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Storm surges and extreme sea levels: Review, establishment of model intercomparison and coordination of surge climate projection efforts (SurgeMIP).

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A B S T R A C T

Coastal flood damage is primarily the result of extreme sea levels. Climate change is expected to drive an increase in these extremes. While proper estimation of changes in storm surges is essential to estimate changes in extreme sea levels, there remains low confidence in future trends of surge contribution to extreme sea levels. Alerting local populations of imminent extreme sea levels is also critical to protecting coastal populations. Both predicting and projecting extreme sea levels require reliable numerical prediction systems. The SurgeMIP (surge model intercomparison) community has been established to tackle such challenges. Efforts to intercompare storm surge prediction systems and coordinate the community's prediction and projection efforts are introduced. An overview of past and recent advances in storm surge science such as physical processes to consider and the recent development of global forecasting systems are briefly introduced. Selected historical events and drivers behind fast increasing service and knowledge requirements for emergency response to adaptation considerations are also discussed. The community's initial plans and recent progress are introduced. These include the establishment of an intercomparison project, the identification of research and development gaps, and the introduction of efforts to coordinate projections that span multiple climate scenarios.

1. Introduction

The world's coastlines are associated with some of the most expensive natural disasters of recent years. Coastal communities worldwide expect precise and accurate guidance to inform and support the response to imminent events and mitigate and adapt to the changing conditions of the decades and centuries to come. Along the world's coastlines, the primary cause of coastal flood damage is extreme sea level (i.e., exceptionally low or high local sea surface height) that results from changes in local mean sea levels in combination with storm surges, astronomical tides and, at times, waves and/or river overflow to raise coastal water levels above a locally critical water level (i.e., above which damages are expected; Fig. 1).

Storm surges are caused by prevailing atmospheric surface pressure and wind conditions (lifting or pushing water towards the shore results in a positive surge, pressing down or pushing water away from the shore results in a negative surge). They are driven by weather disturbances (i.e., storms) and are sensitive to the atmospheric storm's intensity, path, size, and moving speed (e.g., Resio and Westerink, 2008; Resio et al., 2009; Xuan et al., 2021).

Ocean processes and conditions such as water depth, tides, shelf width, ice, and stratification also modulate characteristics of storm surges (e.g., Bernier and Thompson, 2007; Zhang et al., 2010; McInnes et al., 2016; Idier et al., 2019; Arns et al., 2020; Wang and Bernier 2023). When the resulting water level exceeds the local tidal maxima, there is a risk of flooding and/or erosion. When the water drops below local tidal minima, there is a risk to navigation when for example vessels' water draft exceed the water depth (e.g., Jensen et al., 2022). In addition to tide and surge, wave runup, the combination of wave setup (elevation of nearshore mean sea level due to wave breaking in the surfzone) and wave swash uprush (rapid upward-moving water after waves reach the shore), can exacerbate extreme coastal levels with non-trivial contributions that vary over time (e.g., Melet et al., 2016; Pedreros et al., 2018; Marsooli and Lin, 2018; Amores et al., 2020; Lavaud et al., 2020; Toomey et al., 2022). Kirezci et al. (2020) estimated that wave setup alone may contribute as much as 17% to extreme sea levels. Natural barriers such as the presence of mangrove can help alleviate those effects and protect shorelines (e.g., Zhang et al., 2012).

Extreme sea levels are rarely the sole result of an extreme surge occurring at or near high tide. They can also result from a combination of phenomena that individually would not qualify as extreme. At or on the coast, the extreme sea level that arises from any combination of sea-level rise, low-frequency variations (sub-seasonal, seasonal and inter-annual), storm surges, tides, wave run-up, and potential contributions from terrestrial river outflow and heavy precipitation must be considered in order to predict or project coastal impacts. Often, these

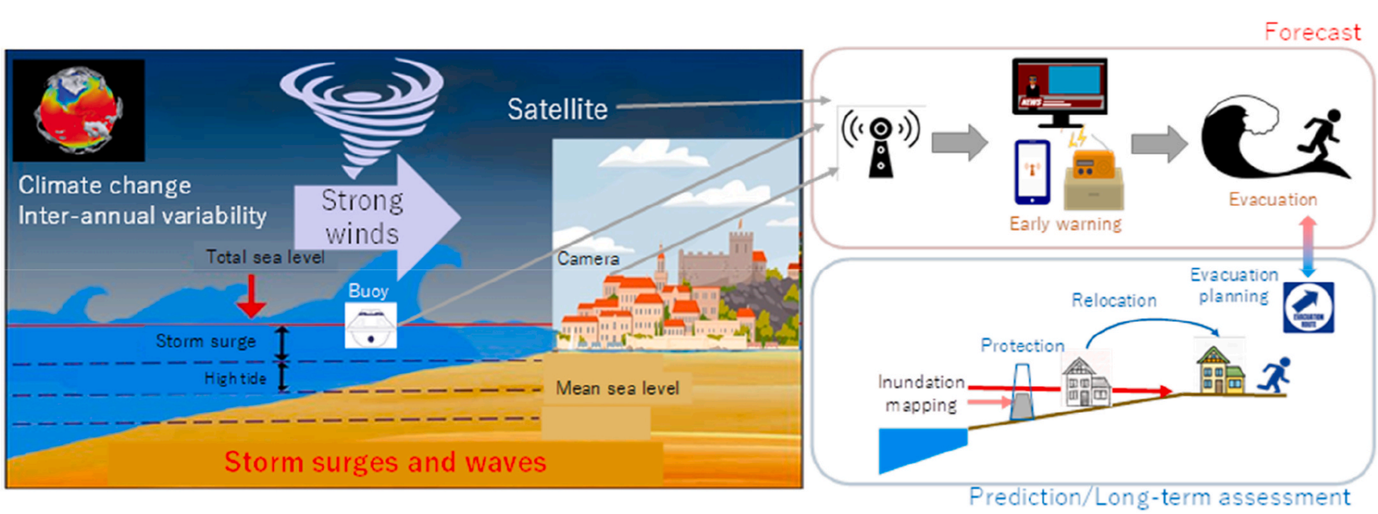

Fig. 1. Example of applications of storm surge forecast to early warning and long-term assessment efforts.

contributions exhibit complex dependency structures that lead to a higher joint probability of occurrence (e.g., Ward et al., 2018; Marcos et al., 2019; Couasnon et al., 2020). Several studies have examined compound flood hazard and have shown, for example, that extreme rainfall and associated riverine floods can compound with water levels and significantly aggravate flooding hazards and impacts (e.g., Couasnon et al., 2020; Camus et al., 2021; Huang et al., 2021; Nasr et al., 2021; Santos et al., 2021; Gori and Lin 2022; Wijetunge and Neluwala 2023). It has also been shown that compound risk associated with tropical cyclones should be treated separately from other types of storms (e.g., Kim et al., 2023; Nederhoff et al., 2023).

Climate change is expected to impact many components of the earth system, including changes in the mean, variance and/or interdependence, that together combine to change compound risks (e.g., Zscheischler et al., 2018, 2020). Of particular relevance to flooding risk projections are changes in the water cycle. A number of studies have shown that compounded effects from river, rain, surge, and or waves, can significantly modify flooding risk (e.g., Rulent et al., 2021; Gori et al., 2022; Xu et al., 2022). Changes in the intensity of extreme precipitation leads to changes in riverine and coastal floods (Bevacqua et al., 2020; Heinrich et al., 2023). Long droughts, forest fires, and/or extreme heat, rapid snowmelt or extreme rainfall can all alter the soil's capacity to catch and slowly drain water through catchment areas, also changing riverine flood risk. For example, prolonged heavy precipitation combined with prolonged storm surge can make it difficult to drain low-lying coastal areas (van den Hurk et al., 2015; Bormann et al., 2024), a situation that will continue to get worse with rising mean sea level (Bormann et al., 2020).

The representation of small (e.g., wave setup or river flow) to large scale processes (e.g., surges and tides) is a major challenge for global modelling systems (e.g., resolution and cost of other numerical systems). In addition, the effects of waves and river flow are typically not well captured by tide gauges as a result of installation choices such as recording frequency or installation in sheltered areas (e.g., Hoeke et al., 2013). This lack of widespread observation record complicates model development, verification, and assessments of the impacts of compounded effects on flooding risk.

Numerous countries are yet to have access to the numerical guidance essential to establish even surge plus tide only robust and reliable coastal flood warning systems for their population. Ongoing efforts to reach unserviced and under-served communities through the Coastal Inundation Forecasting Initiative have had local success (e.g., Swail et al., 2019; Swail 2021; Canterford et al., 2023) but cannot be scaled up easily. The same applies to other hydrometeorological hazards such as riverine flood, avalanche, frost, drought, or extreme precipitation warnings. In recognition of these urgent needs, a United Nation Early Warning for All (EW4ALL) initiative is underway and striving to ensure everyone on Earth is covered by early warning systems by 2027.

In the coming decades, extreme sea levels and associated coastal floods are likely to remain a leading cause of natural disasters due to the combined effects of sea-level rise leading to the critical water level being exceeded more frequently (Fox-Kemper et al., 2021), and increased coastal development associated with greater exposure (e.g., Kirezci et al., 2020). Efforts to rapidly step up our modelling capacities to address near-term emergency response to long-term adaptation needs are required.

In this letter, we present the surge model intercomparison project (SurgeMIP), and introduce activities we have set in motion to address these challenges. We begin with an overview of historical events, we continue with a brief review of water level modelling and warning, and projections of coastal flooding risk science. We introduce plans for recently developed global water level forecast systems to provide the scale up necessary to bring numerical guidance along the world's coastlines from which flood warning services can be developed in time to meet the EW4ALL ambitious target. We introduce our efforts to coordinate storm surges and extreme sea level climate projections ensuring we work together to produce large ensembles so that the uncertainty space is well sampled and provides a global view of expected changes in extreme water levels. Along the way, we briefly mention exploratory work hoping to leverage artificial intelligence to scale up our capacities and present our ambitions around surge model intercomparison climate projections.

2. Historical storm surges and their impacts

Countless storms and their impact on coastal inundations have led to tragic disasters around the world's coastal zones. Asia and the Pacific region are regularly exposed to powerful tropical cyclones and have suffered several catastrophic losses of life. One of the world's deadliest humanitarian natural disasters was the 1970 Bhola cyclone which affected what was then East Pakistan (now Bangladesh) and India's West Bengal, killing at least 300,000 people, primarily due to the associated storm surge that flooded much of the low-lying islands of the Ganges Delta (Cerveny et al., 2017; Frank and Husain, 1971, Needham et al., 2015). The Bangladesh region alone also suffered the loss of some 200, 000 lives in 1 582 and 1876 and a long list of storms have each caused tens of thousands of casualties (Hossain and Mullick, 2020). For example, the Cyclone in 1991 caused 138,000 fatalities (naming of Tropical Cyclones of the North Indian Ocean began in 2004, see tc-names.pdf (imd.gov.in) for details). In 1959 Typhoon Vera resulted in some 5 000 casualties in Japan (e.g., Jiang et al., 2016). In 2018 Jebi affected Japan, causing 10 billion USD in insurance damage (e.g., Mori et al., 2019a), whilst the 2013 super typhoon Haiyan led to 6 000 casualties in the Philippines (e.g., Mori et al., 2014, Needham et al., 2015). Other significant recent cyclones in the Bay of Bengal include Cyclone Sidr, which made landfall in Bangladesh on November 15, 2007, causing over 3 400 fatalities (Paul, 2009), and cyclone Nargis in Myanmar on May 2, 2008, causing over 138,000 fatalities (Murray).

Along the Northwest Atlantic, hurricane and extratropical storm damage reports go as far back as 1775 when a hurricane resulted in the loss of some 4 000 lives (Rappaport and Ruffman, 1999). A century later, the 1869 Saxby Gale storm also brought death and destruction to the Canadian Maritime Provinces (Abraham et al., 1999). Hurricane Ian made landfall on the southwest coast of Florida, USA, 28 September, 2022 causing 144 deaths, 100 billion USD in losses (65 billion of that insured) and drove several insurance companies into bankruptcy or motivated them to pull back from the Florida market. Over the past two decades, the Northwest Atlantic has also been exposed to several other tropical and extratropical cyclones (e.g., Hurricanes Matthew, Dorian, Fiona, and Sandy).

The Gulf of Mexico has a long history of storm surge events that have resulted in disasters. For example, the Chenière Caminada hurricane in 1893 struck Louisiana, causing a storm surge of up to 4.9 m, extensive damage to the coast, and over 2 000 fatalities (Blake et al., 2011). A few years later, the 1900 Galveston Hurricane, the deadliest natural disaster in U.S. history, struck Galveston, Texas, as a Category 4 hurricane. The storm generated a storm surge of up to 4.6 m and caused over 8 000 fatalities (Simpson et al., 2003). In recent decades, the adverse impacts of hurricanes in the Gulf of Mexico have been on the rise due to intensifying storms as well as extensive development in low-lying coastal areas, as exemplified by Hurricane Katrina in 2005 and Hurricane Harvey in 2017. Hurricane Katrina resulted in nearly 1 400 deaths and $125 billion in damage in 2005 dollars, mainly in the New Orleans region (Knabb et al., 2023).

Polar outbreaks generating anticyclonic cold fronts, known as Central American Cold Surges, also influence the Gulf of Mexico by creating extreme waves (Appendini et al., 2014) and flooding along the coast of Mexico (Rey et al., 2018). Despite creating less intense winds than tropical cyclones, their occurrence is more frequent, leading to more widespread impacts along the Mexican coastline (Appendini et al., 2018). In some cases, the storm surge created by these events can dampen river outflow, which, together with the associated rainfall, can exacerbate flooding several kilometers from the coast, as during the floods in Tabasco in 2007 (Perevochtchikova and de la Torres, 2010). Along the NW Atlantic coastline, Nor'easters can also result in large winter surges (e.g., Pringle et al., 2021a).

Europe has also had its share of destructive storms. In 1825 a surge affected parts of the Danish, German, and the Netherlands North Sea coastline causing more than 800 casualties (Poulsen 2021). In November 1872 in the western Baltic Sea an extreme storm surge with heights exceeding 3 m hit the almost tideless Danish and German coastline and became the worst natural disaster in modern Danish history (Aakjær and Buch, 2022). The 1953 and 1962 North Sea storm surge caused Northwest Europe's most severe coastal floods in local living memory, killing more than 2000 people on the coasts of England, the Netherlands, and Belgium in 1953 (Wadey et al., 2015) and more than 300 in Hamburg in 1962 (de Guttry and Ratter 2022). In 2010 storm Xynthia devastated part of the French coastline, causing several deaths and mangling local infrastructure (Genovese and Przyluski, 2013). A decade later, storm Gloria affected the Western Mediterranean causing strong erosion, economic loss, and 13 fatalities (Amores et al., 2020).

Around Oceania, reports of damage also span the past few centuries. For example, in March 1899, Tropical Cyclone Mahina is suggested to have caused the largest reported storm surge along Australia's coasts, along the Coral Sea coast of north Queensland, with over 300 lives lost (Nott and Hayne., 2000), while significant tropical cyclone-induced storm surges have also occurred on the Australian northwest coast (Nott and Hubbert, 2005). In Victoria in Australia's southeast, an intense November 1934 convective storm in Bass Strait drove the worst recorded storm surge in Port Phillip Bay, causing over 30 casualties from flooding and the sinking of a ship in hazardous seas and an estimated £1M damage (McInnes and Hubbert, 2003). South Pacific countries are also affected by tropical cyclones. Recent storms to affect the region include Winston in 2016 (Fiji), Gita in 2018 (Tonga and Fiji) and Harold in 2020 (Solomon Islands, Vanuatu, Fiji, and Tonga). Resulting damages of such storms can at times appear small but must be considered against the size of local populations and economies.

3. Local morphology and related impacts

Every year, low-lying and erodible coastlines around the world are affected by floods, saltwater intrusion and erosion. Coastal morphology such as barrier islands and tidal inlets and coastal infrastructures such as dikes and levees can be modified or damaged by a storm and leave the affected area with significantly modified vulnerabilities to flooding (e.g., Fritz et al., 2007; Cañizares and Irish, 2008). Away from low-lying coastlines, storm surges can also remain a threat. In some regions, erodible land and cliffs are known to recede up to several meters during large storms, endangering infrastructures perched well away from the direct onslaught of the ocean (e.g., McCulloch et al., 2002). Vertical land motion experienced as long-term subsidence (e.g., owing to subsurface resource extraction) may also contribute to increasing storm surge risks with time.

From a navigation perspective, avoiding the grounding of vessels helps maintain the safety of mariners and passengers and reduces the risk of environmental disasters (e.g., leaking oil following damage to a vessel's hull). Economic impacts are also associated with the ability to reach a port in time to avoid a storm or insufficient water draft.

In the polar regions, receding ice and increasing fetch for waves (e.g., Wang et al., 2015; Hošeková et al., 2021;Wang et al., 2021) allow surges to affect coastlines over an increasingly longer period of the year in areas where permafrost is also receding leaving behind friable soil and vulnerable communities (e.g., Whalen et al., 2022). Moreover, melting permafrost also causes land subsidence (O'Neill et al., 2023), which leads to higher relative coastal water levels.

As sea level rises, critically low water levels could be expected to become less of a problem. However, relative sea-level change also depends on local morphology and post-glacial isostatic rebound conditions (e.g., Wang et al., 2021). Together, these may not readily lead to improved conditions everywhere. As a result, it remains important to maintain the ability to predict both maxima and minima.

4. Storm surge prediction

For nearly two centuries, the scientific community has worked at understanding and forecasting sea levels and their extremes (e.g., Lubbock, 1836; Doodson, 1923 & 1924; Welander, 1961; Jarvinen and Lawrence, 1985; Flather et al., 1991; Hubbert and McInnes, 1999; Bernier and Thompson, 2006; Fernández-Montblanc et al., 2019). In the 21st century, models and regional water level prediction systems appeared in operational centers (e.g., Flather, 2000; Verlaan et al., 2005; Daniel et al., 2009; Lane et al., 2009; Werner et al., 2009; Ji et al., 2010; Funakoshi et al., 2012; Sembiring et al., 2015; Georgas et al., 2016; Zampato et al., 2016). Throughout this period, compute capacity continued to grow, supporting higher resolution global atmospheric systems. Ensemble atmospheric systems soon reached sufficient resolution (50–60 km grid spacing) to be used to drive storm surge systems with sufficient skill to be used for extreme sea level and related flood risk forecasting purposes (Bernier and Thompson 2015). Over the past decade, ensemble systems that allow the prediction of risk and an extension (in lead time) of the usefulness of prediction systems were therefore achievable and began to appear in some operational centers (e.g., Flowerdew et al., 2010 & 2013; Bernier and Thompson, 2015; Liu and Taylor, 2016). Ensembles of atmospheric forcing fields have continued to improve and increase in resolution. Nevertheless forecast surges that result from tropical cyclones, a major cause of extreme surges due to their low pressures and high winds, remains a challenge due to cyclone's small-scale features and complex ocean-atmospheric coupling effects (e.g., Irish et al., 2008; Hodges et al., 2017; Dulac et al., 2022; Slocum et al., 2022). A few teams have thus developed ensemble forecast systems that are driven by parametric tropical cyclone wind fields. Those systems have the advantage of sampling a wide array of possibilities and allow for worst-case scenario warning (e.g., (Taylor and Glahn, 2008); Greenslade et al., 2018; Kohno et al., 2018).

Storm surges were long considered to be a primarily regional process. However, it is now known that coastal trapped waves can travel long distances. The origin of a surge can thus be thousands of kilometers away, even in deep water (e.g., equatorial waves). Remotely forced (external) surges, observable as progressive waves in tide gauge data that cover long distances are known from shelf seas like the North Sea (Böhme et al., 2023), the Irish Sea (Brown and Wolf 2009), or the South China Sea (Liu et al., 2018). This along with increased computing capacity, supported a drive toward global scale modelling and led to the extension from regional to global water level forecast systems (e.g., Pringle et al., 2021b; Verlaan et al., 2015; Wang et al., 2021 & 2022) with three global systems now routinely operated by National Centers (Verlaan et al., 2015; Wang and Bernier, 2023; NOAA, 2023).

In recent years, powerful artificial intelligence (AI) methods have rapidly advanced the use of machine learning in environmental science (e.g., Hsieh, 2022) with several promising advances aimed at producing weather forecasts at a fraction of the cost of traditional operational systems. The success of AI methods lies in the availability of sufficient high-quality data to train deep learning algorithms (e.g., Bauer et al., 2023). At present, the fastest developments are around weather systems trained using several decades of ERA5 reanalysis data (e.g., Bi et al., 2022; Bi et al., 2023;Lam et al., 2023 ; Pathak et al., 2022). There remain numerous questions to be addressed such as the ability of such algorithms to perform for cases well outside the range of data they were trained with or just how much data is needed to train these AI systems. Similarly, the amount of additional training needed to refine large scale simulations to smaller scale (e.g., higher resolutions which we still cannot afford globally) remains unknown. In terms of both predictions and projections, there are also questions as to the usefulness of AI to sample the uncertainty space and generate large ensembles at a fraction of the cost of running them with traditional systems. There is now also development underway for applications to storm surge predictability (e.g., Bruneau et al., 2020; Tadesse et al., 2020; Lee et al., 2021; Tiggeloven et al., 2021; Mulia et al., 2023; Wang et al., 2023). Depending on the outcome, such efforts could significantly change the way coastal flooding prediction and projection research and operations are envisioned moving forward.

5. Long-term assessment of extreme sea levels

Long-term assessment of extreme sea levels is important for designing coastal protection and assessing infrastructure viability. The time scale of long-term assessment of storm surge O(10yrs)-O(100yrs), is purpose dependent, and includes, for example, the tolerance to risk (i.e., to a likely exposure or to a catastrophic but highly unlikely event).

Estimates of the frequency of coastal flooding are typically based on the analysis of annual maxima or peaks over threshold (e.g., Gumbel, 1958; Leadbetter et al., 1983; Coles, 2001). Maxima can be taken from historical records or from climate simulations. Classical extreme value analyses performed to estimate expected return sea levels typically assume a generalized extreme value (GEV) distribution or generalized Pareto distribution (GPD), with some taking into account non-stationarities (e.g., sea-level rise, internal climate variability). Several studies have noted that fitting Type I distributions can be problematic when the different contributing physical processes to extreme sea levels have vastly different frequencies of occurrence, as is the case in many tropical cyclone-affected locations that also experience more frequent and less-severe extreme sea levels from tides and moderate storms as well as severe extreme sea levels from rarely occurring tropical cyclones (e.g., Irish et al., 2011; Haigh et al., 2014; O'Grady et al., 2022). Recent work by O'Grady et al. (2022) proposes the use of a mixed-climate statistical approach, formulated from two Gumbel EVDs, as a more appropriate method for representing the extremes and highlights its potential application when combining modelled storm surges from populations of synthetic cyclones with deterministically modelled extreme sea levels from other physical processes. In other recent work, Calafat and Marcos (2020) exploit the spatial dependencies of nearby extreme observations to improve estimates of event probabilities with reduced uncertainties, through a Bayesian hierarchical model to determine GEV parameters and Howard and Williams (2021) demonstrate that downscaling long simulations of the present-day climate to local storm surge can help constrain GEV parameters derived from shorter observational record.

In terms of extreme sea levels of the future, it is well established that global warming is causing global mean sea levels to rise through a combination of ice melting and thermal expansion. Climate change also drives changes in atmospheric patterns and characteristics such as tropical and extra-tropical cyclones, the primary driver of storm surges and waves. Therefore, the plausible impacts of various climate change scenarios must be considered when establishing coastal protection, adaptation, or mitigation measures.

The often-assumed stationarity of the contributing factors (e.g., storminess and mean sea level) has been known to break down when analyzing long records (e.g., Marcos et al., 2015) due to the above-mentioned global warming effects. Coordinated projection of the likely range of expected extremes is needed to support informed responses (e.g., coastal management, changes to building codes, etc.). This is particularly the case for regions affected by tropical cyclones where assessment of future risk and design of adaptation measures must consider tropical cyclones and sea-level rise jointly (e.g., Woodruff et al., 2013).

Regionally sea-level change has been the main driver of changes in extreme sea levels across the global tide gauge network over the 20th Century, and the IPCC suggests this will continue to be the dominant driver of a substantial increase in the frequency of extreme sea levels over the next Century (Fox-Kemper et al., 2021). Global mean sea level will continue to rise beyond 2 100 (Fox-Kemper et al., 2021), with substantial regional variations (e.g., Palmer et al., 2020) arising from, for example, changes in ocean circulation and local density, and the effect of land ice melt on Earth's gravity, rotation, and solid earth deformation. Ongoing glacial isostatic adjustment and underground water exploitation will also continue to affect regional relative sea-level change.

In addition, future climate change-driven projections in tropical cyclones, extra-tropical storms, extreme winds (Seneviratne et al., 2021), and wind-wave climate (Fox-Kemper et al., 2021; Morim et al., 2019; Casas-Prat et al., 2024) suggest the frequency and intensity of storm surges will also be subject to climate change driven variations. IPCC AR6 thus concluded that the inclusion of local processes, such as storm surges, is essential for estimation of changes in extreme sea level events despite the existing uncertainties underlying such changes (Fox-Kemper et al., 2021).

Recent unprecedented severe weather events are in line with an expected increase in the intensity of tropical cyclones and typical events (Seneviratne et al., 2021). This implies larger resulting surges can occur at an expanded portion of the tidal cycle (e.g., at low tide) and still result in an exceedance of critical flood levels.

As a result of sea-level rise alone, the intensity of storms necessary to reach a critical flood level decreases. Thus, the frequency of exceedance of a given critical flood level will continue to increase. Assuming other contributors to extreme sea level remain constant (i.e., the storm surge climate remains unchanged), extreme sea levels that occurred once per century in the recent past will occur annually or more frequently at about 19–31% of tide gauges by 2050, and at about 60 (SSP1-2.6) to 82% (SSP5-8.5) of tide gauges by 2 100 (Fox-Kemper et al., 2021). These estimates remain broad and cannot address local concerns. Over the coming years, we seek to reduce the uncertainty space and provide information that is more location specific.

At present, two pathways are used to produce long-term assessments of extreme sea levels. The first pathway, the static approach, is to derive an assessment based on the analysis of historical data (obtained from tide gauge records, hindcasts, or a combination of both) then projecting risk into the future considering assumptions such as applying a mean sea level rise offset. The second pathway, the dynamic approach, is becoming increasingly feasible. It consists of producing the assessment using data generated from long-term projections of sea levels. The types of numerical systems described in the storm surge prediction section (driven with climate projections instead of weather forecasts) are key tools to greatly help advance the dynamic approach. Assuming storm resolving climate projections are available to drive surge responses under various scenarios, it becomes feasible to derive extremal analyses from these projected records. This capacity is emerging as climate projections are only beginning to sufficiently resolve storms to produce realistic surge statistics. Currently, the availability of storm surge projections remains limited (e.g., Gaslikova et al., 2013; Vousdoukas et al., 2018; Muis et al., 2020, 2023; Shimura et al., 2022) and most existing studies on future projections of extreme water levels extrapolate historical conditions and/or focus on the impact of sea-level rise (assuming stationarity of surges) in line with the static approach. Both pathways are further detailed below. It is followed by a section on challenges we intend to consider over the coming years.

a) Assessment based on Historical Data

Extremal analyses rely on long time series (typically at least 30 years). Decadal to century long records of sea levels are sparse and mostly found in Europe, North America, Japan, and Australia. Satellite observation records now include 30 years of data and provide useful information and better coverage but their temporal resolution and extent limits the study of rare and hazardous extremes.

A common means of filling observation gaps is the reliance on numerical systems such as those described above together with the availability of reanalysis to produce hindcasts of water levels. Over the past few decades, several studies have thus performed long hindcast based assessments of sea levels and related flood hazard and/or examined flood risk at the regional or global scales (e.g., Bernier and Thompson, 2006; Hinkel et al., 2014; Haigh et al., 2016; Muis et al., 2016; Colberg et al., 2019; Kirezci et al., 2023; Tiggeloven et al., 2020) and typically point to gradually increasing risk of exceeding locally critical water levels over the coming decades to centuries as a result of expected climate related change (e.g., changes in storminess, sea-level rise).

Wahl et al. (2017) also relied on historical data but used a different approach. They assessed uncertainties in contemporary extreme sea levels, across 20 representative extreme value assessment methods and concluded that present-day extreme sea level uncertainties exceed those of global sea-level rise projections. A recent study by Hinkel et al. (2021) assessed contributions to uncertainty and bias in current and future coastal flood risk and pointed to large uncertainties in numerous contributing factors, including those associated with adaptation measures and socio-economic responses. We note that long term trends can also be affected by temporal inhomogeneities due to non-climatic factors such as changes in the observational network or increasing quantity and quality of ingested observations in forcing atmospheric reanalyses. Emerging data-driven models (e.g., Tausía et al., 2023) offer complementary approaches for storm surge hindcast development.

Climate change impact on extreme sea level and related risks (e.g., flooding, erosion, salt intrusion) over the coming decades to century has been examined using numerical data and/or statistical techniques to supplement or replace long observation records and/or develop future projections that explicitly account for emission scenarios (e.g., Bernier et al., 2007; Lowe et al., 2010; Muis et al., 2015; Muis et al., 2020, 2022; Vousdoukas et al., 2018; Tadesse et al., 2020; Pringle et al., 2021a; Shimura et al., 2022; Lin et al., 2019; Almar et al., 2021). Various approaches are used. These have allowed growingly sophisticated studies of extreme sea levels and their changes through time to be performed for both areas with and without long observation records (e.g., Bernier et al., 2007). The story-line approach quantitatively considers the impact of global warming based on events that have occurred in the past (e.g., Takayabu et al., 2015). The probabilistic typhoon model approach is based on a probabilistic assessment of a large number of synthetic typhoons generated based on past typhoon statistics and can include worst-case scenario assessments (e.g., Marsooli et al., 2019; Ruiz-Salcines et al., 2021; Pringle et al., 2021a; Shimura et al., 2022).

Together, these results based on historical records and hindcasts point to climate change resulting in significant changes in extreme sea levels and associated risks but sources of uncertainty remain considerable as a result of relying on historical data and broad assumptions of future conditions.

b) Assessments based on long-term projections

A second pathway is to project future changes in storm surges using future projections from global or regional climate models (e.g., Mori et al., 2019b; Palmer et al., 2020). This is gradually becoming possible as the spatial resolution of GCMs increases, their ability to produce tropical cyclones improves (Roberts et al., 2020), and the number of ensembles in projections continues to dramatically increase (e.g., Mizuta et al., 2017). Therefore, available projections based on these methods are improving. Furthermore, alternative climatological approaches have been developed based on the maximum potential tropical cyclone framework (Lin and Emanuel, 2016; Mori et al., 2021). The climatological approach is highly compatible with GCMs but presents low accuracy for storm surges which arise from resolutions generally too coarse to resolve storms.

As previously mentioned, the availability of future storm surge projections that explicitly account for climate change emission scenarios remains limited (e.g., Gaslikova et al., 2013; Vousdoukas et al., 2018; Muis et al., 2020, 2023; Shimura et al., 2022). Moreover, large ensembles (Maher et al., 2021) of extreme water level projections have not been developed to date. These are needed to further investigate the role of different key uncertainty factors, namely climate and sea level modelling approaches, emission scenarios, and natural climate variability, that have been found to have an important role in the assessment of historical and future wave conditions (Casas-Prat et al., 2023; Morim et al., 2019; Grabemann et al., 2015; Grabemann and Weisse, 2008). The above-mentioned ongoing research in AI-based surge modelling has also been recently extended to develop future projections at local and regional scales (e.g., Ayyad et al., 2023). Depending on the success of these methods, similar applications at the global scale could be developed. AI could thus potentially be used to tackle the high computational demand associated with the production of large ensembles and support a wide sampling of the uncertainty of surge projections at a fraction of the cost of running hundreds of numerical simulations with traditional systems.

6. SurgeMIP activities: plans and progress

As the maturity and reliance on numerical systems, extremal analyses, information targeted to early warning systems, and adaptation and mitigation needs are fast growing, a new initiative is bringing together domain experts (SurgeMIP Community) and coordinating our surge modelling community efforts. Objectives of the collaboration include (i) establish regular workshops, (ii) intercompare the various prediction systems currently able to operate, initially at the global scale, (iii) describe the current state of the science, (iv) identify gaps and establish emerging research priorities, and (v) coordinate climate projections and develop studies based on emission scenarios and global warming levels (e.g., 1.5^{o}C or 2.0^{o}C warning). We note in regard to point iv that we expect the field to move rapidly (e.g., emergence of GCM fields to produce projections, fast developing global storm surge systems, AI). To ensure we remain agile and able to respond to emerging challenges and possibilities our research priorities will be reviewed on a regular basis. Our efforts are planned in conjunction with other research communities that focus on sea-level rise or wave climate changes (e.g., Coordinated Ocean Wave Climate Project (COWCLIP; Hemer et al., 2012). The bi-annual International Workshop on Waves, Storm Surges and Coastal Hazards (waveworkshop.org) has been identified to hold our regular face-to-face workshops. The workshop is well established and has a long history of bringing together experts from the research and operational communities. Our first face-to-face meeting was held immediately following the last workshop in October 2023. Our next face-to-face meeting is scheduled for the Fall of 2025 in Spain. In between face-to-face meetings, we hold online meetings as required to advance our objectives.

At present, three global water level systems are known to be in operation (Wang and Bernier, 2023; Verlaan et al., 2015; NOAA, 2023). These systems can now provide data worldwide and are envisioned as a key contribution to the UN Early Warnings for All (Early Warnings for All | World Meteorological Organization (wmo.int)). Their operational production now allows services to be built to provide water level warnings in regions traditionally without numerical guidance. In recognition of the need for robust and reliable numerical guidance to be available along the world's coastline, the World Meteorological Organisation is in the process of establishing regional specialized meteorological centers for global numerical storm surge predictions. The three operational systems listed in this article meet established criteria (e.g., minimal coverage, data availability and metrics). Although each has been extensively validated and shown to meet national standards in the countries that operate them, validations were performed over different periods and sets of observation records. These systems have never been intercompared. Following online and a face-to-face meeting, we

Table 1
Data requirement for storm surge numerical projections. The first column is data type and level when appropriate, the second column is temporal resolution, the third column is spatial resolution.

Data Type	Temporal Resolution	Spatial Resolution
10 m Winds	Hourly	25 km
Surface Pressure	Hourly	25 km
Ice concentration	3 Hourly	25 km
Ice velocity	3 Hourly	25 km
Surface Ocean Currents	3 Hourly	25 km
Ocean T profile (all levels in top 500m, 1000m, 2000m, bottom)	Monthly	25 km
Ocean S profile (all levels in top 500m, 1000m, 2000m, bottom)	Monthly	25 km

established requirements to participate in the intercomparison. We identified a common hindcast period (2013–2018), common forcing fields (ERA5), common set of validation data drawn from GESLA3 including data handling (e.g., detiding), common output fields, and metrics to be considered. We are now performing the intercomparison of these operational and other research systems so that current and future progress can be monitored and communicated, and their skills and limitations are known before they are used to produce high resolution global projections of future coastal water levels. In time, regional systems will also be included in the intercomparison. Results of our intercomparison will help identify remaining gaps in our systems and help us tackle issues such as dealing with diverse gridding and resolution choices, different selection of processes (e.g., allowing for tides, waves, baroclinic processes, wetting and drying), and vertical datums (e.g., geoids, sea-level rise, isostatic post-glacial adjustment), before we further complexify the problem by expanding our intercomparison project to include regional systems, some of which are far more complex (e.g., include wave run-up, river flow), and before combining our global projections. These will be further discussed once the initial intercomparison is completed.

In the surge community, we often work across weather and climate time scales using the same systems. The intercomparison of past and present forecasts will thus inform the interpretation of our climate projections. Over the coming decades and century, changes in extreme sea level drivers (e.g., mean sea-level rise, receding ice, receding permafrost, change in storminess, changes in rainfall and associated riverine effects) will continue to evolve. Several studies have assessed the expected impacts (e.g., Bevacqua et al., 2020; Hanson and Nicholls, 2020) but until recently, available driving fields such as surface pressure and winds have been too coarse (both spatially and temporally) to produce a robust numerical projections-based assessment under various climate scenarios for many regions. Fortunately, projected atmospheric fields necessary to drive the projection of storm surges are increasingly reaching the minimal resolutions required to resolve storms and allow studies of extremes. Following face-to-face and online discussions, the SurgeMIP community has established its data requirements for driving fields it draws from GCM projections with extreme sea level projections in mind (Table 1). We note the data requirements listed in Table 1 are for global systems currently being operated. Projections with systems able to, for example, capture river flow would result in additional requirements such as higher granularity of forcing fields, the addition of precipitation and land information.

With only a handful of teams currently able to perform global projections, tackling challenges listed above such as achieving common datums and coordination will be key to producing large ensembles so that the uncertainty space is well sampled to provide a global view of expected changes in extreme water levels.

The SurgeMIP community now has tools to carry out studies of sea level extremes under various scenarios – both through data-driven approaches which exploit statistical relationships between predictor (atmospheric field) and predictand (extreme water level), and dynamical approaches, now possible owing to the fast-increasing computing capacity and the recently developed abilities to forecast/project surges at the global scale.

7. Summary

In this letter, we highlighted the vulnerability of the world's coastline and coastal communities as we circled the world, briefly pointing to a few historical storms and their local impacts. We briefly reviewed the history of storm surge modelling, introduced the concept of extreme sea levels and related risks, and discussed climate change and its expected impacts. We pointed to the need for early warning systems and discussed recent progress towards the establishment of regional specialized meteorological centers for global numerical storm surge predictions. We briefly reviewed expected climate change contributions to future extreme sea levels and the associated need to further our knowledge in support of the development and implementation of adaptation and mitigation measures. We introduced a new international initiative to intercompare surge forecast systems to inform on current capacities, current research gaps, and to inform on systems to be used to compute projections. SurgeMIP will also serve to coordinate projections developed by its various members to support wider and more complete sampling of projected scenarios. To date, we established data needs for the production of projections that support the study of extreme events (Table 1) and will be addressing some technical challenges such as dealing with various modelling choices and reference frames as we progress through the intercomparison we have initiated. We highlighted planned and in progress activities with outcomes we seek to achieve over the coming years. These include.

a) Document contemporary storm surge modelling/prediction efforts (initially at global scale),
b) Compare performance of contemporary storm surge modelling systems under standardized forcing conditions (as possible), data handling, and evaluation metrics,
c) Compare existing historical storm surge hindcasts, recognizing inhomogeneity of forcing parameters,
d) Build a community-based ensemble of storm surge systems, for both operational prediction, and climate projection scale applications,
e) Produce and assemble projection of a community-based ensemble of storm surge heights at global scale for IPCC AR7.

Through this letter we, the SurgeMIP community, invite research groups not yet involved but interested in joining our efforts to contact us via the corresponding author.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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