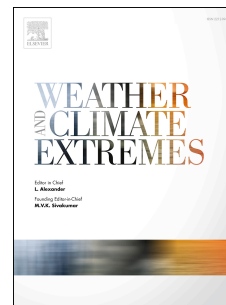


# Journal Pre-proof

Storm Surges and Extreme Sea Levels: Review, Establishment of Model Intercomparison and Coordination of Surge Climate Projection Efforts (SurgeMIP).

Natacha B. Bernier, Mark Hemer, Mori Nobuhito, Christian M. Appendini, Oyvind Breivik, Ricardo de Camargo, Mercè Casas-Prat, Trang M. Duong, Ivan D. Haigh, Tom Howard, Vanessa Hernaman, Oleksandr Huizy, Jennifer L. Irish, Ebru Kirezci, Nadao Kohno, Jun-Whan Lee, Kathleen L. McInnes, Elke.M.I. Meyer, Marta Marcos, Reza Marsooli, Ariadna Martin Oliva, Melisa Menendez, Saeed Moghimi, Sanne Muis, Jeff A. Polton, William J. Pringle, Roshanka Ranasinghe, Thomas Saillour, Grant Smith, Michael Getachew Tadesse, Val Swail, Shimura Tomoya, Evangelos Voukouvalas, Thomas Wahl, Pengcheng Wang, Ralf Weisse, Joannes J. Westerink, Ian Young, Y. Joseph Zhang



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## 134 Abstract

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

## 151 Introduction

152  
153 The world's coastlines are associated with some of the most expensive natural disasters of  
154 recent years. Coastal communities worldwide expect precise and accurate guidance to  
155 inform and support the response to imminent events and mitigate and adapt to the changing  
156 conditions of the decades and centuries to come. Along the world's coastlines, the primary  
157 cause of coastal flood damage is extreme sea level (i.e., exceptionally low or high local sea  
158 surface height) that results from changes in local mean sea levels in combination with storm  
159 surges, astronomical tides and, at times, waves and/or river overflow to raise coastal water  
160 levels above a locally critical water level (i.e., above which damages are expected; Figure 1).

161

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

167

168 Ocean processes and conditions such as water depth, tides, shelf width, ice, and  
169 stratification also modulate characteristics of storm surges (e.g., Bernier and Thompson  
170 2007; Zhang et al 2010.; McInnes, et al., 2016; Idier et al., 2019; Arns et al., 2020; Wang  
171 and Bernier 2023). When resulting water level exceeds the local tidal maxima, there is a risk  
172 of flooding and/or erosion. When the water drops below local tidal minima, there is a risk to  
173 navigation when for example vessels' water draft exceed the water depth (e.g., Jensen et al.  
174 2022). In addition to tide and surge, wave runup, the combination of wave setup (elevation of  
175 nearshore mean sea level due to wave breaking in the surfzone) and wave swash uprush  
176 (rapid upward-moving water after waves reach the shore), can exacerbate extreme coastal  
177 levels with non-trivial contributions that vary over time (e.g., Melet et al., 2016; Predreros et  
178 al., 2018; Marsooli and Lin, 2018; Amores et al., 2020; Lavau et al., 2020; Toomey et al.,  
179 2022). Kirezci et al. (2020) estimated that wave setup alone may contribute as much as 17%  
180 to extreme sea levels. Natural barriers such as the presence of mangrove can help alleviate  
181 those effects and protect shorelines (e.g., Zhang et al., 2012).

182

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

189 impacts. Often, these contributions exhibit complex dependency structures that lead to a  
190 higher joint probability of occurrence (e.g., Ward et al., 2018, Marcos et al., 2019, Couasnon  
191 et al., 2020). Several studies have examined compound flood hazard and have shown, for  
192 example, that extreme rainfall and associated riverine floods can compound with water  
193 levels and significantly aggravate flooding hazards and impacts (e.g., Couasnon et al, 2020,  
194 Camus et al., 2021, Huang et al., 2021, Nasr et al., 2021, Santos et al 2021, Gori and Lin  
195 2022, Wijetunge and Neluwala 2023). It has also been shown that compound risk associated  
196 with tropical cyclones should be treated separately from other types of storms (e.g., Kim et  
197 al., 2022, Nederhoff et al., 2023).

198

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

212

213 The representation of small (e.g., wave setup or river flow) to large scale processes (e.g.,  
214 surges and tides) is a major challenge for global modelling systems (e.g., resolution and cost  
215 of other numerical systems). In addition, the effects of waves and river flow are typically not  
216 well captured by tide gauges as a result of installation choices such as recording frequency

217 or installation in sheltered areas (e.g., Hoeke et al., 2013). This lack of widespread  
218 observation record complicates model development, verification, and assessments of the  
219 impacts of compounded effects on flooding risk.

220

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

230

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

237

238 In this letter, we present the surge model intercomparison project (SurgeMIP), and introduce  
239 activities we have set in motion to address this challenge. We begin with an overview of  
240 historical events, we continue with a brief review of water level modelling and warning, and  
241 projections of coastal flooding risk science. We introduce plans for recently developed global  
242 water level forecast systems to provide the scale up necessary to bring numerical guidance  
243 along the world's coastlines from which flood warning services can be developed in time to  
244 meet the EW4ALL ambitious target. We introduce our efforts to coordinate storm surges

245 and extreme sea level climate projections ensuring we work together to produce large  
 246 ensembles so that the uncertainty space is well sampled and provides a global view of  
 247 expected changes in extreme water levels. Along the way, we briefly mention exploratory  
 248 work hoping to leverage artificial intelligence to scale up our capacities and present our  
 249 ambitions around surge model intercomparison climate projections.

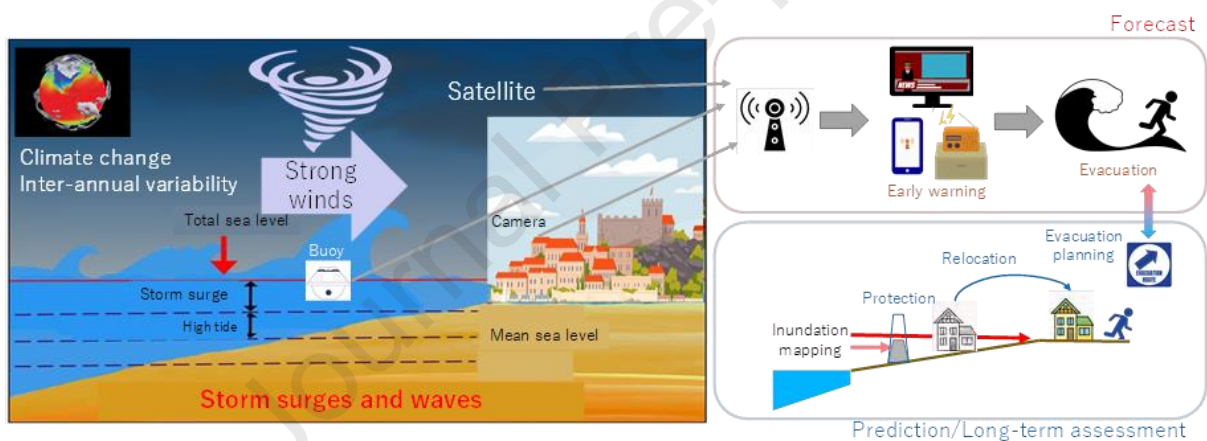
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253

## 254 Historical storm surges and their impacts



255

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

258

259 Countless storms and their impact on coastal inundations have led to tragic disasters around  
 260 the world's coastal zones. Asia and the Pacific region are regularly exposed to powerful  
 261 tropical cyclones and have suffered several catastrophic losses of life. One of the world's  
 262 deadliest humanitarian natural disasters was the 1970 Bhola cyclone which affected what  
 263 was then East Pakistan (now Bangladesh) and India's West Bengal, killing at least 300,000  
 264 people, primarily due to the associated storm surge that flooded much of the low-lying  
 265 islands of the Ganges Delta (Cervený et al., 2017; Frank and Husain, 1971, Needhan et al.,

266 2015). The Bangladesh region alone also suffered the loss of some 200,000 lives in 1582  
267 and 1876 and a long list of storms have each caused tens of thousands of casualties  
268 (Hossain and Mullick, 2020). For example, the Cyclone in 1991 caused 138,000 fatalities  
269 (naming of Tropical Cyclones of the North Indian Ocean began in 2004, see [tc-names.pdf](#)  
270 [\(imd.gov.in\)](#) for details). In 1959 Typhoon Vera resulted in some 5000 casualties in Japan  
271 (e.g., Jiang et al., 2015). In 2018 Jebi affected Japan, causing 10 billion USD in insurance  
272 damage (e.g., Mori et al., 2019a), whilst the 2013 super typhoon Haiyan led to 6000  
273 casualties in the Philippines (e.g., Mori et al., 2014, Needhan et al., 2015). Other significant  
274 recent cyclones in the Bay of Bengal include Cyclone Sidr, which made landfall in  
275 Bangladesh on 15 November 2007, causing over 3,400 fatalities (Paul, 2009), and cyclone  
276 Nargis in Myanmar on 2 May 2008, causing over 138,000 fatalities (Murray et al., 2012).

277

278 Along the Northwest Atlantic, hurricane and extratropical storm damage reports go as far  
279 back as 1775 when a hurricane resulted in the loss of some 4000 lives (Rapaport and  
280 Ruffman, 1999). A century later, the 1869 Saxby Gale storm also brought death and  
281 destruction to the Canadian Maritime Provinces (Abraham et al., 1999). Hurricane Ian made  
282 landfall on the southwest coast of Florida, USA, 28 September 2022 causing 144 deaths,  
283 100 billion USD in losses (65 billion of that insured) and drove several insurance companies  
284 into bankruptcy or motivated them to pull back from the Florida market. Over the past two  
285 decades, the Northwest Atlantic has also been exposed to several other tropical and  
286 extratropical cyclones (e.g., Hurricanes Matthew, Dorian, Fiona, and Sandy).

287

288 The Gulf of Mexico has a long history of storm surge events that have resulted in disasters.  
289 For example, the Chenière Caminada hurricane in 1893 struck Louisiana, causing a storm  
290 surge of up to 4.9 m, extensive damage to the coast, and over 2,000 fatalities (Blake et al.,  
291 2011). A few years later, the 1900 Galveston Hurricane, the deadliest natural disaster in U.S.  
292 history, struck Galveston, Texas, as a Category 4 hurricane. The storm generated a storm  
293 surge of up to 4.6 m and caused over 8,000 fatalities (Simpson et al., 2003). In recent

294 decades, the adverse impacts of hurricanes in the Gulf of Mexico have been on the rise due  
295 to intensifying storms as well as extensive development in low-lying coastal areas, as  
296 exemplified by Hurricane Katrina in 2005 and Hurricane Harvey in 2017. Hurricane Katrina  
297 resulted in nearly 1400 deaths and \$125 billion in damage in 2005 dollars, mainly in the New  
298 Orleans region (Knabb et al., 2023).

299

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

309

310 Europe has also had its share of destructive storms. In 1825 a surge affected parts of the  
311 Danish, German, and the Netherlands North Sea coastline causing more than 800 casualties  
312 (Poulsen 2021). In November 1872 in the western Baltic Sea an extreme storm surge with  
313 heights exceeding 3 meters hit the almost tideless Danish and German coastline and  
314 became the worst natural disaster in modern Danish history (Aakjær and Buch 2022). The  
315 1953 and 1962 North Sea storm surge caused Northwest Europe's most severe coastal  
316 floods in local living memory, killing more than 2000 people on the coasts of England, the  
317 Netherlands, and Belgium in 1953 (Wadey et al., 2015) and more than 300 in Hamburg in  
318 1962(de Guttry and Ratter 2022). In 2010 storm Xynthia devastated part of the French  
319 coastline, causing several deaths and mangling local infrastructure (Genovese and  
320 Przyluski, 2013). A decade later, storm Gloria affected the Western Mediterranean causing  
321 strong erosion, economic loss, and 13 fatalities (Amores et al., 2020).

322

323 Around Oceania, reports of damage also span the past few centuries. For example, in March  
324 1899, Tropical Cyclone Mahina is suggested to have caused the largest reported storm  
325 surge along Australia's coasts, along the Coral Sea coast of north Queensland, with over  
326 300 lives lost (Nott and Hayne., 2000), while significant tropical cyclone-induced storm surges  
327 have also occurred on the Australian northwest coast (Nott and Hubbert, 2005). In Victoria in  
328 Australia's southeast, an intense convective storm in Bass Strait caused the worst recorded  
329 storm surge in Port Phillip Bay in November 1934, causing over 30 casualties from flooding and  
330 the sinking of a ship in hazardous seas and an estimated £1M damage (McInnes and Hubbert,  
331 2003). South Pacific countries are also affected by tropical cyclones. Recent storms to affect  
332 the region include Winston in 2016 (Fiji), Gita in 2018 (Tonga and Fiji) and Harold in 2020  
333 ( Solomon Islands, Vanuatu, Fiji, and Tonga). Resulting damages of such storms can at  
334 times appear small but must be considered against the size of local populations and  
335 economies.

336

## 337 Local morphology and related impacts

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

348

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

353

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

360

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

366

## 367 Storm surge prediction

368 For nearly two centuries, the scientific community has worked at understanding and  
369 forecasting sea levels and their extremes (e.g., Lubbock, 1836; Doodson, 1923 & 1924;  
370 Welander, 1961; Jarvinen and Lawrence, 1985; Flather et al., 1991; Hubbert and McInnes,  
371 1999; Bernier and Thompson, 2006; Fernández-Montblanc et al., 2019). In the 21<sup>st</sup> century,  
372 models and regional water level prediction systems appeared in operational centers (e.g.,  
373 Flather, 2000; Verlaan et al., 2005; Daniel et al., 2009; Lane et al., 2009; Werner et al.,  
374 2009; Ji et al., 2010; Funakoshi et al., 2011, Sembiring et al., 2015, Georgas et al. 2016,  
375 Zampato et al., 2016). Throughout this period, compute capacity continued to grow,

376 supporting higher resolution global atmospheric systems. Ensemble atmospheric systems  
377 soon reached sufficient resolution (50-60 km grid spacing) to be used to drive storm surge  
378 systems with sufficient skill to be used for extreme sea level and related flood risk  
379 forecasting purposes (Bernier and Thompson 2015). Over the past decade, ensemble  
380 systems that allow the prediction of risk and an extension (in lead time) of the usefulness of  
381 prediction systems were therefore achievable and began to appear in some operational  
382 centers (e.g., Flowerdew et al., 2010 & 2013; Bernier and Thompson, 2015; Liu and Taylor,  
383 2016). Ensembles of atmospheric forcing fields have continued to improve and increase in  
384 resolution. Nevertheless forecast surges that result from tropical cyclones, a major cause of  
385 extreme surges due to their low pressures and high winds, remains a challenge due to  
386 cyclone's small-scale features and complex ocean-atmospheric coupling effects (e.g., Irish  
387 et al., 2008; Hodges et al, 2017; Dulac et al, 2022; Slocum et al, 2022). A few teams have  
388 thus developed ensemble forecast systems that are driven by parametric tropical cyclone  
389 wind fields. Those systems have the advantage of sampling a wide array of possibilities and  
390 allow for worst-case scenario warning (e.g., Taylor et al., 2008; Greenslade et al., 2018;  
391 Kohno et al., 2018).

392

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

403

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

## 423 Long-term assessment of extreme sea levels

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

428

429 Estimates of the frequency of coastal flooding are typically based on the analysis of annual  
430 maxima or peaks over threshold (e.g., Gumbel, 1958; Leadbetter et al., 1983; Coles, 2001).

431 Maxima can be taken from historical records or from climate simulations. Classical extreme  
432 value analyses performed to estimate expected return sea levels typically assume a  
433 generalized extreme value (GEV) distribution or generalized Pareto distribution (GPD), with  
434 some taking into account non-stationarities (e.g., sea-level rise, internal climate variability).  
435 Several studies have noted that fitting Type I distributions can be problematic when the  
436 different contributing physical processes to extreme sea levels have vastly different  
437 frequencies of occurrence, as is the case in many tropical cyclone-affected locations that  
438 also experience more frequent and less-severe extreme sea levels from tides and moderate  
439 storms as well as severe extreme sea levels from rarely occurring tropical cyclones (e.g.,  
440 Irish et al 2011; Haigh et al., 2014; O'Grady et al., 2022). Recent work by O'Grady et al.  
441 (2022) proposes the use of a mixed-climate statistical approach, formulated from two  
442 Gumbel EVDs, as a more appropriate method for representing the extremes and highlights  
443 its potential application when combining modelled storm surges from populations of synthetic  
444 cyclones with deterministically modelled extreme sea levels from other physical processes.  
445 In other recent work, Calafat and Marcos (2020) exploit the spatial dependencies of nearby  
446 extreme observations to improve estimates of event probabilities with reduced uncertainties,  
447 through a Bayesian hierarchical model to determine GEV parameters and Howard and  
448 Williams (2021) demonstrate that downscaling long simulations of the present-day climate to  
449 local storm surge can help to constrain GEV parameters derived from the shorter  
450 observational record.

451

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

458

459 The often-assumed stationarity of the contributing factors (e.g., storminess and mean sea  
460 level) has been known to break down when analyzing long records (e.g., Marcos et al.,  
461 2015) due to the above-mentioned global warming effects. Coordinated projection of the  
462 likely range of expected extremes is needed to support informed responses (e.g., coastal  
463 management, changes to building codes, etc.). This is particularly the case for regions  
464 affected by tropical cyclones where assessment of future risk and design of adaptation  
465 measures must consider tropical cyclones and sea-level rise jointly (e.g., Woodruff et al  
466 2013).

467

468 Regionally sea-level change has been the main driver of changes in extreme sea levels  
469 across the global tide gauge network over the 20th Century, and the IPCC suggests this will  
470 continue to be the dominant driver of a substantial increase in the frequency of extreme sea  
471 levels over the next Century (Fox-Kemper et al., 2021). Global mean sea level will continue  
472 to rise beyond 2100 (Fox-Kemper et al., 2021), with substantial regional variations (e.g.,  
473 Palmer et al., 2020) arising from, for example, changes in ocean circulation and local  
474 density, and the effect of land ice melt on Earth's gravity, rotation, and solid earth  
475 deformation. Ongoing glacial isostatic adjustment and underground water exploitation will  
476 also continue to affect regional relative sea-level change.

477

478 In addition, future climate change-driven projections in tropical cyclones, extra-tropical  
479 storms, extreme winds (Seneviratne et al., 2021), and wind-wave climate (Fox-Kemper et al.,  
480 2021; Mori et al., 2020; Casas-Prat et al., 2024) suggest the frequency and intensity of storm  
481 surges will also be subject to climate change driven variations. IPCC AR6 thus concluded  
482 that the inclusion of local processes, such as storm surges, is essential for estimation of  
483 changes in extreme sea level events despite the existing uncertainties underlying such  
484 changes (Fox-Kemper et al, 2021).

485

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

490

491 As a result of sea-level rise alone, the intensity of storms necessary to reach a critical flood  
492 level decreases. Thus, the frequency of exceedance of a given critical flood level will  
493 continue to increase. Assuming other contributors to extreme sea level remain constant (i.e.,  
494 the storm surge climate remains unchanged), extreme sea levels that occurred once per  
495 century in the recent past will occur annually or more frequently at about 19-31% of tide  
496 gauges by 2050, and at about 60 (SSP1-2.6) to 82% (SSP5-8.5) of tide gauges by 2100  
497 (Fox-Kemper et al., 2021). These estimates remain broad and cannot address local  
498 concerns. Over the coming years, we seek to reduce the uncertainty space and provide  
499 information that is more location specific.

500

501 At present, two pathways are used to produce long-term assessments of extreme sea levels.  
502 The first pathway, the static approach, is to derive an assessment based on the analysis of  
503 historical data (obtained from tide gauge records, hindcasts, or a combination of both) then  
504 projecting risk into the future considering assumptions such as applying a mean sea level  
505 rise offset. The second pathway, the dynamic approach, is becoming increasingly feasible.  
506 It consists of producing the assessment using data generated from long-term projections of  
507 sea levels. The types of numerical systems described in the storm surge prediction section  
508 (driven with climate projections instead of weather forecasts) are key tools to greatly help  
509 advance the dynamic approach. Assuming storm resolving climate projections are available  
510 to drive surge responses under various scenarios, it becomes feasible to derive extremal  
511 analyses from these projected records. This capacity is emerging as climate projections are  
512 only beginning to sufficiently resolve storms to produce realistic surge statistics. Currently,  
513 the availability of storm surge projections remains limited (e.g., Gaslikova et al., 2013,

514 Vousdoukas et al., 2018, Muis et al., 2020, 2023; Shimura et al., 2022) and most existing  
515 studies on future projections of extreme water levels extrapolate historical conditions and/or  
516 focus on the impact of sea-level rise (assuming stationarity of surges) in line with the static  
517 approach. Both pathways are further detailed below. It is followed by a section on  
518 challenges we intend to consider over the coming years.

519

## 520 a) Assessment based on Historical Data

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

526

527 A common means of filling observation gaps is the reliance on numerical systems such as  
528 those described above together with the availability of reanalysis to produce hindcasts of  
529 water levels. Over the past few decades, several studies have thus performed long hindcast  
530 based assessments of sea levels and related flood hazard and/or examined flood risk at the  
531 regional or global scales (e.g., Bernier and Thompson, 2006, Hinkel et al., 2014, Haigh et al.,  
532 2016, Muis et al., 2016, Colberg et al., 2019; Kirezci et al., 2023, Tiggeloven et al., 2020)  
533 and typically point to gradually increasing risk of exceeding locally critical water levels over  
534 the coming decades to centuries as a result of expected climate related change (e.g.,  
535 changes in storminess, sea-level rise).

536

537 Wahl et al. (2017) also relied on historical data but used a different approach. They  
538 assessed uncertainties in contemporary extreme sea levels, across 20 representative  
539 extreme value assessment methods and concluded that present-day extreme sea level  
540 uncertainties exceed those of global sea-level rise projections. A recent study by Hinkel et al.

541 (2021) assessed contributions to uncertainty and bias in current and future coastal flood risk  
542 and pointed to large uncertainties in numerous contributing factors, including those  
543 associated with adaptation measures and socio-economic responses. We note that long  
544 term trends can also be affected by temporal inhomogeneities due to non-climatic factors  
545 such as changes in the observational network or increasing quantity and quality of ingested  
546 observations in forcing atmospheric reanalyses. Emerging data-driven models (e.g., Tausía  
547 et al., 2023) offer complementary approaches for storm surge hindcast development.

548

549 Climate change impact on extreme sea level and related risks (e.g., flooding, erosion, salt  
550 intrusion) over the coming decades to century has been examined using numerical data  
551 and/or statistical techniques to supplement or replace long observation records and/or  
552 develop future projections that explicitly account for emission scenarios (e.g., Bernier et al.,  
553 2007, Lowe et al 2010, Muis et al., 2015, Muis et al., 2020, 2022; Vousdoukas et al., 2018;  
554 Tadese et al., 2020; Pringle et al., 2021a; Shimura et al., 2022; Lin et al., 2019; Almar et al.,  
555 2021). Various approaches are used. These have allowed growingly sophisticated studies of  
556 extreme sea levels and their changes through time to be performed for both areas with and  
557 without long observation records (e.g., Bernier et al., 2007). The story-line approach  
558 quantitatively considers the impact of global warming based on events that have occurred in  
559 the past (e.g., Takayabu et al., 2015). The probabilistic typhoon model approach is based on  
560 a probabilistic assessment of a large number of synthetic typhoons generated based on past  
561 typhoon statistics and can include worst-case scenario assessments (e.g., Marsooli et al.,  
562 2019; Ruiz-Salcines et al., 2021; Pringle et 2021a; Shimura et al., 2022).

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

## 567 b) Assessments based on long-term projections

568

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

579

580 As previously mentioned, the availability of future storm surge projections that explicitly  
581 account for climate change emission scenarios remains limited (e.g., Gaslikova et al., 2013,  
582 Vousdoukas et al., 2018, Muis et al., 2020, 2023; Shimura et al., 2022). . Moreover, large  
583 ensembles (Maher et al., 2021) of extreme water level projections have not been developed  
584 to date. These are needed to further investigate the role of different key uncertainty factors,  
585 namely climate and sea level modelling approaches, emission scenarios, and natural climate  
586 variability, that have been found to have an important role in the assessment of historical  
587 and future wave conditions (Casas-Prat et al., 2023; Morim et al., 2019; Grabemann et al.,  
588 2015; Grabemann and Weisse, 2008). The above-mentioned ongoing research in AI-based  
589 surge modelling has also been recently extended to develop future projections at local and  
590 regional scales (e.g., Ayyad et al., 2023). Depending on the success of these methods,  
591 similar applications at the global scale could be developed. AI could thus potentially be used  
592 to tackle the high computational demand associated with the production of large ensembles  
593 and support a wide sampling of the uncertainty of surge projections at a fraction of the cost  
594 of running hundreds of numerical simulations with traditional systems.

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## SurgeMIP activities: plans and progress

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As the maturity and reliance on numerical systems, extremal analyses, and information targeted to early warning systems, adaptation and mitigation 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°C or 2.0°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](http://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

622 [Warnings for All | World Meteorological Organization \(wmo.int\)](https://www.wmo.int)). Their operational production  
623 now allows services to be built to provide water level warnings in regions traditionally without  
624 numerical guidance. In recognition of the need for robust and reliable numerical guidance to  
625 be available along the world's coastline, the World Meteorological Organisation is in the  
626 process of establishing regional specialized meteorological centers for global numerical  
627 storm surge predictions. The three operational systems listed in this article meet established  
628 criteria (i.e., minimal coverage, data availability and metrics). Although each has been  
629 extensively validated and shown to meet national standards in the countries that operate  
630 them, validations were performed over different periods and sets of observation records.  
631 These systems have never been intercompared. Following online and a face-to-face  
632 meeting, we established requirements to participate in the intercomparison. We established  
633 a common hindcast period (2013-2018), common forcing fields (ERA5), common set of  
634 validation data drawn from GESLA3 including data handling (e.g., detiding), common output  
635 fields, and metrics to be considered. We are now performing the intercomparison of these  
636 operational and other research systems so that current and future progress can be  
637 monitored and communicated, and their skills and limitations are known before they are  
638 used to produce high resolution global projections of future coastal water levels. In time,  
639 regional systems will also be included in the intercomparison. Results of our intercomparison  
640 will help identify remaining gaps in our systems and help us tackle issues such as dealing  
641 with diverse gridding and resolution choices, different selection of processes (e.g., allowing  
642 for tides, waves, baroclinic processes, wetting and drying), and vertical datums (e.g., geoids,  
643 sea-level rise, isostatic post-glacial adjustment), before we further complexify the problem by  
644 expanding our intercomparison project to include regional systems, some of which are far  
645 more complex (e.g., include wave run-up, river flow), and before combining our global  
646 projections. These will be further discussed once the initial intercomparison is completed.  
647  
648 In the surge community, we often work across weather and climate time scales using the  
649 same systems. The intercomparison of past and present forecasts will thus inform the

650 interpretation of our climate projections. Over the coming decades and century, changes in  
 651 extreme sea level drivers (e.g., mean sea-level rise, receding ice, receding permafrost,  
 652 change in storminess, changes in rainfall and associated riverine effects) will continue to  
 653 evolve. Several studies have assessed the expected impacts (e.g., Bevacqua et al, 2020;  
 654 Hanson and Nicholls, 2020) but until recently, available driving fields such as surface  
 655 pressure and winds have been too coarse (both spatially and temporally) to produce a  
 656 robust numerical projections-based assessment under various climate scenarios for many  
 657 regions. Fortunately, projected atmospheric fields necessary to drive the projection of storm  
 658 surges are increasingly reaching the minimal resolutions required to resolve storms and  
 659 allow studies of extremes. Following face-to-face and online discussions, the SurgeMIP  
 660 community has established its data requirements for driving fields it draws from GCM  
 661 projections with extreme sea level projections in mind (table 1). We note the data  
 662 requirements listed in Table 1 are for global systems currently being operated. Projections  
 663 with systems able to, for example, capture river flow would result in additional requirements  
 664 such as higher granularity of forcing fields, the addition of precipitation and land information.  
 665

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

Ocean S profile (all levels in top 500m, 1000m, 2000m, bottom)	Monthly	25km
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666 Table 1: Data requirement for storm surge numerical projections. The first column is data  
667 type and level when appropriate, the second column is temporal resolution, the third column  
668 is spatial resolution.

669

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

674

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

680

## 681 Summary

682 In this letter, we highlighted the vulnerability of the world's coastline and coastal communities  
683 as we circled the world, briefly pointing to a few historical storms and their local impacts. We  
684 briefly reviewed the history of storm surge modelling, introduced the concept of extreme sea  
685 levels and related risks, and discussed climate change and its expected impacts. We pointed  
686 to the need for early warning systems and discussed recent progress towards the  
687 establishment of regional specialised meteorological centres for global numerical storm  
688 surge predictions. We briefly reviewed expected climate change contributions to future

689 extreme sea levels and the associated need to further our knowledge in support of the  
690 development and implementation of adaptation and mitigation measures. We introduced a  
691 new international initiative to intercompare surge forecast systems to inform on current  
692 capacities, current research gaps, and to inform on systems to be used to compute  
693 projections. SurgeMIP will also serve to coordinate projections developed by its various  
694 members to support wider and more complete sampling of projected scenarios. To date, we  
695 established data needs for the production of projections that support the study of extreme  
696 events (Table 1) and will be addressing some technical challenges such as dealing with  
697 various modelling choices and reference frames as we progress through the intercomparison  
698 we have initiated. We highlighted planned and in progress activities with outcomes we seek  
699 to achieve over the coming years. These include:

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

710

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

713

714

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**Declaration of interests**

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.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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