org/10.1016/j.asr.2016.11.005>, 2017.
- 795 Birol, F., Léger, F., Passaro, M., Cazenave, A., Niño, F., Calafat, F. M., Shaw, A., Legeais, J.-F., Gouzenes, Y., Schwatke, C., and Benveniste, J.: The X-TRACK/ALES multi-mission processing system: New advances in altimetry towards the coast, *Advances in Space Research*, 67(8), 2398–2415, <https://doi.org/10.1016/j.asr.2021.01.049>, 2021.
- Bonaduce, A., Staneva, J., Grayek, S. et al.: Sea-state contributions to sea-level variability in the European Seas, *Ocean Dynamics*, 70, 1547–1569, <https://doi.org/10.1007/s10236-020-01404-1>, 2020.
- 800 Bonaduce, A., Pham, N. T., Staneva, J. et al.: Sea state contributions to thermosteric sea-level in high-resolution ocean-wave coupled simulations, *Ocean Dynamics*, 74, 743–761, <https://doi.org/10.1007/s10236-024-01632-9>, 2024.
- Caballero, A., Mulet, S., Ayoub, N., Manso-Narvarte, I., Davila, X., Boone, C., Toubanc, F., and Rubió, A.: Integration of HF Radar Observations for an Enhanced Coastal Mean Dynamic Topography, <https://doi.org/10.3389/fmars.2020.588713>, 2020.
- 805 Caires, S. and Sterl, A.: Validation of ocean wind and wave data using triple collocation, *Journal of Geophysical Research: Oceans*, 108(C2), 3098, <https://doi.org/10.1029/2002JC001491>, 2003.
- Camargo, C. M., Piecuch, C. G., and Raubenheimer, B.: Do ocean dynamics contribute to coastal floods? A case study of the Shelfbreak Jet and coastal sea level along Southern New England (US), *Earth's Future*, 13(10), e2025EF006708, 2025.
- Cavaleri, L., Bertotti, L., Ferrarin, C., Passaro, M., Pezzutto, P., and Pomaro, A.: Synergic use of altimeter and model sea-level data in inner and coastal seas, *Remote Sensing of Environment*, 261, 112500, <https://doi.org/10.1016/j.rse.2021.112500>, 2021.
- 815 Cazenave, A., Gouzenes, Y., Birol, F., Léger, F., Passaro, M., Calafat, F. M., Shaw, A., Niño, F., Legeais, J.-F., Oelsmann, J., Restano, M., and Benveniste, J.: Sea level along the world's coastlines can be measured by a network of virtual altimetry stations, *Communications Earth & Environment*, 3, Article 117, <https://doi.org/10.1038/s43247-022-00448-z>, 2022.
- Cerrone, A. R., Westerink, L. G., Ling, G., Blakely, C. P., Wirasaet, D., Dawson, C., and Westerink, J. J.: Correcting Physics-Based Global Tide and Storm Water Level Forecasts with the Temporal Fusion Transformer, *Ocean Modelling*, 195, 102509, doi:10.1016/j.ocemod.2025.102509, 2025.
- 820 Chaigneau, A. A., Melet, A., Voldoire, A., Irazoqui Apecechea, M., Reffray, G., Law-Chune, S., and Aouf, L.: Dynamic projections of extreme sea levels for western Europe based on ocean and wind-wave modelling, *Nat. Hazards Earth Syst. Sci.*, 24, 4031–4048, <https://doi.org/10.5194/nhess-24-4031-2024>, 2024a.
- Chaigneau, A. A., Menéndez, M., Ramírez-Pérez, M., and Toimil, A.: Regional modelling of extreme sea levels induced by hurricanes, *Nat. Hazards Earth Syst. Sci.*, 24, 4109–4131, <https://doi.org/10.5194/nhess-24-4109-2024>, 2024b.
- Cipollini, P., Calafat, F. M., Jevrejeva, S., Melet, A., and Prandi, P.: Monitoring sea level in the coastal zone with satellite altimetry and tide gauges, *Surveys in Geophysics*, 38(1), 33–57, <https://doi.org/10.1007/s10712-016-9392-0>, 2016.



- 825 Collings, T., Murphy-Barltrop, C., Murphy, C., Haigh, I., Bates, P., and Quinn, N.: Automated tail-informed threshold selection for extreme coastal sea levels, *Natural Hazards and Earth System Sciences*, [https://doi.org/10.5194/nhess-25-4545-](https://doi.org/10.5194/nhess-25-4545-2025)2025, 2025.
- Costa, W., Bryan, K., Stephens, S., and Coco, G.: A regional analysis of tide–surge interactions during extreme water levels in complex coastal systems of Aotearoa New Zealand, *Frontiers in Marine Science*, 10, 1170756, <https://doi.org/10.3389/fmars.2023.1170756>, 2023.
- 830 Couasnon, A., Eilander, D., Muis, S., Veldkamp, T., Haigh, I., Wahl, T., Winsemius, H., and Ward, P.: Measuring compound flood potential from river discharge and storm surge extremes at the global scale, *Natural Hazards and Earth System Sciences*, 20, 489–504, <https://doi.org/10.5194/nhess-20-489-2020>, 2020.
- Dalinghaus, C., Coco, G., and Higuera, P.: Assessing Total Water Level Uncertainties Using Global Sensitivity Analysis, *Journal of Geophysical Research: Oceans*, 130, e2025JC023011, <https://doi.org/10.1029/2025JC023011>, 2025.
- 835 De Almeida, L., Almar, R., Meyssignac, B., and Viet, N.: Contributions to Coastal Flooding Events in Southeast of Vietnam and their link with Global Mean Sea Level Rise, *Geosciences*, <https://doi.org/10.3390/geosciences8120437>, 2018.
- De Carlo, M. and Ardhuin, F.: Along-track resolution and uncertainty of altimeter-derived wave height and sea level: Re-defining the significant wave height in extreme storms, *Journal of Geophysical Research: Oceans*, 129(6), Article e2023JC020832, <https://doi.org/10.1029/2023JC020832>, 2024.
- 840 De Mey-Frémaux, P., Ayoub, N., Barth, A., Brewin, R., Charria, G., Campuzano, F., Ciavatta, S., Cirano, M., Edwards, C., Federico, I., Gao, S., Hermosa, I., Sotillo, M., Hewitt, H., Hole, L., Holt, J., King, R., Kourafalou, V., Lu, Y., Murre, B., Pascual, A., Staneva, J., Stanev, E., Wang, H., and Zhu, X.: Model-Observations Synergy in the Coastal Ocean, *Frontiers in Marine Science*, <https://doi.org/10.3389/fmars.2019.00436>, 2019.
- 845 <https://doi.org/10.5194/nhess-25-1769-2025>
- Diouf, A., Salameh, E., Sakho, I., Sow, B. A., Deloffre, J., López Solano, C., Turki, E. I., and Lafite, R.: Use of SWOT Data for Hydrodynamic Modelling in a Tropical Microtidal Estuarine System: The Case of Casamance (Senegal), *Remote Sens.*, 17, 3252, <https://doi.org/10.3390/rs17183252>, 2025.
- Dodet, G., Piecuch, C., and Broche, R.: Error characterization of significant wave heights in global altimeter wave products using the triple collocation technique, *Journal of Atmospheric and Oceanic Technology*, 39(7), 887-901, <https://doi.org/10.1175/JTECH-D-21-0179.1>, 2022.
- 850 Dodet, G., Piolle, J.-F., Quilfen, Y., Abdalla, S., Accensi, M., Ardhuin, F., Ash, E., Bidlot, J.-R., Gommenginger, C., Marechal, G., Passaro, M., Quartly, G., Stopa, J., Timmermans, B., Young, I., Cipollini, P., and Donlon, C.: The Sea State CCI dataset v1: Towards a sea state climate data record based on satellite observations, *Earth System Science Data*, 12(3), 1929–1951, <https://doi.org/10.5194/essd-12-1929-2020>, 2020.
- 855 Dodd, D., Mills, J., Battilana, D., and Gourley, M.: Hydrographic surveying using the ellipsoid as the vertical reference surface, In *FIG Congress 2010, Sydney, Australia*, 11–16 April 2010, 2010.



- 860 Du, H., Fei, K., and Gao, L.: Nonlinear Tide-River-Surge Interactions and Their Impacts on Compound Flooding During Typhoon Hato in the Pearl River Delta, *Journal of Geophysical Research: Oceans*, <https://doi.org/10.1029/2023jc020673>, 2024.
- Dulac, W., Cattiaux, J., Chauvin, F., Bourdin, S., and Fromang, S.: How Realistic are Tropical Cyclones in the ERA5 Reanalysis?, *EGU General Assembly 2022*, Vienna, Austria, 23–27 May 2022, EGU22-5755, <https://doi.org/10.5194/egusphere-egu22-5755>, 2022.
- 865 Dullaart, J. C. M., Muis, S., Bloemendaal, N. et al.: Advancing global storm surge modelling using the new ERA5 climate reanalysis, *Clim Dyn*, 54, 1007–1021, <https://doi.org/10.1007/s00382-019-05044-0>, 2020.
- Edwards, C., De Mey-Frémaux, P., Barceló-Llull, B., Charria, G., Choi, B., Halliwell, G., Hole, L., Kerry, C., Kourafalou, V., Kurapov, A., Moore, A., Mourre, B., Oddo, P., Pascual, A., Roughan, M., Skandrani, C., Storto, A., Vervatis, V., and Wilkin, J.: Assessing impacts of observations on ocean circulation models with examples from coastal, shelf, and marginal seas, *Frontiers in Marine Science*, <https://doi.org/10.3389/fmars.2024.1458036>, 2024.
- 870 Eilander, D., Couasnon, A., Muis, S., Veldkamp, T. I. E., Haigh, I. D., Wahl, T., Winsemius, H. C., and Ward, P. J.: The effect of surge on riverine flood hazard and impact in deltas globally, *Environmental Research Letters*, 15(10), 104007, <https://doi.org/10.1088/1748-9326/ab8ca6>, 2020.
- Evensen, G.: Sequential data assimilation with a nonlinear quasi-geostrophic model using Monte Carlo methods to forecast error statistics, *Journal of Geophysical Research: Oceans*, 99(C5), 10 143–10 162, <https://doi.org/10.1029/94JC00572>, 1994.
- 875 Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., and Taylor, K. E.: Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization, *Geosci. Model Dev.*, 9, 1937–1958, <https://doi.org/10.5194/gmd-9-1937-2016>, 2016.
- Farahani, H. H., Klees, R., and Slobbe, C.: Data requirements for a 5-mm quasi-geoid in the Netherlands, *Stud Geophys Geod*, 61, 675–702, <https://doi.org/10.1007/s11200-016-0171-7>, 2017.
- 880 Flather, R. A.: Storm surges, in: *Encyclopedia of Ocean Sciences*, edited by: Steele, J. H., Thorpe, S. A., and Turekian, K. K., Academic Press, 2882–2892, 2001.
- Glavovic, B. C., Dawson, R., Chow, W., Garschagen, M., Haasnoot, M., Singh, C., and Thomas, A.: Cross-Chapter Paper 2: Cities and Settlements by the Sea, in: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by: Pörtner, H. O., Roberts, D. C., Tignor, M., Poloczanska, E. S., Mintenbeck, K., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., Okem, A., and Rama, B., Cambridge University Press, 2163–2194, <https://doi.org/10.1017/9781009325844.019.2163>, 2022.
- 885 Guarneri, H., Verlaan, M., Slobbe, D. C., Veenstra, J., Zijl, F., Pietrzak, J., Snellen, M., Keyzer, L., Afrasteh, Y., and Klees, R.: The impact of nonlinear tide–surge interaction on satellite radar altimeter-derived tides, *Marine Geodesy*, 46(3), 251–270, <https://doi.org/10.1080/01490419.2023.2175084>, 2023.
- 890



- Guarneri, H., Verlaan, M., Slobbe, D. C., Zijl, F., Pietrzak, J., Keyzer, L., Afrasteh, Y., and Klees, R.: Estimating tidal constituents in shallow waters from satellite altimetry using a 2D hydrodynamic model with nonlinear tide–surge interactions, *Ocean Dynamics*, 75, 24, <https://doi.org/10.1007/s10236-025-01667-6>, 2025.
- Guo, W., Zhang, F., Ge, J., and Zhang, H.: Tide-surge interaction and its impact on coastal inundation: a case study of super typhoon Meranti, *Frontiers in Marine Science*, <https://doi.org/10.3389/fmars.2025.1536339>, 2025.
- Green, J., Haigh, I. D., Quinn, N., Neal, J., Wahl, T., Wood, M., Eilander, D., de Ruiter, M., Ward, P., and Camus, P.: Review article: A comprehensive review of compound flooding literature with a focus on coastal and estuarine regions, *Natural Hazards and Earth System Sciences*, 25, 747–816, <https://doi.org/10.5194/nhess-25-747-2025>, 2025.
- Haigh, I. D. et al.: GESLA Version 3: A major update to the global higher-frequency sea-level dataset, <https://doi.org/10.1002/gdj3.174>, 2022.
- Han, G., Ma, Z., Chen, N., Chen, N., Yang, J., and Chen, D.: Hurricane Isaac storm surges off Florida observed by Jason-1 and Jason-2 satellite altimeters, *Remote Sensing of Environment*, 198, 244–253, <https://doi.org/10.1016/j.rse.2017.06.005>, 2017.
- Hart-Davis, M. G., Piccioni, G., Dettmering, D., Schwatke, C., Passaro, M., and Seitz, F.: EOT20: a global ocean tide model from multi-mission satellite altimetry, *Earth Syst. Sci. Data*, 13, 3869–3884, <https://doi.org/10.5194/essd-13-3869-2021>, 2021.
- Hart-Davis, M., Laan, S., Schwatke, C., Backeberg, B., Dettmering, D., Zijl, F., Verlaan, M., Passaro, M., and Seitz, F.: Altimetry-derived tide model for improved tide and water level forecasting along the European continental shelf, *Ocean Dynamics*, 73(8), 475–491, <https://doi.org/10.1007/s10236-023-01560-0>, 2023.
- Heemink, A. W., Mouthaan, E. E. A., Roest, M. R. T., Vollebregt, E. A. H., Robaczewska, K. B., and Verlaan, M.: Inverse 3D shallow water flow modelling of the continental shelf, *Continental Shelf Research*, 22, 465–484, 2002.
- Hersbach, H., Bell, B., Berrisford, P., et al.: The ERA5 global reanalysis, *Q J R Meteorol Soc.*, 146, 1999–2049, <https://doi.org/10.1002/qj.3803>, 2020.
- Hofmann-Wellenhof, B. and Moritz, H.: Physical geodesy, Springer-Verlag, [https://doi.org/10.1016/0378-3839\(86\)90002-5](https://doi.org/10.1016/0378-3839(86)90002-5), 2005.
- Horsburgh, K. J. and Wilson, C.: Tide–surge interaction and its role in the distribution of surge residuals in the North Sea, *Journal of Geophysical Research: Oceans*, 112(C08003), <https://doi.org/10.1029/2006JC004033>, 2007.
- Hughes, C. W. and Bingham, R. J.: An oceanographer’s guide to GOCE and the geoid, *Ocean Science*, 4, 15–29, 2008.
- Idier, D., Bertin, X., Thompson, P., and Pickering, M. D.: Interactions between mean sea level, tide, surge, waves and flooding: Mechanisms and contributions to sea level variations at the coast, *Surveys in Geophysics*, 40(6), 1603–1630, <https://doi.org/10.1007/s10712-019-09549-5>, 2019.
- Idier, D., Dumas, F., and Muller, H.: Tide–surge interaction in the English Channel, *Natural Hazards and Earth System Sciences*, 12, 3709–3718, <https://doi.org/10.5194/nhess-12-3709-2012>, 2012.



- Idier, D., Paris, F., Le Cozannet, G., et al.: Sea-level rise impacts on the tides of the European Shelf, Continental Shelf
925 Research, 137, 56–71, <https://doi.org/10.1016/j.csr.2017.01.007>, 2017.
- Ikeuchi, H., Hirabayashi, Y., Yamazaki, D., Muis, S., Ward, P. J., Winsemius, H. C., Verlaan, M., and Kanae, S.: Compound simulation of fluvial floods and storm surges in a global coupled river-coast flood model: Model development and its application to 2007 Cyclone Sidr in Bangladesh, Journal of Advances in Modeling Earth Systems, 9(4), 1847–1862, <https://doi.org/10.1002/2017MS000943>, 2017.
- 930 Iliffe, J. C., Ziebart, M. K., and Turner, J. F.: The derivation of vertical datum surfaces for hydrographic applications, Hydrographic Journal, 125, 3–8, 2007.
- Iraozqui Apecechea, M., Melet, A., Reffray, G., and Thieblemont, R.: Impact of dynamical downscaling on sea level projections in the north-east Atlantic Ocean and regional seas, Journal of Geophysical Research: Oceans, 130, e2025JC022737, <https://doi.org/10.1029/2025JC022737>, 2025.
- 935 Jahanmard, V., Hordoir, R., Delpeche-Ellmann, N., and Ellmann, A.: Quantification of Hydrodynamic Model Sea Level Bias Utilizing Deep Learning and Synergistic Integration of Data Sources, Ocean Modelling, <https://doi.org/10.1016/j.ocemod.2023.102286>, 2023.
- Jean-Michel, L., Eric, G., Romain, B.-B., Gilles, G., Angélique, M., Marie, D., Clément, B., Mathieu, H., Olivier, L. G., Charly, R., Tony, C., Charles-Emmanuel, T., Florent, G., Giovanni, R., Mounir, B., Yann, D., and Pierre-Yves, L. T.: The
940 Copernicus Global 1/12° Oceanic and Sea Ice GLORYS12 Reanalysis, Front. Earth Sci., 9, 698876, <https://doi.org/10.3389/feart.2021.698876>, 2021.
- Ji, T. and Li, G.: Contemporary monitoring of storm surge activity, Progress in Physical Geography: Earth and Environment, 44, 299–314, <https://doi.org/10.1177/0309133319879324>, 2020.
- Ji, T., Li, G., and Zhang, Y.: Observing storm surges in China’s coastal areas by integrating multi-source satellite altimeters,
945 Estuarine, Coastal and Shelf Science, 225, Article 106224, <https://doi.org/10.1016/j.ecss.2019.05.006>, 2019.
- Johns, B., Rao, A. D., Dube, S. K., and Sinha, P. C.: Numerical modelling of tide–surge interaction in the Bay of Bengal, Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences, 313(1522), 507–535, 1985.
- Johnson, J., Passaro, M., Hart-Davis, M., Backeberg, B., and Connors, S.: Validation of satellite altimetry for coastal storm
950 surge detection, Paper presented at the EGU General Assembly 2026, Vienna, Austria, May 3–8, <https://doi.org/10.5194/egusphere-egu26-14366>, 2026.
- Jousset, S., Mulet, S., Greiner, E., Wilkin, J., Vidar, L., Chafik, L., Raj, R., Bonaduce, A., Picot, N., and Dibarboure, G.: New global mean dynamic topography CNES-CLS-22 combining drifters, hydrography profiles and high frequency radar data, Earth Syst. Sci. Data, 18, 2285–2303, <https://doi.org/10.5194/essd-18-2285-2026>, 2026.
- 955 Kernkamp, H. W. J., van Dam, A., Stelling, G. S., and de Goede, E. D.: Efficient scheme for the shallow water equations on unstructured grids with application to the Continental Shelf, Ocean Dynamics, 61(8), 1175–1188, <https://doi.org/10.1007/s10236-011-0423-6>, 2011.



- Khanal, S., Ridder, N., de Vries, H., Terink, W., and van den Hurk, B.: Storm surge and extreme river discharge: A compound event analysis using ensemble impact modelling, *Frontiers in Earth Science*, 7, <https://doi.org/10.3389/feart.2019.00224>, 2019.
- Kirezci, E., Young, I. R., Ranasinghe, R., Muis, S., Nicholls, R. J., Lincke, D., and Hinkel, J.: Projections of global-scale extreme sea levels and resulting episodic coastal flooding over the 21st century, *Scientific Reports*, 10, 11629, <https://doi.org/10.1038/s41598-020-67736-6>, 2020.
- Kodaira, T., Thompson, K. R., and Bernier, N. B.: The effect of density stratification on the prediction of global storm surges, *Ocean Dynamics*, 66, 1733–1743, <https://doi.org/10.1007/s10236-016-1003-6>, 2016.
- Krien, Y., Testut, L., Islam, A. K. M. S., Bertin, X., Durand, F., Mayet, C., Tazkia, A. R., Becker, M., Calmant, S., Papa, F., Ballu, V., Shum, C. K., and Khan, Z. H.: Towards improved storm surge models in the northern Bay of Bengal, *Continental Shelf Research*, 135, 58–73, <https://doi.org/10.1016/j.csr.2017.01.014>, 2017.
- Lázaro, C., Fernandes, M. J., Vieira, T., and Vieira, E.: A coastally improved global dataset of wet tropospheric corrections for satellite altimetry, *Earth Syst. Sci. Data*, 12, 3205–3228, <https://doi.org/10.5194/essd-12-3205-2020>, 2020.
- Leijnse, T. W., van Ormondt, M., van Dongeren, A., Aerts, J. C., and Muis, S.: Estimating nearshore infragravity wave conditions at large spatial scales, *Frontiers in Marine Science*, 11, 1355095, 2024.
- Li, S., Wahl, T., Talke, S. A., Jay, D. A., Orton, P., Liang, X., Wang, G., and Liu, L.: Evolving tides aggravate nuisance flooding along the U.S. coastline, *Science Advances*, 7(2), eabe2412, <https://doi.org/10.1126/sciadv.abe2412>, 2021.
- Li, S., Wahl, T., Barroso, A., Coats, S., Dangendorf, S., Piecuch, C. G., Sun, Q., Thompson, P., and Liu, L.: Contributions of different sea-level processes to high-tide flooding along the U.S. coastline, *Journal of Geophysical Research: Oceans*, 127, e2021JC018276, <https://doi.org/10.1029/2021JC018276>, 2022.
- Li, Y., Zhou, J., Li, J. et al.: Global marine gravity from 27 cycles of SWOT satellite data: accuracy and spatial resolution evaluation, *J Geod*, 99, 51, <https://doi.org/10.1007/s00190-025-01972-4>, 2025.
- Li, Y., Jiang, Z., Wu, S., Gao, J., and Sharma, A.: Systematic evaluation and correction of extreme water level in global storm surge simulation, *Geophysical Research Letters*, 53, e2025GL119793, <https://doi.org/10.1029/2025GL119793>, 2026.
- Lin, N. and Chavas, D.: On hurricane parametric wind and applications in storm surge modeling, *Journal of Geophysical Research: Atmospheres*, 117(D9), 2012.
- Lobeto, H., Menéndez, M., Méndez, F. J., and Gómez-Navarro, J. J.: Toward a methodology for estimating coastal extreme sea levels from satellite altimetry, *Journal of Geophysical Research: Oceans*, 123(11), 7852–7871, <https://doi.org/10.1029/2018JC014487>, 2018.
- Lobeto, H. and Menéndez, M.: Variability assessment of global extreme coastal sea levels using altimetry data, *Remote Sensing*, 16, 1355, <https://doi.org/10.3390/rs16081355>, 2024.
- Lorenz, M., Arns, A., and Gräwe, U.: How sea level rise may hit you through the backdoor: Changing extreme water levels in shallow coastal lagoons, *Geophysical Research Letters*, 50, e2023GL105512, <https://doi.org/10.1029/2023GL105512>, 2023.



- Losch, M., Sloyan, B. M., Schröter, J., and Sneeuw, N.: Box inverse models, altimetry and the geoid: Problems with the omission error, *J. Geophys. Res.*, 107(C7), doi:10.1029/2001JC000855, 2002.
- Louis, G., Lequentrec-Lalancette, M.-F., Royer, J.-Y., Rouxel, D., Géli, L., Maïa, M., and Faillot, M.: Ocean Gravity Models
995 From Future Satellite Missions, *Eos Trans. AGU*, 91(3), 21–22, doi:10.1029/2010EO030001, 2010.
- Lyddon, C., Brown, J., Leonardi, N., and Plater, A.: Sensitivity of flood hazard and damage to modelling approaches, *Journal of Marine Science and Engineering*, 8, 724, <https://doi.org/10.3390/jmse8090724>, 2020.
- Lyard, F. H., Allain, D. J., Cancet, M., Carrère, L., and Picot, N.: FES2014 global ocean tide atlas: design and performance, *Ocean Science*, 17(3), 615–649, 2021.
- 1000 Marcos, M., Rohmer, J., Vousedoukas, M., Mentaschi, L., Cozannet, L., and Amores, Á.: Increased Extreme Coastal Water Levels Due to the Combined Action of Storm Surges and Wind Waves, *Geophysical Research Letters*, 46, 4356 – 4364, <https://doi.org/10.1029/2019gl082599>, 2019.
- Melet, A., Teatini, P., Le Cozannet, G., Jamet, C., Conversi, A., Benveniste, J., and Almar, R.: Earth observations for monitoring marine coastal hazards and their drivers, *Surveys in Geophysics*, 41(6), 1489–1534,
1005 <https://doi.org/10.1007/s10712-020-09594-5>, 2020.
- Mentaschi, L., Vousedoukas, M. I., García-Sánchez, G., Fernández-Montblanc, T., Roland, A., Voukouvalas, E., ... and Feyen, L.: A global unstructured, coupled, high-resolution hindcast of waves and storm surge, *Frontiers in Marine Science*, 10, 1233679, 2023.
- Meyer, T. H., Roman, D. R., and Zilkoski, D. B.: What does height really mean? Part III: Height systems, *Surveying and
1010 Land Information Science*, 66(2), 149–160, 2006.
- Moftakhari, H., Muñoz, D., Asanjan, A., Aghakouchak, A., Moradkhani, H., and Jay, D.: Nonlinear Interactions of Sea-Level Rise and Storm Tide Alter Extreme Coastal Water Levels: How and Why?, *AGU Advances*, 5, <https://doi.org/10.1029/2023av000996>, 2024.
- Mostafavi, M., Delpeche-Ellmann, N., Ellmann, A., and Jahanmard, V.: Determination of Accurate Dynamic Topography
1015 for the Baltic Sea Using Satellite Altimetry and a Marine Geoid Model, *Remote Sensing*, 15, 2189, <https://doi.org/10.3390/rs15082189>, 2023.
- Mouthaan, E. E. A., Heemink, A. W., and Robaczewska, K. B.: Assimilation of ERS-1 altimeter data in a tidal model of the continental shelf, *Deutsche Hydrographische Zeitschrift*, 46, 285–319, 1994.
- Muis, S., Haigh, I. D., Guimarães Nobre, G., Aerts, J. C. J. H., and Ward, P. J.: Influence of El Niño-Southern Oscillation on
1020 global coastal flooding, *Earth's Future*, 6, 1311–1322, <https://doi.org/10.1029/2018EF000909>, 2018.
- Muis, S., Verlaan, M., Winsemius, H. C., Aerts, J. C. J. H., and Ward, P. J.: A global reanalysis of storm surges and extreme sea levels, *Nature Communications*, 7, Article 11969, <https://doi.org/10.1038/ncomms11969>, 2016.
- Muis, S., Apecechea, M. I., Dullaart, J., de Lima Rego, J., Madsen, K. S., Su, J., Yan, K., and Verlaan, M.: A High-Resolution Global Dataset of Extreme Sea Levels, Tides, and Storm Surges, Including Future Projections, *Front. Mar. Sci.*,
1025 7, 263, doi:10.3389/fmars.2020.00263, 2020.



- Muis, S., Aerts, J. C. J. H., Á. Antolínez, J. A., Dullaart, J. C., Duong, T. M., Erikson, L., et al.: Global projections of storm surges using high-resolution CMIP6 climate models, *Earth's Future*, 11, e2023EF003479, <https://doi.org/10.1029/2023EF003479>, 2023.
- 1030 Müller, M., Cherniawsky, J. Y., Foreman, M. G. G. et al.: Seasonal variation of the M 2 tide, *Ocean Dynamics*, 64, 159–177, <https://doi.org/10.1007/s10236-013-0679-0>, 2014.
- Oelsmann, J., Passaro, M., Dettmering, D., Schwatke, C., Sánchez, L., and Seitz, F.: The zone of influence: Matching sea level variability from coastal altimetry and tide gauges for vertical land motion estimation, *Ocean Science*, 17, 35–57, <https://doi.org/10.5194/os-17-35-2021>, 2021.
- Opel, L., Schindelegger, M., and Ray, R. D.: A likely role for stratification in long-term changes of the global ocean tides, *Commun Earth Environ*, 5, 261, <https://doi.org/10.1038/s43247-024-01432-5>, 2024.
- 1035 Orton, P. M., Hall, T. M., Talke, S. A., Blumberg, A. F., Georgas, N., and Vinogradov, S.: A validated tropical–extratropical flood hazard assessment for New York Harbor, *Journal of Geophysical Research: Oceans*, 121(12), 8904–8929, <https://doi.org/10.1002/2016JC011679>, 2016.
- Parker, K., Erikson, L., Thomas, J., Nederhoff, K., Barnard, P., and Muis, S.: Relative contributions of water-level components to extreme water levels along the US Southeast Atlantic Coast from a regional-scale water-level hindcast, *Natural Hazards*, 117(1), 2219–2248, <https://doi.org/10.1007/s11069-023-05939-6>, 2023.
- 1040 Passaro, M., Cipollini, P., Vignudelli, S., Quartly, G. D., and Snaith, H. M.: ALES: A multi-mission adaptive subwaveform retracker for coastal and open ocean altimetry, *Remote Sensing of Environment*, 145, 173–189, <https://doi.org/10.1016/j.rse.2014.02.008>, 2014.
- 1045 Passaro, M., Dodet, G., Ardhuin, A., and Cipollini, P.: WHALES: An enhanced retracker for satellite radar altimeter delay-only waveforms in sea state application, *Remote Sensing of Environment*, 342, 115482, <https://doi.org/10.1016/j.rse.2026.115482>, 2026.
- Pedrerros, R., Idier, D., Muller, H., et al.: Relative contribution of wave setup to storm surge: Observations and modelling based analysis in open and protected environments, *Journal of Coastal Research*, SI85, 1046–1050, <https://doi.org/10.2112/SI85-210.1>, 2018.
- 1050 Peng, F., et al.: The International Altimetry Service 2024 coastal product: A review of coastal-optimised altimetry, *Earth System Science Data*, <https://doi.org/10.5194/essd-17-1441-2025>, 2024.
- Plag, H.-P. and Tsimplis, M. N.: Temporal variability of the seasonal sea-level cycle in the North Sea and Baltic Sea in relation to climate variability, *Global and Planetary Change*, [https://doi.org/10.1016/S0921-8181\(98\)00069-1](https://doi.org/10.1016/S0921-8181(98)00069-1), 1999.
- 1055 Ponte, R., Carson, M., Cirano, M., Domingues, C., Jevrejeva, S., Marcos, M., Mitchum, G., Van De Wal, R., Woodworth, P., Ablain, M., Ardhuin, F., Ballu, V., Becker, M., Benveniste, J., Birol, F., Bradshaw, E., Cazenave, A., De Mey-Frémaux, P., Durand, F., Ezer, T., Fu, L., Fukumori, I., Gordon, K., Gravelle, M., Griffies, S., Han, W., Hibbert, A., Hughes, C., Idier, D., Kourafalou, V., Little, C., Matthews, A., Melet, A., Merrifield, M., Meyssignac, B., Minobe, S., Penduff, T., Picot, N., Piecuch, C., Ray, R., Rickards, L., Santamaría-Gómez, A., Stammer, D., Staneva, J., Testut, L., Thompson, K., Thompson,



- 1060 P., Vignudelli, S., Williams, J., Williams, S., Wöppelmann, G., Zanna, L., and Zhang, X.: Towards Comprehensive Observing and Modeling Systems for Monitoring and Predicting Regional to Coastal Sea Level, *Frontiers in Marine Science*, <https://doi.org/10.3389/fmars.2019.00437>, 2019.
- Pringle, W. J., Wirasaet, D., Roberts, K. J., and Westerink, J. J.: Global storm tide modeling with ADCIRC v55: unstructured mesh design and performance, *Geoscientific Model Development Discussions*, 2020, 1-30, 2020.
- 1065 Pugh, D. T. and Woodworth, P. L.: *Sea-level science: Understanding tides, surges, tsunamis and mean sea-level changes*, Cambridge University Press, 2014.
- Probst, P. and Annunziato, A.: Tropical Cyclone Idai: analysis of the wind, rainfall and storm surge impact, European Commission – Joint Research Centre, <https://reliefweb.int/report/mozambique/tropical-cyclone-idai-analysis-wind-rainfall-and-storm-surge-impact-9-april-2019>, 2019.
- 1070 Radfar, S., Taheri, P., and Moftakhari, H.: Global evidence for co-variability of tidal constituents, *Environmental Research Letters*, 21(2), 024019, <https://doi.org/10.1088/1748-9326/ae2c0c>, 2026.
- Rasquin, C., Seiffert, R., Wachler, B., and Winkel, N.: The significance of coastal bathymetry representation for modelling the tidal response to mean sea level rise in the German Bight, *Ocean Science*, 16, 31–44, <https://doi.org/10.5194/os-16-31-2020>, 2020.
- 1075 Ray, R., Loomis, B., and Zlotnicki, V.: The mean seasonal cycle in relative sea level from satellite altimetry and gravimetry, *Journal of Geodesy*, 95, <https://doi.org/10.1007/s00190-021-01529-1>, 2021.
- Roberts, C. D., Senan, R., Molteni, F., Boussetta, S., Mayer, M., and Keeley, S. P. E.: Climate model configurations of the ECMWF Integrated Forecasting System (ECMWF-IFS cycle 43r1) for HighResMIP, *Geosci. Model Dev.*, 11, 3681–3712, <https://doi.org/10.5194/gmd-11-3681-2018>, 2018.
- 1080 Roelvink, D., Van Ormondt, M., Reyns, J., and Van Der Lugt, M.: SnapWave: fast, implicit wave transformation from offshore to nearshore, *Geoscientific Model Development*, 18(23), 9469-9495, 2025.
- Ruan, X., Sun, H., Shou, W., and Wang, J.: The impact of climate change and urbanization on compound flood risks in coastal areas: A comprehensive review of methods, *Applied Sciences*, 14(21), 10019, <https://doi.org/10.3390/app142110019>, 2024.
- 1085 Rulent, J., Calafat, F. M., Banks, C., Bricheno, L., Gommenginger, C., Green, J. A. M., Haigh, I. D., Lewis, H., and Martin, A. C. H.: Comparing water level estimation in coastal and shelf seas from satellite altimetry and numerical models, *Frontiers in Marine Science*, 7, 549467, <https://doi.org/10.3389/fmars.2020.549467>, 2020.
- Sánchez, L., Čunderlík, R., Dayoub, N. et al.: A conventional value for the geoid reference potential W_0 , *J Geod*, 90, 815–835, <https://doi.org/10.1007/s00190-016-0913-x>, 2016.
- 1090 Sandwell, D. T., Harper, H., Tozer, B., and Smith, W. H. F.: Gravity field recovery from geodetic altimeter missions, *Advances in Space Research*, 68(2), 1059–1072, <https://doi.org/10.1016/j.asr.2019.09.011>, 2021.
- Scharroo, R., Smith, D. E., Milne, A., Becker, M., and Nederhoff, K.: The global ocean tide model GOT4.8 and its impact on satellite altimetry and gravity field recovery, *Earth Observation*, <https://doi.org/10.1029/2005EO400004>, 2011.



- Schlembach, F., Passaro, M., Quartly, G. D., Kurekin, A., Nencioli, F., Dodet, G., Piollé, J.-F., Ardhuin, F., Bidlot, J.,
1095 Schwatke, C., Seitz, F., Cipollini, P., and Donlon, C.: Round robin assessment of radar altimeter low-resolution mode and
delay-Doppler retracking algorithms for significant wave height, *Remote Sensing*, 12(8), 1254,
<https://doi.org/10.3390/rs12081254>, 2020.
- Schumann, G., Giustarini, L., Tarpanelli, A., Jarihani, B., and Martinis, S.: Flood Modeling and Prediction Using Earth
Observation Data, *Surveys in Geophysics*, 44, 1553-1578, <https://doi.org/10.1007/s10712-022-09751-y>, 2022.
- 1100 Schumann, G. and Neal, J.: Integrating Earth Observation Data of Floods with Large-Scale Hydrodynamic Models, *Global
Drought and Flood*, <https://doi.org/10.1002/9781119427339.ch6>, 2021.
- Schutgens, N., Tsyro, S., Gryspeerdt, E., Goto, D., Weigum, N., Schulz, M., and Stier, P.: On the spatio-temporal
representativeness of observations, *Atmospheric Chemistry and Physics*, 17, 9761–9780, <https://doi.org/10.5194/acp-17-9761-2017>, 2017.
- 1105 Schwatke, C., Dettmering, D., Passaro, M., Hart-Davis, M. G., Scherer, D., Müller, F. L., Bosch, W., and Seitz, F.:
OpenADB: DGFI TUM's Open Altimeter Database, *Geoscience Data Journal*, <https://doi.org/10.1002/gdj3.233>, 2023.
- Serafin, K., Ruggiero, P., and Stockdon, H.: The relative contribution of waves, tides, and nontidal residuals to extreme total
water levels on U.S. West Coast sandy beaches, *Geophysical Research Letters*, 44, 1839 – 1847,
<https://doi.org/10.1002/2016gl071020>, 2017.
- 1110 Slater, L., Anderson, B., Buechel, M., Dadson, S., Han, S., Harrigan, S., Kelder, T., Kowal, K., Lees, T., Matthews, T.,
Murphy, C., and Wilby, R.: Nonstationary weather and water extremes: a review of methods for their detection, attribution,
and management, *Hydrology and Earth System Sciences*, <https://doi.org/10.5194/hess-2020-576>, 2020.
- Slobbe, D. C., Verlaan, M., Klees, R., and Gerritsen, H.: Obtaining instantaneous water levels relative to a geoid with a 2D
storm surge model, *Cont. Shelf Res.*, 52, 172-189, 2013.
- 1115 Slobbe, D. C. and Klees, R.: The impact of the dynamic sea surface topography on the quasi-geoid in shallow coastal waters,
J Geod, 88, 241–261, <https://doi.org/10.1007/s00190-013-0679-3>, 2014.
- Srinivasan, M. and Tsontos, V.: Satellite Altimetry for Ocean and Coastal Applications: A Review, *Remote. Sens.*, 15, 3939,
<https://doi.org/10.3390/rs15163939>, 2023.
- Stanev, E., Schulz-Stellenfleth, J., Staneva, J., Grayek, S., Grashorn, S., Behrens, A., Koch, W., and Pein, J.: Ocean
1120 forecasting for the German Bight: from regional to coastal scales, *Ocean Science*, 12, 1105-1136, <https://doi.org/10.5194/os-12-1105-2016>, 2016.
- Sun, H., Zhang, X., Ruan, X., Jiang, H., and Shou, W.: Mapping Compound Flooding Risks for Urban Resilience in Coastal
Zones: A Comprehensive Methodological Review, *Remote. Sens.*, 16, 350, <https://doi.org/10.3390/rs16020350>, 2024.
- Taherkhani, M., Vitousek, S., Barnard, P. L., Frazer, N., Anderson, T. R., and Fletcher, C. H.: Sea-level rise exponentially
1125 increases coastal flood frequency, *Scientific Reports*, 10, 6466, <https://doi.org/10.1038/s41598-020-62188-4>, 2020.



- Taburet, G., Sánchez-Román, A., Ballarotta, M., Pujol, M., Legeais, J., Fournier, F., Faugère, Y., and Dibarboure, G.: DUACS DT2018: 25 years of reprocessed sea level altimetry products, *Ocean Science*, <https://doi.org/10.5194/os-15-1207-2019>, 2019.
- Trošelj, J., Ninomiya, J., Takewaka, S., and Mori, N.: Dynamical Downscaling of Coastal Dynamics for Two Extreme Storm Surge Events in Japan, *Front. Mar. Sci.*, 7, 566277, doi: 10.3389/fmars.2020.566277, 2021.
- Tsimplis, M. N. and Woodworth, P. L.: The global distribution of the seasonal sea level cycle calculated from coastal tide gauge data, *J. Geophys. Res.*, 99(C8), 16031–16039, doi:10.1029/94JC01115, 1994.
- Umgiesser, G., Ferrarin, C., Bajo, M., Bellafore, D., Cucco, A., De Pascalis, F., Ghezzi, M., McKiver, W., and Arpaia, L.: Hydrodynamic modelling in marginal and coastal seas — The case of the Adriatic Sea as a permanent laboratory for numerical approach, *Ocean Modelling*, <https://doi.org/10.1016/j.ocemod.2022.102123>, 2022.
- van de Wal, R. S. W., Zhang, X., Minobe, S., Jevrejeva, S., Riva, R. E. M., Little, C., Richter, K., and Palmer, M. D.: Uncertainties in long-term twenty-first-century process-based coastal sea-level projections, *Surveys in Geophysics*, 40(6), 1655–1671, <https://doi.org/10.1007/s10712-019-09575-3>, 2019.
- Vignudelli, S. and Biasio, F.: Coastal Sea Level Trends from a Joint Use of Satellite Radar Altimetry, GPS and Tide Gauges: Case Study of the Northern Adriatic Sea, *Geodetic Sciences - Theory, Applications and Recent Developments*, <https://doi.org/10.5772/intechopen.98243>, 2021.
- Vignudelli, S., Birol, F., Benveniste, J., Fu, L., Picot, N., Raynal, M., and Roinard, H.: Satellite altimetry measurements of sea level in the coastal zone, *Surveys in Geophysics*, 40, 1319–1349, <https://doi.org/10.1007/s10712-019-09569-1>, 2019.
- Vignudelli, S., Kostianoy, A. G., Cipollini, P., and Benveniste, J. (Eds.): *Coastal Altimetry*, Springer, <https://doi.org/10.1007/978-3-642-12796-0>, 2011.
- Vinogradov, S. V., Ponte, R. M., Heimbach, P., and Wunsch, C.: The mean seasonal cycle in sea level estimated from a data-constrained general circulation model, *J. Geophys. Res.*, 113, C03032, doi:10.1029/2007JC004496, 2008.
- Vitousek, S., Barnard, P., Fletcher, C., Frazer, N., Erikson, L., and Storlazzi, C.: Doubling of coastal flooding frequency within decades due to sea-level rise, *Scientific Reports*, 7, <https://doi.org/10.1038/s41598-017-01362-7>, 2017.
- Vousdoukas, M. I., Voukouvalas, E., Annunziato, A., Giardino, A., and Feyen, L.: Projections of extreme storm surge levels along Europe, *Climate Dynamics*, 47(9), 3171–3190, 2016.
- Vousdoukas, M. I., Mentaschi, L., Voukouvalas, E. et al.: Global probabilistic projections of extreme sea levels show intensification of coastal flood hazard, *Nat Commun*, 9, 2360, <https://doi.org/10.1038/s41467-018-04692-w>, 2018.
- Wahl, T., Jain, S., Bender, J., Meyers, S. D., and Luther, M. E.: Increasing risk of compound flooding from storm surge and rainfall for major US cities, *Nature Climate Change*, 5(12), 1093–1097, <https://doi.org/10.1038/nclimate2736>, 2015.
- Wang, H., Zhu, J., and Yang, J.: Error analysis on ESA’s Envisat ASAR wave mode significant wave height retrievals using the triple collocation model, *Remote Sensing*, 6(12), 12217–12233, <https://doi.org/10.3390/rs61212217>, 2014.
- Wang, X. and Babovic, V.: Enhancing water level prediction through model residual correction based on chaos theory and kriging, *International Journal for Numerical Methods in Fluids*, 75, 1–19, <https://doi.org/10.1002/fld.3883>, 2014.



- 1160 Wang, P., Bernier, N. B., and Thompson, K. R.: Adding baroclinicity to a global operational model for forecasting total water level: Approach and impact, *Ocean Modelling*, 174, Article 102031, <https://doi.org/10.1016/j.ocemod.2022.102031>, 2022a.
- Wang, X., Verlaan, M., Veenstra, J., and Lin, H. X.: Data-assimilation-based parameter estimation of bathymetry and bottom friction coefficient to improve coastal accuracy in a global tide model, *Ocean Science*, 18(4), 881–904, <https://doi.org/10.5194/os-18-881-2022>, 2022b.
- 1165 Wang, Z., Leung, M., Mukhopadhyay, S., Sunkara, S., Steinschneider, S., Herman, J., Abellera, M., Kucharski, J., Nederhoff, K., and Ruggiero, P.: A hybrid statistical–dynamical framework for compound coastal flooding analysis, *Environmental Research Letters*, 20, <https://doi.org/10.1088/1748-9326/ad96ce>, 2024.
- Wang, P. and Bernier, N. B.: Advancing global hindcast of extreme sea levels: Insights from a 65-year study, *Weather and Climate Extremes*, 100805, 2025.
- 1170 Ward, P. J., de Perez, E. C., Dottori, F., Jongman, B., Luo, T., Safaie, S., and Uhlemann-Elmer, S.: The Need for Mapping, Modeling, and Predicting Flood Hazard and Risk at the Global Scale, in: *Global Flood Hazard*, edited by: Schumann, G. J.-P., Bates, P. D., Apel, H., and Aronica, G. T., <https://doi.org/10.1002/9781119217886.ch1>, 2018.
- Ward, P. J., Blauhut, V., Bloemendaal, N., Daniell, J. E., de Ruiter, M. C., Duncan, M. J., Emberson, R., Jenkins, S. F., Kirschbaum, D., Kunz, M., Mohr, S., Muis, S., Riddell, G. A., Schäfer, A., Stanley, T., Veldkamp, T. I. E., and Winsemius, H. C.: Review article: Natural hazard risk assessments at the global scale, *Nat. Hazards Earth Syst. Sci.*, 20, 1069–1096, <https://doi.org/10.5194/nhess-20-1069-2020>, 2020.
- 1175 Watts, A. B., Tozer, B., Harper, H., Boston, B., Shillington, D. J., and Dunn, R.: Evaluation of shipboard and satellite-derived bathymetry and gravity data over seamounts in the northwest Pacific Ocean, *Journal of Geophysical Research: Solid Earth*, 125, e2020JB020396, <https://doi.org/10.1029/2020JB020396>, 2020.
- Wessel, P. and Watts, A. B.: On the accuracy of marine gravity measurements, *J. Geophys. Res.*, 93(B1), 393–413, doi:10.1029/JB093iB01p00393, 1988.
- Wilkin, J., Levin, J., Moore, A., Arango, H., López, A., and Hunter, E.: A data-assimilative model reanalysis of the U.S. Mid Atlantic Bight and Gulf of Maine: Configuration and comparison to observations and global ocean models, *Progress in Oceanography*, <https://doi.org/10.1016/j.pocean.2022.102919>, 2022.
- 1185 Woodruff, J., Dietrich, J. C., Wirasaet, D. et al.: Storm surge predictions from ocean to subgrid scales, *Nat Hazards*, 117, 2989–3019, <https://doi.org/10.1007/s11069-023-05975-2>, 2023.
- Woodworth, P. L., Melet, A., Marcos, M., Ray, R. D., Wöppelmann, G., Sasaki, Y. N., Cirano, M., Hibbert, A., Huthnance, J. M., Monserrat, S., and Merrifield, M. A.: Forcing factors affecting sea level changes at the coast, *Surveys in Geophysics*, 40(6), 1351–1397, <https://doi.org/10.1007/s10712-019-09531-1>, 2019.
- 1190 Wolf, J.: Interaction of tide and surge in a semi-infinite uniform channel, with application to surge propagation down the east coast of Britain, *Appl Math Model*, 2, 245–253, 1978.



- Wolf, J.: Coastal flooding: Impacts of coupled wave–surge–tide models, *Natural Hazards*, 49, 241–260, <https://doi.org/10.1007/s11069-008-9316-5>, 2009.
- 1195 Wu, Y., Haigh, I., Gao, C., Jenkins, L., Green, J., Jane, R., Xu, Y., Hu, H., and Wu, N.: Compound Flooding Potential from the Joint Occurrence of Precipitation and Storm Surge in the Qiantang Estuary, China, *Journal of Hydrometeorology*, <https://doi.org/10.1175/jhm-d-23-0102.1>, 2024.
- Xu, H., Tian, Z., Sun, L., Ye, Q., Ragno, E., Bricker, J., Tan, J., Ke, Q., Wang, S., and Toumi, R.: Compound flood impact of water level and rainfall during tropical cyclone periods in a coastal city: the case of Shanghai, *Natural Hazards and Earth*
- 1200 *System Sciences*, 22(7), 2347–2358, <https://doi.org/10.5194/nhess-22-2347-2022>, 2022a.
- Xu, K., Wang, C., and Bin, L.: Compound flood models in coastal areas: A review of methods and uncertainty analysis, *Natural Hazards*, 116, 469–496, <https://doi.org/10.1007/s11069-022-05683-3>, 2022b.
- Ye, F., Zhang, Y. J., Yu, H., Sun, W., Moghimi, S., Myers, E., Núñez, K., Zhang, R., Wang, H. V., Roland, A., Martins, K., Bertin, X., Du, J., and Liu, Z.: Simulating storm surge and compound flooding events with a creek-to-ocean model: Importance of baroclinic effects, *Ocean Modelling*, 145, 101526, <https://doi.org/10.1016/j.ocemod.2019.101526>, 2020.
- 1205 Zaron, E. and Ray, R.: Aliased Tidal Variability in Mesoscale Sea Level Anomaly Maps, *Journal of Atmospheric and Oceanic Technology*, 35(12), 2421–2435, <https://doi.org/10.1175/jtech-d-18-0089.1>, 2018.
- Zhang, W., Luo, M., Gao, S., Chen, W., Hari, V., and Khouakhi, A.: Compound hydrometeorological extremes: Drivers, mechanisms and methods, *Frontiers in Earth Science*, <https://doi.org/10.3389/feart.2021.673495>, 2021.
- 1210 Zhang, W.-Z., Shi, F., Hong, H.-S., et al.: Tide–surge interaction intensified by the Taiwan Strait, *Journal of Geophysical Research: Oceans*, 115(C06012), <https://doi.org/10.1029/2009JC005762>, 2010.
- Zhu, C., Guo, J., Ya, S., Li, W., Gao, J., and Qiu, L.: Moving geoid gradient method for high-precision and high-resolution gravity recovery from SWOT wide-swath data, *IEEE Transactions on Geoscience and Remote Sensing*, 63, Article 4205613, <https://doi.org/10.1109/TGRS.2025.3563949>, 2025.
- 1215 Zijl, F., Groenenboom, J., Laan, S., and Zijker, T.: DCSM-FM 100m: a sixth-generation model for the NW European Shelf, *Deltares*, report 11208054-004-ZKS-0002, 2022.